ULTIMO

Advancing Sustainable User-centric
Mobility with Automated Vehicles

DELIVERABLE

D6.1
Multivariate evaluation of ULTIMO CCAM ecosystem

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Acronyms

ADS	Automated Driving Systems
AI	Artificial Intelligence
AM	Automated Minibus
AP	Air Pollution
API	Application Protocol Interface
AV	Automated Vehicle
BEV	Battery Electric Vehicle
CAV	Connected and Automated Vehicles
CCAM	Cooperative Connected Automated Mobility
CCC	Climate Change Costs
CO_2eq	Carbon Dioxide equivalents
DB	Deutsche Bahn
DMP	Data Management Plan
EC	European Commission
E-LCA	Environmental Life Cycle Assessment
EU	European Union
EUCAD	European Conference on Connected and Automated Driving
GDPR	General Data Protection Regulation
GHG	Greenhouse Gas
GWP	Global Warming Potential
ICEV	Internal Combustion Engine Vehicle
IPR	Intellectual Property Rights
ITS	Intelligent Transport System
LaaS	Logistics-as-a-Service
LC	Life Cycle
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCSA	Life Cycle Sustainability Assessment
LIDAR	Light Detection And Ranging
MaaS	Mobility-as-a-Service
NMVOC	Non-Methane Volatile Organic Compounds
NO_x	Nitrogen Oxides
NIS2	Directive on Security of Networks and Information Systems
PHEV	Plugin Hybrid Electric Vehicle
pkm	Passenger km
PM	Particulate Matter
PTA	Public Transport Authority
PTO	Public Transport Operator
SAV	Shared Automated Vehicles
SAE	Society for Automotive Engineers
SAEV	Shared Automated Electric Vehicles
S-LCA	Social Life Cycle Assessment
SO_2	Sulphur dioxide
SQ	Status Quo
vkm	Vehicle km
TPG	Transport Publics Genevois
UITP	Union Internationale des Transports Publics (International Transport Union)
WP	Work Package
WPL	Work Package Leader

Executive Summary

This report analyses the multivariate (governance, economic, social, environmental, and technical) impact assessment of the ULTIMO CCAM ecosystem as a contribution to some key objectives of the ULTIMO project: (i.) To develop and validate cross-sectoral business models (ii.) To develop a realistic, long-term transition planning design for deploying AV in MaaS and LaaS and (iii.) To provide automated passenger services for safety and service quality. We discuss the key insights from each of the assessment as follows:

Governance Impact Assessment

- ### Data Governance

We explain data governance as a system of decision rights for data-related processes that describe who can take what actions with what data, when and under what circumstances. We discuss that AV requires a robust data governance framework, considering the vast amount of data it produces. Then, we discuss that in-vehicle AV data can be analysed to generate economically valuable insights for stakeholders. Nonetheless, in-vehicle AV data has to be accessible to maximise its benefits, and the decision on its access depends on the specific economic and technological context. From an economic viewpoint, we discuss the debate on AV in-vehicle data access, which hinges on market failure issues and how to address them. Market failure issues include competition problems, lock-in problems, quasi-monopolistic markets, information asymmetry, behavioural issues, externalities, low levels of interoperability and standardisation, and innovation problems. From the technical viewpoint, we discuss that the fundamental debate hinges on whether AV in-vehicle data should be ‘closed’ or ‘open’ and to what extent. We discuss three technical solutions for in-vehicle data access in a closed system: (i.) On-board application platform, (ii.) an internal or external applications programming interface (API) to access in-vehicle data, and (iii.) an external data server to manage third-party applications and data access, which offers possibilities with (a) extended vehicle concept, (b) shared/neutral server and (c) B2B marketplace.

Moreover, we discuss that open API and open data are essential to realise interoperability and coordination of all the stakeholders in the AV ecosystem. Open data and open APIs are paramount to facilitating CCAM and enable access to all means of transportation, which is required for Mobility-as-a-Service (MaaS). Thus, we argue that a standardised and harmonised open data and open API could be promising when AV is integrated into the MaaS ecosystem. Building upon theoretical insights, we argue that a scenario where public and private transportation entities would make their data available on an open data and open API platform and serve as integrators could address AV integrated in MaaS innovation data governance issues. The open data platform would be set up by a public authority or a neutral party with rules that apply to both parties. We argue that this scenario could facilitate AV in MaaS innovation, enable sharing of mobility data, avoid competition between private and public transport, and facilitate MaaS that includes integrating societal goals. We explain that the ULTIMO project will work on this scenario to contribute to the harmonised and standardised open data and open API objectives of the European Commission.

Then, we propose an analytical framework from the EU CCAM project knowledge base that ULTIMO partners could apply in co-creation workshops to deliberate on data governance issues. The analytical framework could serve as a decision support tool to address the technical and some economic challenges for the open data and open API governance framework in the ULTIMO project. Furthermore, we propose to conduct semi-structured interviews to investigate how to address the techno-economic data governance challenges for the ULTIMO project partners. We discuss our work plan for the second deliverable, due for submission in September 2026. This task will offer the following insights:

- Guidelines for decision-makers on designing robust data governance framework for AV and AV integrated in MaaS among public and private sector stakeholders in a mutually beneficial partnership while preserving the private sector and general interests.
- Context-specific roadmaps on data governance for AV and AV integrated in MaaS innovations to achieve sustainable business models.
- Insights on the governance framework to balance between privacy and the Intellectual Property Rights of Ultimo partners in accordance with the Consortium Agreement.
- Insight on practitioners' views on themes related to collaboration around open data and open data for AV integrated in MaaS and their relevance to practice.
- Insights on how to avoid a closed data ecosystem and prevent a dominant market position of some stakeholders or mitigate a winner-takes-all situation.

• Regulatory Analysis

This assessment contributes to the AV integrated in MaaS governance debate from the regulatory viewpoint. We focus on how AV and MaaS regulations (at the EU, national and local levels) can support market development and serve the general interest. We discuss the multi-faceted regulatory issues such as the tendency of technological advancement to eclipse regulatory oversight, regulation lagging behind technological innovation, regulation lagging behind marketplace changes, the winner-takes-all market problem, decision making challenge on whether to use ex-ante or ex-post regulation, regulations favouring particular interest group(s), regulatory silos at the national and local levels, and the intriguing challenge of balancing stakeholders' diverse interests. Then, we discuss learnings from related EU CCAM projects that have analysed AV regulation in urban transport systems at the EU, national, and local levels. We find that:

- there is a lack of harmonised regulations for testing and deploying AVs.
- there is a challenge to harmonise regulations because of the different and specific national and local contexts among the EU countries.
- there are diverse regulatory barriers for AV among EU countries.
- national frameworks are structured differently among EU countries.

We propose adapting the collaborative governance model for the ULTIMO project to address context-specific regulatory barriers at the national and local levels for AV integrated in MaaS innovation in Switzerland, Norway, and Germany. We hypothesise that public transport authorities and operators could play a central role in fostering AV integrated in MaaS innovation from a regulatory viewpoint. We hypothesise that insights from the collaborative governance model could help bridge the knowledge gaps and overcome context-specific regulatory barriers at the national and local levels for AV integrated in MaaS innovation in Switzerland, Norway, and Germany.

Then, we discuss our methodology for the second deliverable. We propose to combine three data collection and analysis methods: machine learning (text mining/analytics and clustering), semi-structured interviews, and co-creation workshops (to test our collaborative governance hypotheses). We argue that combining epistemologically inductive and deductive research approaches in a complementary manner could offer insights to address AV integrated in MaaS regulatory issues. Finally, we discuss our work plan for the second deliverable, due for submission in September 2026. The deliverable will offer the following insights:

- Context-specific guidelines and roadmaps to adopt collaborative governance for AV integrated in MaaS innovation to support sustainable business models in Norway, Switzerland, and Germany at the national and local levels.
- Context-specific recommendations for PTA/PTOs on collaborative regulation to foster the integration of all transport modes that contribute to safer, sustainable, inclusive, and efficient mobility in the urban transport system.
- Guidelines for policymakers to design adaptable and fit-for-purpose regulatory governance to support AV and MaaS innovations.
- Guidelines for collaborative governance among regulatory institutions at the national and local levels in Norway, Switzerland, and Germany.
- Insights on how to align regulations with industry requirements to meet the needs of local and national innovators, build mutually beneficial partnerships and preserve the private sector and general interests.

Economic Impact Assessment

• Economic cost-benefit analysis

We conduct a comprehensive analysis of the existing literature and from EU CCAM project deliverables. We find the following knowledge gaps:

- A lack of empirical data for designing sustainable business models.
- A lack of systemic economic evaluations considering social and environmental impacts.

These knowledge gaps highlight the need for a detailed understanding of the economic impact of AV services, particularly within the MaaS and LaaS ecosystems. We conduct preliminary analysis for two ULTIMO project scenarios: ‘AV as a bus line’ and ‘AV in MaaS’ using the Oslo site. We find that:

- labour costs (including the salaries of on-board supervisors) contribute significantly to the total operations costs in both scenarios.
- We find that energy and maintenance cost savings led to a slight decrease in the total cost per kilometre under the scenarios.
- The ‘AV as a bus line’ scenario had a lower cost per kilometre compared to ‘AV in MaaS’, although the latter offered greater flexibility in service provision.
- Using offboard supervisors led to potential cost reductions, for ‘AV as a bus line’, where the cost per kilometre decreased by over 50% in the most extreme case.

We propose to use the Total Cost of Mobility (TCM) framework to provide a quantitative economic impact assessment in line with the larger goal of developing sustainable business models. We anticipate that the economic insights could become integral to a holistic approach that considers social and environmental dimensions, favouring balanced and sustainable business models. Finally, we discuss our work plan for the second deliverable, due for submission in September 2026. The task will offer the following insights:

- Enhance understanding of the cost benefit implications of AV services by delving deeper into the factors influencing cost structures and exploring scenarios for optimising operational efficiency and cost-effectiveness of AV in MaaS and LaaS.
- Propose a multi-layered approach that includes state-of-the-art analysis, stakeholder engagement, empirical data analysis and in-depth case studies.

- Propose a comprehensive cost-benefit assessment framework tailored to the objectives of the ULTIMO project to provide further perspectives and practical implications for assessing the economic feasibility of AV services.
- The potential costs of AV adoption and implementation for policymakers to inform decisions about integrating AVs in a more sustainable manner.
- The cost-benefit analysis extended to consider the MaaS ecosystem's actors will be treated in the form of a sustainable business model.

• Dynamic Price Modelling of AV integrated in MaaS.

We analyse dynamic pricing strategies for the integration of AV in MaaS. First, we conduct a comparative analysis of dynamic pricing and static pricing for AV. The insights drawn from the review of existing literature suggest that:

- Dynamic pricing could offer a strategic advantage for private transport operators integrating AV in MaaS.
- Adopting dynamic pricing to assess the economic viability of AV integrated in MaaS could offer a step towards realising an adaptable transport model aligned with the evolving transport needs of urban societies.

Then, we review different methodologies for dynamic price modelling, including demand estimation models, machine learning techniques, price optimisation models, game theory, agent-based/simulation models, statistical models and elasticity models, to understand what methodology could be more suitable for developing an efficient dynamic pricing algorithm for AV in MaaS. Our analysis includes an evaluation of the strengths and weaknesses of each methodology and the types of data or variables required to design dynamic pricing algorithms using these methodologies. We find that:

- The adoption of machine learning (in particular, reinforcement learning) technique for dynamic price modelling appears more promising than the other methodologies, given its efficacy in refining pricing strategies to align with fluctuating market demands and operational challenges.
- Reinforcement learning seems promising in contributing to the economic viability and sustainability of AV integrated in MaaS innovation.
- Reinforcement learning could offer a pivotal step towards realising the full potential of AV technology within the evolving transportation landscape.
- Reinforcement learning could offer a robust framework for understanding decision-making in complex environments while highlighting the intricate balance between operational efficiency, revenue maximisation, and customer satisfaction.

Nonetheless, reinforcement learning could be computationally challenging. Therefore, its successful application in dynamic price modelling requires quality data to model market dynamics and customer behaviour complexities. Thus, applying reinforcement learning in ULTIMO will require collaborative efforts with many partners, especially collaboration with the PTA/PTOs and research institutions, to access the necessary data to train the reinforcement learning models. Finally, we discuss our work plan for the second deliverable, due for submission in September 2026. The second deliverable will offer the following insights:

- Optimal pricing strategies specific to the different ULTIMO use cases for public transport operators and authorities (PTAs and PTOs).
- Commercially viable and sustainable solution when AVs are integrated in MaaS.
- Understanding the relationship between user demand and price changes (elasticity).

- Policy recommendations to support AV integrated in MaaS in urban transport systems.

Social Acceptance

We conduct a literature review and analyse learnings from other EU CCAM projects on user acceptance of AV. We find that:

- there is a lack of a holistic and citizen-centric approach that predicts the adoption of automated vehicles integrated in MaaS.
- There is a lack of empirical evidence on the relationship between the antecedents of intention to use and behavioural intention to use.

Therefore, we propose to bridge this knowledge gap within the social acceptance assessment in the ULTIMO project. We will design a representative survey of potential users at the city level and test the hypothesised relationships between the antecedents of the behavioural intention to use AV and the behavioural intention to use. Our conceptual model will incorporate sociodemographic, socioeconomic, service characteristics, travel behaviour patterns, beliefs, attitudes, and perceptions about automated vehicles integrated in MaaS in a holistic approach. Then, we discuss our proposed methodology for the second deliverable due for submission in September 2026. The second deliverable will provide insights on:

- The significant and relevant behavioural determinants that could influence the behavioural intention to use AV integrated in MaaS.
- Constructs to predict the adoption of AV integrated in MaaS.
- The behavioural determinants that could encourage potential AV users to use the service and facilitate acceptance of AV integrated in MaaS.
- The conditions to improve to increase the usability of the proposed AV service and satisfy the users' need to facilitate a shift from private cars to AV services.
- The willingness to pay of potential AV users for the offered AV services to support PTO/PTA pricing strategies.
- Appropriate public policies to facilitate acceptance of AV in MaaS.

This task will offer key results to support PTO/PTA with guidelines and recommendations to create a positive public perception and to make potential users become AV regular users. It will also provide recommendations for policymakers on the economic and non-economic incentives that could lead to higher acceptance of AV integrated in MaaS.

Environmental Assessment

This task will examine the external costs of integrating AV in MaaS at the three ULTIMO pilot sites. We conduct a preliminary analysis of the environmental impact of mobility innovation. We find that AV in MaaS could be a promising innovation with low environmental impact. We argue that using a Life Cycle Sustainability Assessment (LCSA) methodology will provide insights beyond environmental factors to include social and economic factors in order to understand the hidden costs of mobility to the society. Then, we discuss our work plan for the second deliverable. The second deliverable will offer the following insights:

- A comprehensive assessment encompassing environmental, social, and economic costs to promote a holistic sustainability-based life cycle approach.
- Guidelines to support inclusive, and environmentally responsible mobility solutions.
- Total life cycle emissions and impacts (environmental and social) with monetary values and insights to support policymakers.

Technical Assessment

We discuss that safety is also a foremost concern in adopting AVs, even though AVs are envisaged to curtail most road accidents that are largely due to human errors. We explain that this task will offer insights into enhancing the safety of Level 4 AV occupants and vulnerable road users (VRUs) at the ULTIMO pilot sites. We explain the technical complexities of the level 4 AV system because of the interconnected system of sensors, processors, and external units. Therefore, the complex array of sensors need to function properly, which are essential for interpreting the surrounding environment and facilitating decision-making processes to avoid safety hazards. Then, we argue that to enhance the safety of AV users and VRUs, there is a need to correctly predict potential failures and quality defects to protect users and VRUs in normal AV operations and emergency events. We argue that addressing safety issues of Level 4 AV is the sine qua non to facilitating public acceptance and trust in AV systems. Stakeholders' interviews and V2X technologies analysis could be insightful to increase the safety of Level 4 AV.

We propose to apply a qualitative approach (semi-structured expert interviews) to provide insightful contributions on Level 4 AV safety issues. Then, we discuss our work plan for the second deliverable, due for submission in September 2026. The second deliverable will offer the following insights to stakeholders: (i.) Guidelines to improve safety, reliability and inclusiveness, to achieve an integration of AV in MaaS in the public transport system. (ii.) Guidelines to understand technical obstacles to integrate LaaS in a MaaS system (iii.) Recommendations to support the PTA/PTOs in designing sustainable business models.

Takeaways for Policymakers

- AV requires a robust data governance framework, and the decisions to access in-vehicle AV data to maximise societal welfare depend on specific economic and technological contexts.
- Standardised and harmonised open data and open API could facilitate AV in MaaS innovation.
- A scenario where public and private transportation entities would make their data available on an open data and open API platform and serve as integrators could provide insights to address AV in MaaS data governance issues.
- Despite regulations at the EU level, regulatory issues for AV in MaaS are multifaceted and challenging to address at the national and local levels, and require careful analysis.
- A collaborative governance model where PTA/PTOs could play a central role in fostering AV in MaaS innovation could help address context-specific regulatory barriers at the national and local levels for AV in MaaS innovation.
- Combining epistemologically inductive and deductive interdisciplinary research approaches: machine learning techniques (text mining/analytics and clustering), semi-structured interviews, and co-creation workshops in a complementary manner could offer insights to address AV in MaaS regulatory governance issues.
- Preliminary cost-benefit analysis of two ULTIMO project scenarios: ‘AV as a bus line’ and ‘AV in MaaS’ shows that using offboard supervisors led to operating cost reductions. This shows that Level 4 AV could support sustainable business models compared to Level 3.
- Comprehensive total cost of mobility methodology could be integral to a holistic approach that considers social and environmental dimensions to support sustainable business models.
- Adopting dynamic pricing could offer a strategic advantage over static pricing for PTOs/PTA integrating AV in MaaS.
- Adopting dynamic pricing to assess the economic viability of AV integrated in MaaS could offer a step towards realising an adaptable transport model aligned with the evolving transport needs of urban societies.
- A review of dynamic pricing modelling methodologies to understand the most efficient technique for AV in MaaS shows that adopting machine learning (reinforcement learning) seems more promising than others, given its efficacy in refining/optimising pricing strategies to align with fluctuating market demands and operational challenges.
- Understanding the intention to use AV will support PTO/PTA to offer AV in MaaS, create positive public perception, and provide insights to make potential users become regular users
- Understanding the intention to use AV will provide insight to PTO/PTA to design economic and non-economic incentives that could lead to higher acceptance of AV in MaaS.
- Preliminary analysis of the environmental impact of new mobility innovation shows that AV in MaaS could be a promising innovation with low environmental impact.
- Life Cycle Sustainability Assessment (LCSA) is a robust methodology to provide holistic insights beyond environmental factors (that is, it includes social and economic factors) to understand the hidden costs of mobility to society.
- Even though AVs are envisaged to curtail most road accidents mainly due to human errors, the safety of AV occupants and vulnerable road users is also a key concern in adopting AVs.
- Addressing safety issues of Level 4 AV is the sine qua non to facilitate public acceptance and trust in AV systems.
- Stakeholder interviews and V2X technologies analysis, could be insightful to increase the safety of Level 4 AV.

1 Introduction

During the past few years, many projects and initiatives have been undertaken to deploy and test automated vehicles (AVs) for public transportation and logistics. However, despite their ambition, all of these projects stayed on the level of elaborate experimentation and never reached the level of a large-scale commercial deployment of transport services. There are many reasons for this, the most important being the lack of economically viable and commercially realistic models, the lack of scalability of the business and operating models, and the lack of user-oriented services required for large end-user adoption of the solutions. The ULTIMO project will create the first economically feasible and sustainable integration of AVs for MaaS public transportation and LaaS urban goods transportation. ULTIMO aims to deploy 15 or more multi-vendor SAE L4 AVs per site in three European sites. A user-centric holistic approach, applied throughout the project, will ensure that all elements in a cross-sector business environment are incorporated to deliver large-scale, on-demand, door-to-door, well-accepted, shared, seamless-integrated and economically viable CCAM services. We target the operation without a safety driver onboard, in a fully automated and mission management mode, with the support of innovative user-centric passenger services.

ULTIMO's innovative transportation models are designed for a long-term sustainable impact for automated transportation in Europe, around the globe, and society. The composition of the consortium ensures interoperability between multiple stakeholders by adopting new technology at minimum costs and maximum safety. The integration of the ongoing experiments of previous AV-demonstrator projects ensures the highest possible technical and societal impacts from the very beginning of the project, as well as during the project's lifetime and after its completion.

1.1 On-demand Mobility

Public transportation is a key element of a region's economic development and the quality of life of its citizens. Governments worldwide are defining strategies for developing efficient public transport based on different criteria of importance to their regions, such as topography, citizens' needs, social and economic barriers, environmental concerns, and historical development. However, new technologies, modes of transport and services are appearing, which seem promising to support regional strategies for developing public transport.

On-demand transport is a public transport service that only works when a reservation has been recorded. It will be a relevant solution where the demand for transport is diffuse and regular transport is inefficient. On-demand transport differs from other public transport services in that vehicles do not follow a fixed route and do not use a predefined timetable. Unlike taxis, on-demand public transport is usually also not individual. An operator or an automated system handles the booking, planning and organisation. It is recognised that the use and integration of on-demand automated vehicles have the potential to significantly improve services and provide solutions to many of the problems encountered today in the development of sustainable and efficient public transport.

1.1.1. Fully Automated Vehicles

A self-driving car, referred to in the ULTIMO project as a Fully Automated Vehicle (AV), is a vehicle that can sense its environment and move safely with no human input.
The terms *automated vehicles* and *autonomous vehicles* are often used together. The Regulation 2019/2144 of the European Parliament and of the Council of 27 November 2019 on type-approval requirements for motor vehicles defines "automated vehicle" and "fully automated vehicle" based on their autonomous capacity:
An "automated vehicle" means a motor vehicle designed and constructed to move autonomously for certain periods of time without continuous driver supervision but in respect of which driver intervention is still expected or required "Fully automated vehicle" means a motor vehicle that has been designed and constructed to move autonomously without any driver supervision.
In ULTIMO, we operate ***Fully Automated mini and micro shuttles for shared public transportation***. In relation to the SAE levels, the ULTIMO project will operate SAE Level 4 vehicles (see Figure 1).

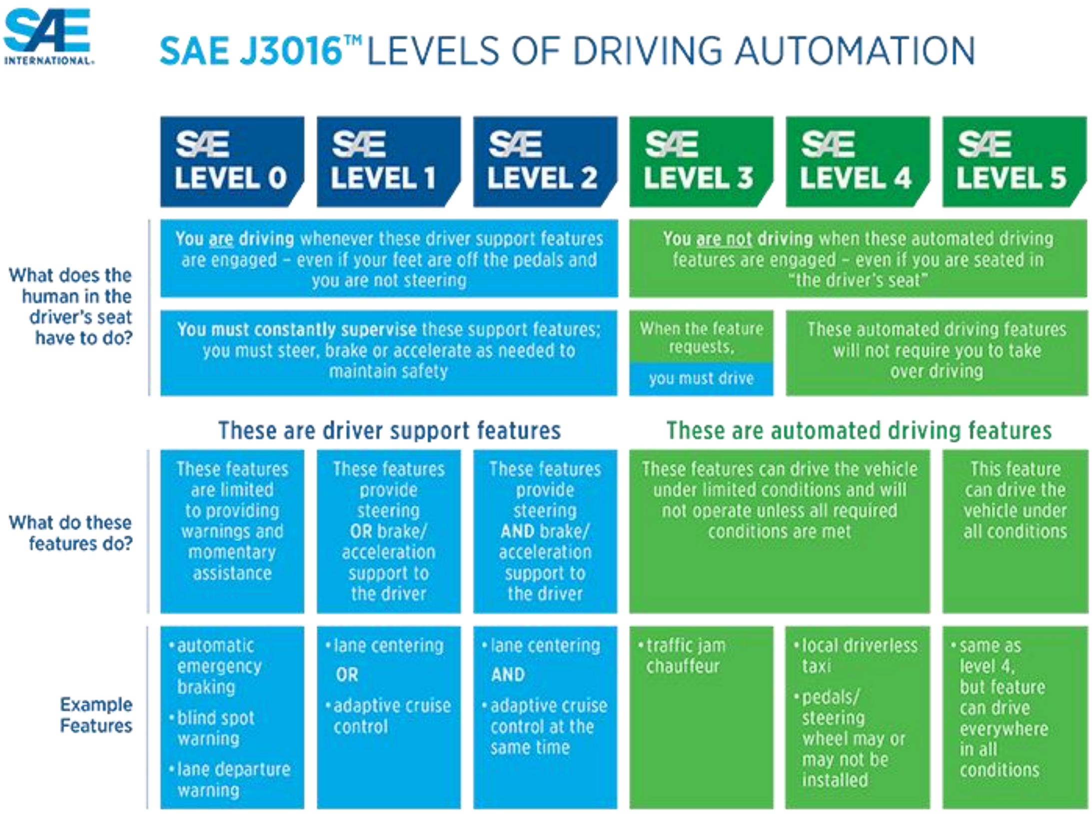


Figure 1: SAE Driving Automation levels (©2020 SAE International)

1.2 The ULTIMO dream for public transportation

Our city has a population of 700.000, and the local PTO (Public Transport Operator) deploys 3.000 Km of public transportation services' routes, with 4 backbone tram lines, 8 backbone large bus/trolley lines, and 340 fully automated multi-manufacturer mini and micro-shuttles in an on-demand, door-to-door shared public transport service. The fleet of the 340 automated mini-busses is composed of different vehicle generations and models from different manufacturers, as it was purchased in different batches during the last 12 years (it all started with the first 15 bought by a European project in 2023/24). It is today composed of the first 15 twelve-years old vehicles from manufacturer A, 160 eight-years old vehicles from manufacturer B and 160 two-years old vehicles from manufacturer A, which are the new generation of manufacturer's A vehicles. These last 160 vehicles replaced the last 70 old, driver-based, thermic busses that reached the end of their life after 18 years in operation. The change from driver large busses to automated mini-buses and from fixed line service to on-demand, door-to-door for the last area of the city was decided 6 years ago and was based on the great success of the already deployed AV-based services in the other parts of the city.

The integration of new vehicles in the PTO fleet was done within just a few days, thanks to the now standardised APIs of the automated vehicles' connection with the AV fleet management and orchestration service, that allows a plug-and-operate functionality, but also enables the combination of AVs with all other means of transport, offering a seamless citizen centric journey to the users. Similarly, the now standardised High Definition (HD) maps between the vehicle manufacturers, allowed us to reuse the maps created in the past for the 3.000 Kms of routes of the city, with small adaptations for the new vehicle capabilities. At the same time of the purchase of the last 160 AVs, we also switched to a new AV fleet management and orchestration service, from another provider, which offers more precise trip time estimations, considering also traffic jams in the city and weather conditions (that affect traffic in the city). The replacement was made within just two weeks, thanks to the new standardised interfaces between AV fleet management and PTO MaaS services.

Passengers are now able to reserve, via their mobile phone app, on the fly or with pre-reservation trips from one side of the city to another, using the optimal transport mode available for them, with a combination of different transport modes, and having the automated vehicle arriving next (or almost) to their door entrance and bringing them to their final destination or to a backbone transport connection. All trips are offered with highly reliable and accurate transport and arrival times based on real-time, dynamic route changes of the vehicles, responding to the passenger needs. Many passenger services are available in the AVs via a mobile phone app, adapted to all passengers' needs, from special needs passengers (visually impaired, wheel-chair users, pregnant women, elderly, children) to persons transporting suitcases or a baby-stroller, providing adapted information of their trip (where to get-off, PTO general information, and even infotainment, like city related information and historical facts and anecdotes, related to their current position).

With the full suppression of onboard operators, automated in-vehicle monitoring provides many passenger services, which were developed with continuous collaboration and innovation between users and the PTO. An on-board unit identifies locally (that is, in the bus) incidents and events, like aggressions, vandalism, forgotten objects, littering, accidents, etc., and raises incident alarms to the PTO back office. Based on the operator's policies, the PTO officer at the back office evaluates the incident and decides what action to take: dismiss the incident or stop the vehicle and call one of the intervention teams to go to the vehicle and take the required action. Based on the number of incidents and intervention time legal obligations, the back-office operator can deploy any of the 15 intervention teams available in the city, ready to reach any AV within a few minutes. At the back-office, service operators are able, with one set of screens linked to the fleet management, to follow the vehicle status, trip reservations, routes chosen, open and closed road segments (due to works, accidents, etc., thus adapting

dynamically the trip routings), while in a second set of screens, the back-office operators can follow the passenger services' incidents and the status and location of the intervention teams. Although independent, the two systems are linked so that the back-office operator can transfer incidents to intervention teams and turn on video connection when possible and under the local legal restrictions to inspect the incident.
The public transport services operate 24/7 with different active vehicles, depending on passenger transport demands. The PTO, being eco-sensible, has defined that the vehicle must have an average occupancy of at least three passengers. This has implications, especially in off-peak hours, on the transport delays, but it is fully justified for an optimal and eco-responsible operation. Exceptions are made for people with special needs or when the passenger is ready to pay an additional price.

While at peak hours, the entire 340-strong fleet of AVs is in service for public transportation, in the off-peak and night hours, due to the reduced transportation needs, part of the fleet is not serving passenger transportation. However, because having an idle vehicle is a waste of resources, the PTO has signed an agreement with Logistics as a Service (LaaS) Service providers. During the off-peak hours, the unused vehicles are dynamically chartered by the different LaaS providers to be used for other types of incidental transport of goods or even non-public transportation of passengers. Local shops and enterprises use the service, on-demand with dynamic reservation, to offer home delivery of online purchases or B2B delivery of goods from an urban consolidation centre to the distribution centre (hub, many to one or one to many, or even transport their VIP customers directly to their offices or exposition centres. This way they can deliver the goods to their customers in the city, with a delay of just 60 minutes with affordable prices, as the last mile is the most inefficient part of the goods delivery chain. The goods sent can include books from local bookshops or libraries, supermarket bags or documents exchanged between companies or waste. The local shops can even use the service in the early hours (5 a.m.) to re-provision their shops for the day. The chartered AVs are "returned" to the PTO for public transport at peak hours automatically at the end of the chartered period.

1.3 Preamble

The ULTIMO project is divided into seven (7) Work Packages (WP 1-7). Specifically, WP 6 has three tasks (Task 6.1, Task 6.2, and Task T6.3) and focuses on the impact evaluation and transformation towards an AV in the ITS/CCAM ecosystem. Task 6.1 is the technical, social, economic, environmental, business and governance evaluation of seamless transport of persons and goods. Task 6.2 is the concept, operating models, and business development for a future intelligent citizen-centric transport ITS/CCAM ecosystem for persons and goods. Task 6.3 is the transformation strategy towards a future intelligent citizen-centric transport ITS/CCAM ecosystem for persons and goods.

This deliverable D6.1 on multivariate evaluation of the ULTIMO CCAM ecosystem is for Task 6.1. It focuses on the key scenarios of the ULTIMO project as follows:

- Scenario 1: AV without MaaS, privately owned cars, traditional taxis, and private/public transport (TPG, Geneva, Switzerland).
- Scenario 2: AV integrated in MaaS, private transport competing with or not complementing public transport (Ruter, Oslo, Norway; DB, Herford, Germany).
- Scenario 3: AV replacing traditional bus line (DB, Herford, Germany).

Each chapter of this deliverable D6.1 discusses each impact assessment dimension.

Chapter 2 is the *governance impact assessment.* It is divided into two parts: *data governance and regulatory analysis*. The *data governance* task aims to achieve the 'European Data Strategy' to create a single data market for safer and cleaner transport systems and automated data exchange through harmonised data formats and standards. In this context, open API and open data are required to realise interoperability and coordinate stakeholders to achieve the highest benefits for the stakeholders and the general interest. The *regulatory analysis* task aims to explore a model where public authorities could play a central and crucial coordination role in integrating AV in the MaaS or ITS ecosystem. The regulatory analysis task will focus on assessing appropriate governance approaches to strike a balance between private and general interests to maximise societal benefits. This task will consider relevant regulations within the EU and the European Economic Area (EEA) and other applicable regulations at the national and local levels. It will focus on the role regulation can play both as an enabler and a challenge for transport system innovation, emphasising regulations such as the GDPR, NIS 2 and the Data Governance Act.

Chapter 3 is the *economic impact assessment*. It is divided into two parts*: economic cost-benefit analysis* and *dynamic price modelling* of AV in MaaS innovation. The economic cost-benefit analysis task evaluates suitable innovative models for value creation for citizens, PTA/PTOs, and municipal governments. This task will focus on identifying all costs linked to implementing an AV within a MaaS and evaluating them monetarily. We plan to use the total cost of mobility (TCM) approach, including monetising externalities. The results will feed into T6.2, which studies value creation models with AV services for transporting people and goods. *The dynamic price modelling task* aims to design appropriate pricing to support cross-sectoral business models using data from AVs, passengers, service providers, and PTAs/PTOs for the 'AV in MaaS' business ecosystem. The objective, among others, is to design how the integration of door-to-door and on-demand data from AVs in MaaS can support informed decision-making on tariff design and transform 'AV in MaaS' towards an intelligent self-learning (AI-based) system to improve automated decisions of 'AVs in MaaS' for PTOs, PTAs, cities, and mobility service providers. We anticipate to adapt and test AI-based algorithms and tools in this task.

Chapter 4 is the *social acceptance of AVs***.** This task aims to understand the requirements of AV integrated in MaaS to function in a citizen-centric approach. This task aims to provide insight into understanding under what circumstances potential AV users can become regular users and replace their private cars with AV in MaaS. Furthermore, this task will analyse the user acceptance of AV in MaaS. The goal is to assess how mobility behaviour can change if AV service is offered to focus on reducing private car use.

Chapter 5 is the *environmental impact assessment.* This task will analyse the external costs and rebound effects of AV in MaaS in urban transport systems. Based on the external cost evaluation (environmental and social), we will provide insights on the 'hidden' transportation costs to the society. Then, based on a life cycle perspective (Life Cycle Sustainable Analysis), this task will analyse the type and extent of impact of potential externalities for the deployment of AVs at the different sites and the whole integrated system.

Chapter 6 is the *technical impact assessment.* This task will focus on AV safety (vehicle, passenger and vulnerable road users safety). The objective is to provide insights to improve safety, reliability, inclusiveness to achieve a cost-optimised integration of AV in MaaS in the public transport system.

Chapter 7 is the general conclusion with a recap of the key insights from the other chapters and the next steps.

In sum, this deliverable D6.1 provides holistic insights into the governance, economic, social, environmental, and technical impact assessments for stakeholders based on the ULTIMO scenarios above. Furthermore, we apply the SUMP methodology in this deliverable. SUMP methodology is Europe's urban transport planning concept designed to meet people's mobility needs for a better quality of life and to deal effectively with the complexities of urban transport (Rupprecht, 2019). This D6.1 deliverable will support sustainable urban mobility and promote cooperation across institutional boundaries (PTA, PTOs, business entities, private actors, and citizens). We will involve stakeholders, assess current impact assessment scenarios, and promote the integration of AV in MaaS in an integrated and interdisciplinary manner. Moreover, we will define a long-term vision and implementation plan, build and assess potential future scenarios, co-create a shared vision with stakeholders, agree on actions and responsibilities among the consortium partners, and develop visions and strategies with stakeholders. Thus, we will apply SUMP to deal with the complexity and dynamism of integrating AV in urban transport systems.

2 Governance Impact Assessment

2.1 Data Governance Assessment

2.1.1 Introduction

The European Commission has identified a lack of data access for innovative reuse as an obstacle to realising its data economy potential (Graef and Prüfer, 2021; European Commission, 2020). To support data access and sharing, there is a need for more coherent data governance frameworks as data access and sharing increasingly occur across sectors (OECD, 2021). Data governance is a system of decision rights and accountabilities for data-related processes, executed according to agreed-upon models that describe who can take what actions with what data, when, under what circumstances, and using what methods (Vial, 2023). Many benefits stemming from data access and sharing are based on the fact that data created in one domain or sector can provide further insights when applied in another domain or sector (OECD, 2021). The European Commission has enacted the Data Act (European Commission, 2022a) to ensure fairness in allocating value from data among actors in the data economy and to foster data access. Also, the Data Governance Act (European Commission, 2022b; Richter, 2023) aims to facilitate individuals' and businesses' voluntary data sharing and harmonises conditions for using certain public sector data and the GDPR for data privacy and protection (European Commission, 2016). Nonetheless, there are still apparent challenges. Data access and sharing barriers prevent an optimal data allocation for societal benefit. The barriers include the lack of incentives for data holders to enter into data sharing agreements, uncertainty about rights and obligations on data issues, costs of contracting and implementing technical interfaces, data fragmentation in silos, the absence of standards for technical interoperability, and a lack of standard data sharing practices (European Commission, 2022a).

Mobility is crossing a new digital frontier, allowing vehicles to communicate with one another, with the road infrastructure and other road users (CCAM, 2023). Data is essential for data-driven innovation (Baloup et al., 2021). Automated systems are a key segment of disruptive technologies for which data are constantly collected, processed, and shared to enable their operations (Tan et al., 2023). Automated Vehicles (AV) can receive, produce, process, and transmit vast amounts of data. Levels 2 and 3 AVs (on the SAE scale) are estimated to generate around twenty-five gigabytes of data per hour. In comparison, fully automated vehicles could generate up to 3,600 gigabytes of data per hour (Gill, 2022). These include in-vehicle data, data sent from other vehicles or infrastructure, and traffic data (Kerber, 2018; Andraško et al., 2021a). In-vehicle AV data includes technical data about the vehicle, road traffic conditions, weather, and driving behaviour. In-vehicle data helps to ensure the correct operation of the vehicle, check proper functioning, and offer new innovative services for vehicle repair and maintenance, as well as other services. In-vehicle data can also be used for different purposes, such as road safety and traffic management, fleet management, quality management and product development (Andraško et al., 2021b; ACEA, 2016). In-vehicle data can be analysed to generate economically valuable insights for stakeholders (Ditfurth and Leeneman, 2022). In-vehicle AV data has to be accessible to maximise its benefits, and the decision on its access depends on the specific economic and technological context (Kerber, 2020). Among others, the AV data governance debate hinges on these two dimensions.

From an economic perspective, the fundamental questions are: under which conditions is the data holder willing to share data? What are the welfare consequences? This is also relevant in B2B, where innovative firms may be less inclined to share their data than socially optimal for the general interest (Kerber, 2020). The crux of the debate is on market failure issues and how to address them. The market failure issues are competition problems (foreclosing competitors and leveraging market power through exclusive data control), lock-in problems and quasi-monopolistic markets. Others are information asymmetry, behavioural issues (that is, transparency about the collection and use of data by data-collecting firms, high transaction costs of self-managing privacy), externalities (regarding data provision but also to harms caused by data breaches and cybersecurity risks), low levels of interoperability and standardisation (due to biased incentives of firms regarding interoperability and standardisation), and innovation problems (due to insufficient sharing and use of data) for data-driven innovations (Graef and Prüfer, 2021; Kerber, 2020).

From the technical perspective, a fundamental debate is whether AV data should be ‘closed’ or ‘open’ and to what extent.

Closed AV system.
In a closed AV system, the OEM controls access to the AV, and consumers could be ‘locked in’. The technological choice between a ‘closed’ or an ‘open’ system is important to understand (i.) who has control of the data and (ii.) the choice between an interoperable ‘open’ or ‘closed’ AV model. OEMs prefer a closed system; they argue that a closed system helps ensure the vehicle operates safely and securely and avoids any risk of attack on or access to the vehicle’s security system. Besides, the OEMs argue that any external systems or software programs not under their control should be avoided, and third parties should not have direct access to in-vehicle data (ACEA, 2016). Therefore, to remove barriers to a well-functioning internal market for data, it is necessary to lay down a harmonised framework to specify who, other than the OEMs, is entitled to access the data generated by AVs, under which conditions and on what basis (European Commission, 2022a).

Three main technical solutions for in-vehicle data access in a closed system are being discussed among stakeholders: (i.) On-board application platform: an internal in-vehicle operating system that supports installing third-party applications which can access the in-vehicle data (ii.) an internal or external applications programming interface (API) to access in-vehicle data and (iii.) an external data server to manage third-party applications and data access (data is uploaded to the server) (Kerber and Jonas, 2017; Kerber, 2018). API is a software tool designed to enable communication between two computer applications (Borgogno and Colangelo, 2019). API allows a digital application to interact with an associated program by describing the kind of data that can be retrieved, how to do it and the format. With APIs, applications can communicate and use the datasets of one another, thus facilitating stakeholders’ interactions. APIs could represent the building blocks of modular industrial architecture platform business models and provide a scalable governance mechanism for managing platforms. However, data sharing via APIs requires a complex implementation process, and sound standardisation initiatives are essential for its success (Domeyer et al., 2021; Borgogno and Colangelo, 2019).

Furthermore, three external data server-based solutions exist: (i.) extended vehicle concept, (ii.) shared/neutral server and (iii.) B2B marketplace (Kerber, 2018). The extended vehicle concept makes it possible to access AV data through some interfaces depending on the purpose for which access is sought: an on-board diagnosis interface with limited access to in-vehicle data for diagnosis, repair and maintenance; ad hoc communication interface and a web interface for other third-party remote diagnostic support services (ACEA, 2016). (ii.) B2B marketplace means an agreement between the service provider and the OEM to access in-vehicle data; the OEM will not monitor data access except to prevent unauthorised access and system attacks and to the extent required for quality management, compliance with data protection legislation, and to enable payment. (iii.) A shared/neutral server gives service providers the choice between direct data access through the OEM's server or via 'neutral' servers that would gather the data from the OEM's servers. The neutral server operator(s) will be required to have a B2B agreement with the OEM and to implement state-of-the-art security and data protection measures. Neutral servers could facilitate data access by offering multi-brand data access on one server rather than multiple servers of different OEMs (ACEA, 2016).

Open AV system.
An open data ecosystem is an emerging concept for data sharing and access that involves co-creation and collaboration to harness innovation potential from data and manage costs. The stakeholders collaborate on data access and sharing (software and standards) by exchanging data, resources, and artefacts to create value (Runeson et al., 2021). Open data offers opportunities for user-led and intelligent planning decisions. However, the critical risk is that the shift in knowledge control and associated power to private stakeholders could make governing mobility more challenging in the long term (Docherty et al., 2018). Furthermore, the open data ecosystem is quite complex because of the need to share and interoperate open data among the stakeholders. To access and use data efficiently, there is a need for technical standards for automated data exchange through harmonised data formats and standards (Domeyer et al., 2021; Borgogno and Colangelo, 2019; Charalabidis and Zuiderwijk, 2018; CCAM, 2023). Data interoperability is essential, as the quality and consistency of shared open data and the data format are crucial (UITP, 2019).

Open API and open data are vital to realising interoperability and coordination of all the stakeholders in the AV ecosystem. Open data and open APIs are paramount to facilitating CCAM and enabling access to all means of transportation. Access to all means of transport is required for Mobility-as-a-Service (MaaS). MaaS may have the potential to provide an attractive alternative to private car use and promote a shift towards sustainable transport modes. Therefore, MaaS is seen as a tool for reducing congestion and negative environmental impacts and for the renaissance of more lively urban areas and connected communities (Ertico-ITS Europe, 2019). Nonetheless, creating a thriving MaaS ecosystem requires (i.) an open ecosystem for service providers with open and secure APIs, (ii) interoperable IT systems for open data exchange, (iii) user- and market-centricity (iv) flexible and adaptable ecosystem and (v) high quality and reliable data exchange (MaaS Alliance, 2017). An open and competitive MaaS ecosystem with interoperable and standardised APIs can support a sustainable mobility ecosystem (MaaS Alliance, 2020). Therefore, a standardised and harmonised open data and open API could be promising when AV is integrated in the MaaS ecosystem.
The following section discusses the Ultimo project's data governance context to achieve open data and open API for AV integrated in MaaS innovation.

2.1.2 The Ultimo project's data governance context

Notably, the European Commission advocates an open data and open API ecosystem where data could be made freely accessible (or for a small fee to cover the costs of running a secure and safe data governance system) in a non-discriminatory way (European Commission, 2022c). Moreover, (the European Commission 2018, 2020, 2021) has set the following objectives for CCAM data.

- Develop a harmonised data-sharing approach based on open and interoperable programming interfaces (APIs) and access control by defined user rights.
- Allow access to in-vehicle real-time data and resources, as needed, available on-board and remotely to all authorised service and application providers.
- Allow access to in-vehicle real-time data and resources in a context of innovation, open access, cross-industry interoperability, choice, portability of services for the user, price affordability, and competitiveness.
- Allow access to in-vehicle real-time data and resources for third-party maintenance, repair, and improvement of vehicles throughout their lifecycle.
- A focus on the data value chains, data storage needs, related standards or data formats and related infrastructure.
- Provide a secure system architecture and comply with data security and cybersecurity requirements.

The ULTIMO project (Ultimo) aims to achieve the objectives of the European Commission pragmatically for Level 4 AV by bringing together public sector institutions (PTOs/PTA, research institutes) and private entities (such as competing fleet orchestrators, technology companies and OEMs) in the project's consortium. It is anticipated that open data and open API should help break data silos and facilitate public-private cooperation under the intellectual property rights agreement of the consortium partners. Furthermore, ULTIMO aims to achieve a standardised API for the in-vehicle on-board unit (OBU), supervision dashboard and user-centric mobile application for passenger services.

In the context of ULTIMO, there will be different APIs: an API for the fleet orchestrators (ZF, Padam Mobility, Trapeze), an API for the OEMs [Gamma, Sensible4 (replaced by Padam Mobility)], and an API for the AV passenger service data collection and management (CERTH). The OEMs, fleet orchestrators and passenger service data providers will have to add a layer to translate their proprietary APIs to the standardised API. The goal is to achieve a standardised open-source API among the proprietary APIs of Gamma and Padam Mobility[1] for the different AV models for the vehicle control and monitoring interface. The V2X OEM's API will have to be connected to the harmonised APIs of the AV fleet orchestrators (to be achieved among ZF, Padam Mobility, and Trapeze). This should facilitate interoperability and the seamless integration of new AVs from different OEMs into the PTOs /PTA (Ruter, DB and TPG) AV fleet, V2X communication, and the harmonised and standardised APIs of the fleet orchestrators and passenger service providers into the MaaS services of the PTOs/PTA following ULTIMO's defined scenarios. The ULTIMO scenarios are:

- Scenario 1: AV without MaaS, privately owned cars, traditional taxis, and private/public transport (TPG, Geneva).

[1] Padam Mobility took over the role of responsibility of Sensible4 following their bankruptcy.

- Scenario 2: AV integrated in MaaS, private transport competing with or not complementing public transport (Ruter, Oslo; DB, Herford).
- Scenario 3: AV replacing traditional bus line (DB, Herford).

Open data and open API may also help combine MaaS and LaaS[2] under a single Intelligent Transportation System (ITS). In other words, all the APIs need to be standardised, and a harmonised and standardised API achieved for the project. It is anticipated that the harmonised and standardised open-source (in-vehicle and out-of-vehicle) APIs will allow fleet orchestration services to directly connect to any AV model with a standard interface, thus eliminating data flow incompatibilities among OEMs, fleet orchestrators and other passenger service providers. Capgemini Engineering is the technology and system integrator and will offer the architecture for the onboard (PS-OBU) passenger service unit to integrate passenger services and communications with the different systems. The standardised open-source in-vehicle API will connect the data stream to the in-vehicle OBU (Mobile Thinking) and, through its communication channel, connect to the PTO and PTA back-office for safety and security. Both APIs are expected to integrate AV in MaaS/LaaS (with fleet orchestrators, OEMs, and service providers) for passengers, other road users and goods services. To validate the interoperability of the developed APIs and ensure there are no technical incompatibilities, each project site (Oslo, Geneva, Herford) will operate and switch among the fleet orchestration service providers of the three providers (ZF, Padam Mobility and Trapeze).

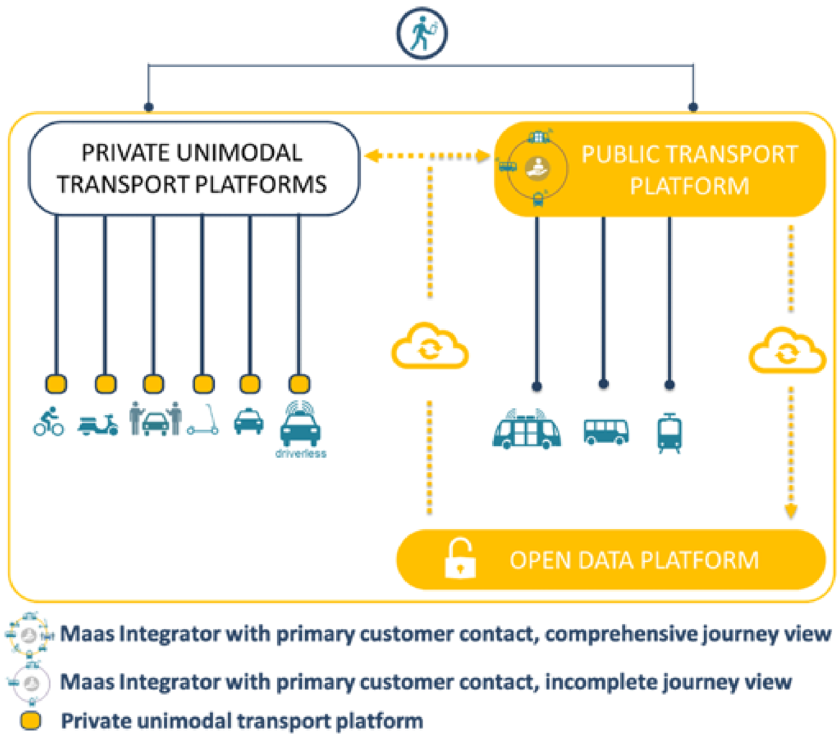
From a theoretical perspective, different integrator models have their perceived strengths and weaknesses. Building upon the works of Shapiro and Varian (1999), UITP (2019), Sochor et al. (2018); Fournier et al. (2023) analyse four possible data governance scenarios with different MaaS operators as integrators.

Governance scenario 1 – No mobility integration

In the first scenario (Figure 2), private transport competes with public transport. Private mobility service providers would have their mobility data and databases to operate their unimodal platforms. In this scenario, data protection is essential and should be ensured. The private companies act in a customer-centric manner. Therefore, customer-centric action would be classified as high in this scenario.

[2] LaaS means Logistics-as-a-Service.

Figure 2: Governance scenario 1 - No mobility integration

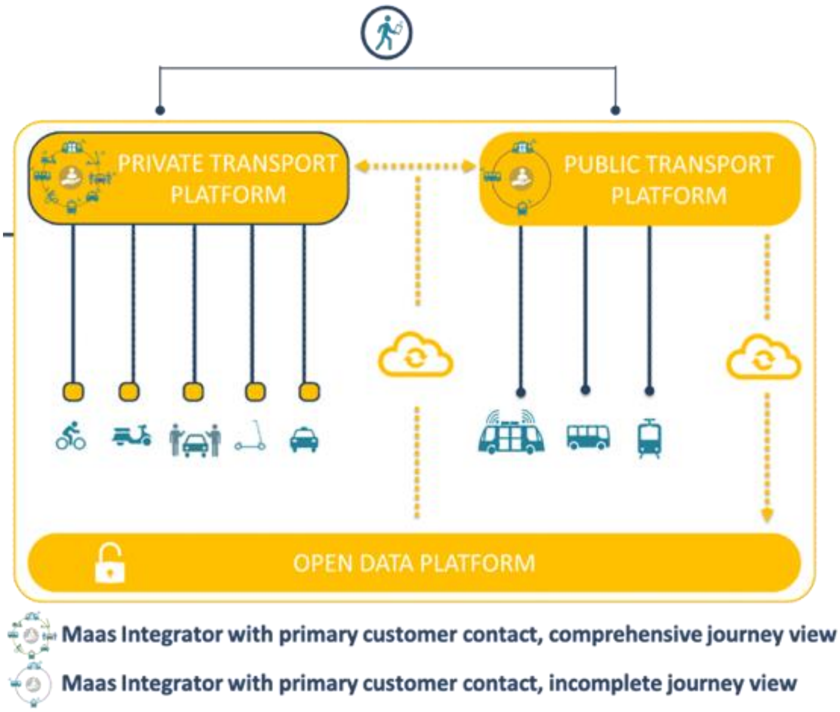


Source: Fournier et al. (2023)

Governance scenario 2 – Private transport as integrator

In the second scenario (Figure 3), commercial integrators would act as MaaS operators within a marketplace with other transport operators. Private mobility service providers would take on the integrator role. Private mobility service providers would not provide data, leading to an asymmetry in competition. In this scenario, public transport would make its data available on an open data platform, to which both private and public transport would have access. Then, private mobility service providers could build their own MaaS systems and complement them with public transport, offer better services and act in a customer-centric way. This could lead to a situation where public mobility service providers cannot improve and optimise their services to offer a comprehensive range of more sustainable travel options. As a result, private transport services could appear significantly more attractive to customers. This scenario could be more customer-centric and innovative, as competition between integrators would be encouraged.

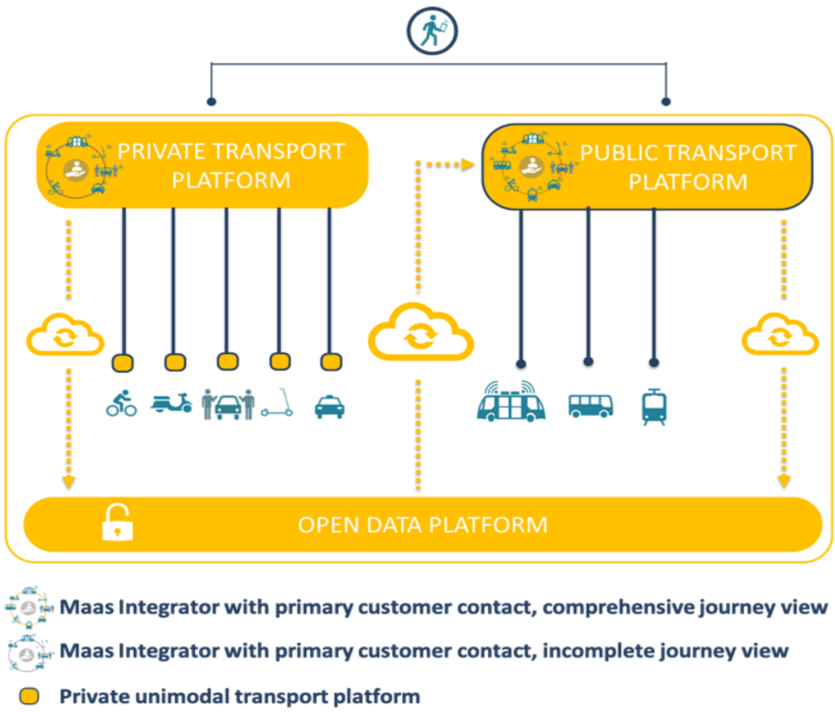
Figure 3: Governance scenario 2 - Private transport as integrator



Source: Fournier et al. (2023)

Governance scenario 3 – Public Transportation as Integrator
In the third scenario, public transport would take on the integrator role. Both private and public transport would share their data on an open data platform. This would allow public transport to offer a comprehensive range of mobility services, as it can access the data of private mobility providers. In this scenario, the MaaS service could either be developed and operated entirely by the public sector or contracted out and licensed to a private organisation. This would help public transportation remain relevant to existing customers and become more attractive to new users (UITP, 2019). Public transport could offer customers a comprehensive range of services and complement their services with private mobility service providers. If the public transport operator manages to integrate a wide range of mobility partners, this scenario has the potential to achieve more sustainable mobility aligned with public policy objectives. In addition, regulating and protecting public interests and data protection could be easier through close contractual relations with the authorities.

Figure 4: Governance scenario 3 - Public Transportation as Integrator



Source: Fournier et al. (2023)

This scenario could be classified as less customer-oriented and innovative than the second scenario. The public MaaS operators could only make the necessary effort to keep the system running; a 'public-transportation-takes-all' situation could happen (Ackermann, 2021). Also, due to the lack of innovation, car-based mobility services could emerge as a reaction to the public sector monopoly. In addition, due to unclear responsibilities and legal barriers, the public sector could have fewer scaling opportunities at the national or even international level.

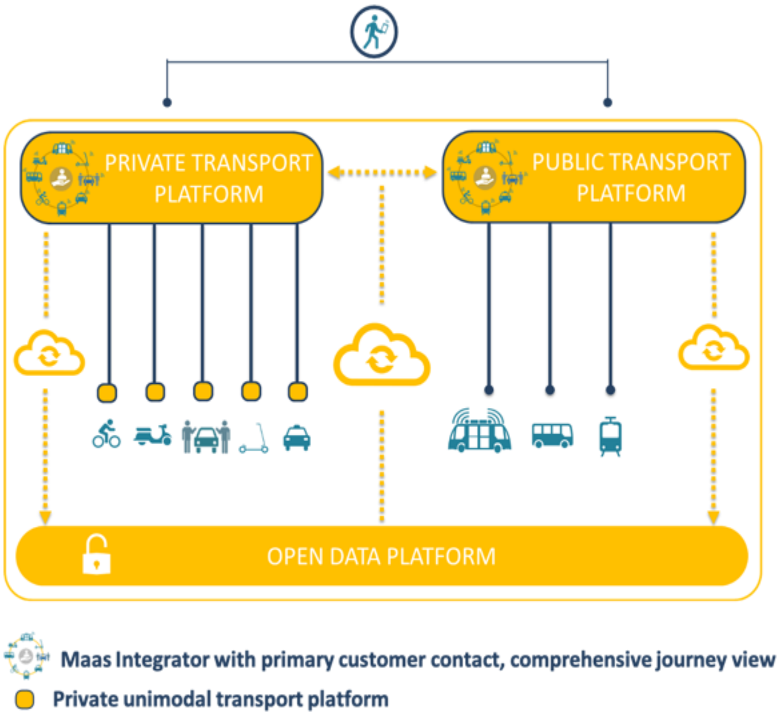
Governance scenario 4 - Public and Private Transportation as Integrator

Public and private transportation entities would make their data available on an open data platform and serve as integrators. The open data platform would be set up by a public authority or a neutral party with rules that apply to both parties. The open data platform would be a back end for private and public MaaS providers to build their systems and source data (UITP, 2019). In this scenario, all mobility service providers, both private and public, would need to support their open APIs to integrate with the platform. This is also highlighted in the 'Passau Declaration'[3]. This scenario could create room for transparent competition. It would be a customer-oriented, innovative, and impartial approach. For this scenario to materialise, concepts such as "Open Data" and "Open API" would have to be implemented. Open application interfaces would enable intermodal ticketing (customers can complete entire intermodal and multimodal journeys with a payment transaction). It could also ensure a seamless combination of public and private mobility services and encourage sharing mobility services. The scalability of this scenario would be high, as local and international service providers could enter the market and thus improve the overall offering of mobility services. As

[3] For data mobility, the free flow of information must be enabled, interoperability must be ensured, and the values and interests of the broader society must be safeguarded, as private actors will play a central role in exploiting the data value chain (Passau Declaration, 2020).

a result, it would be possible to target different market segments with various differentiated offerings.

Figure 5: Governance scenario 4 - Public and Private Transportation as Integrator



Source: Fournier et al. (2023)

Public and Private Transportation as integrators could facilitate AV in MaaS scenarios that enable the sharing of mobility data, avoid competition between private and public transport, and facilitate MaaS that includes integrating societal goals.

The ULTIMO project mirrors scenario four (4), as described by Fournier et al. (2023). In the ULTIMO project, the public transport integrators are the PTA/PTOs (Ruter, DB and TPG), while the private integrator will be Capgemini Engineering. Then, the open data platform will be transferred to a neutral party, such as the CCAM association[4] or Ertico-ITS Europe[5]. The proposed ULTIMO data governance framework is expected to contribute to achieving the EU Commission objectives.

The harmonised and standardised open-source (in and out-of-vehicle) APIs are envisaged to break technical barriers and address some of the economic (market failure) challenges (discussed above)—notably, lock-in problems, monopolistic tendencies, winner-takes-all phenomenon, information asymmetry, and foster innovation. Adopting APIs according to consistent standardisation initiatives could help balance stakeholders' multifarious interests (Borgogno and Colangelo, 2019). Therefore, ULTIMO could serve as a case study to achieve the European Commission's standardised open data and open API CCAM objectives.

Achieving the standardised open API objectives will require collaboration among ULTIMO consortium partners. Therefore, it is paramount to develop a data governance framework that helps facilitate partners' cooperation, breaks technical barriers, addresses market failure

4 CCAM Association is a not-for-profit organisation representing the private side of the CCAM Partnership, with more than 180 innovation stakeholders involved in the connected, cooperative, and automated mobility field.

5 Ertico-ITS Europe is a PPP with the goal to develop, promote, and deploy Intelligent Transport Systems and Services (ITS)

issues, and that is workable within the scope of the intellectual property rights of the consortium partners. In order words, the data governance framework should combine elements of economically efficient centralisation with legally necessary decentralisation (Inge and Prüfer, 2021). Also, the choice of optimal governance design could depend on the different stakeholders' perspectives. Therefore, the governance framework should align the stakeholders' perspectives with the project's goals (Delft, 2018; Veeneman et al., 2018) while appropriately balancing the consortium partners and the general interests. In sum, adaptive, innovative, and responsive strategies are required for the governance of AV (Tan and Taeihagh, 2021).

Next, we will explain how this deliverable will contribute to the data governance debate to support a commercially viable and sustainable solution when AV is integrated in MaaS to achieve a standardised open data, open API under private and public transportation as an integrator (or PTA/PTO as integrator).

2.1.3 Link between the data governance deliverable and the other tasks in the Ultimo project

This task will provide insight into Task 6.2 on the business strategies, models, and cases for future intelligent citizen-centric transport and sustainable business model design for AV integrated in MaaS. We will contribute to designing a mobility business ecosystem and support the strategy design or transformation concept towards a future intelligent citizen-centric transport ITS/CCAM ecosystem for persons and goods. We will identify data governance challenges to the diffusion of AV and AV in MaaS innovations and offer policy recommendations for cities, public transport operators and authorities. This data governance deliverable is linked to Task 1.5, which aims to provide an overview of the critical ethical and legal considerations in the Ultimo project. This task is also linked to WP2 (Task 2.1) on the passenger and PTO needs and use cases, and WP4 on the automated passenger services for MaaS, LaaS, vehicle and infrastructure and ITS management.

This task will contribute to a holistic impact assessment of AV and AV integrated in MaaS in urban transport systems (Task 6.1). We will provide insights on how effective data governance can contribute to developing and validating innovative cross-sectoral business models for private and public stakeholders (ULTIMO's key objective 6). We will also provide insights on achieving realistic, long-term transition planning and design to deploy AV in MaaS with context-specific governance frameworks to serve the general interest (ULTIMO's key objective 8). The following section will discuss our research methodology for the second deliverable.

2.1.4 Methodology

Starting from a literature review on open data and open API, we will explore practitioners' views on collaboration-related themes around open data and their relevance to practice (Runeson, 2019). The service descriptions and the data list of the project (WP4) will be used for the deliberation on the data governance framework for the different use cases (WP2) at the ULTIMO project sites (WP5). We intend to organise co-creation workshops with public transport authorities, operators, research institutions and all the technical partners. In the co-creation workshops, we intend to build upon the EU CCAM project's existing knowledge base on data sharing and reuse framework (CAD, 2023).

In the co-creation workshops, we will deliberate on the ownership and access to data and data tools, storage, access, areas of use, post-project reuse, and financing. During each co-creation workshop, we will note salient points brought up by participants, allowing us to account for the emergence of new issues that require further investigation in the next co-creation workshop (Vial, 2023). The list of questions (below) provides a good analytical lens (CAD, 2023).

Table 1: Knowledge Base on Connected & automated Driving in Europe (CAD, 2023)

Ownership and access to data and data tools	• Who owns the data? • Is adding a specific ownership clause for the collected data necessary? • How could the data be used, and on which conditions? • Will all partners have access to all/part of the data? • May the data be licensed to third parties? • May third parties have access to the data, and on what conditions? • Are there constraints related to personal data, especially video and tracked location data or location data in general? • Are there future agreements with data providers to take into account? • Who will own the analysis tools, and on what conditions are they licensed during and after the project? • Has a partner included previous work as background in the tools? • Who owns the IPR for this work, and how does it affect the project? • How can data be reused if one partner owns the data and this partner ceases operation or leaves the project?
Storage and download of data	• How will the data be stored - centrally or distributed? • What are the general requirements for data protection, and how are they assured? • Shall all/part of the data be downloadable for all partners, and if so, under which conditions? • Shall all/part of the data be downloadable for third parties, and if so, under which conditions? • Is there a time limit for requesting data for download? • Is there a time limit for keeping the data?
Access methods	• Can the data be downloaded, remotely accessed, or only accessed at the premises of any partner? • Shall a specific access procedure be used, and by whom? • Who should manage the access procedure? • How will the data be accessed? • What are the requirements for data protection for partners/third parties analysing the data?

Areas of use	• Can the data be used for education, research, and commercial purposes? • Are there special conditions for commercial use? • In which research/commercial areas could the data be used? (i.e., safety, mobility)
Post-project reuse of data	• Which partner is responsible for maintaining the data after the project? • Shall a non-partner provide the project data after the project? • Which application procedure shall be used? • Who will grant access to the data after the project? • Are there conditions, such as legal and ethical constraints and availability of funding for data storage and access services, to be considered? • Are there time limits after which the data needs to be deleted?
Post-project financing	• How will the storage and support services for data reuse be financed after the project? • Known or to be decided? • How will this funding be distributed?

The analytical framework could serve as a decision support tool to address the technical and some economic challenges of the open data and open API governance framework in the ULTIMO project.
Then, we will conduct semi-structured interviews with stakeholders to address the techno-economic data governance challenges for the ULTIMO project partners. Semi-structured interviews are usually one-on-one discussions between an interviewer and a respondent to gather information on specific topics and are conducted in person or over the phone (Harrell and Bradley, 2009). It is an appropriate method to resolve seemingly conflicting information because the researcher can directly ask about the apparent conflict. When interested in determining the relative emphasis on an issue, that is, how strongly someone holds an opinion, semi-structured interviews permit the researcher to ask for emphasis (Harrell and Bradley, 2009). Furthermore, a semi-structured interview is suitable when the objective of the research is to understand complex elements and their intersection with perceptions, beliefs, and values (Noel, 2019).

Our respondents will be selected to represent a diverse array of stakeholders. We target a minimum of 50 interviewees from the ULTIMO consortium partners - the persons involved in the events (Yin, 2003). The interview will last thirty to ninety minutes and will be conducted face-to-face, online or by phone. We will maintain the anonymity of the respondents. The interviews will address the data governance techno-economic challenges. To ensure correct understanding, we will explain ‘seemingly’ technical terms to the respondents before the commencement of the interviews. We provide below a (tentative) list of possible interview questions:

- What are the risks of market foreclosure from consortium competitors and other players who could exercise market power through access to in-vehicle data?

- What are the consequences of externalities, such as data breaches and cybersecurity risks regarding access and sharing of in-vehicle data, and how do we mitigate them?
- How do we address information asymmetry problems regarding in-vehicle data access and sharing among the consortium competitors?
- How do we avoid lock-in problems among competitor partners?
- How do we avoid behavioural problems such as the lack of trust and transparency on data sharing and access among consortium competitors?

Data processing and analysis

The interviews will be coded using NVIVO[6] or a similar software package to transcribe and organise the recorded audio data. NVIVO provides tools that assist in undertaking qualitative data analysis to collect, organise, analyse and produce reports from data (Jackson and Bazeley, 2019). We intend to tag each feedback systematically to facilitate our analysis. In addition, we intend to contact the respondents to verify the accuracy of our transcriptions and request their permission to use their feedback with or without attribution. We shall analyse the results to gain insights into the opportunities, challenges, and suggestions to overcome the techno-economic data governance challenges.

With the co-creation workshop and semi-structured interviews, we anticipate to have insights into how to address some of the central techno-economic data governance challenges and to contribute to achieving ULTIMO's and EU's CCAM goals. The following section will discuss our proposed work plan for the second data governance deliverable.

2.1.5 Proposed Work Plan

The ULTIMO general assembly (GA) could be utilised for the co-creation workshops. We expect all the technical partners, PTAs, and PTOs at the GAs to participate in the co-creation workshops. The semi-structured interviews will be held between Q3 2024 and Q1 2026. We will then integrate the insights from the co-creation workshops and the stakeholder interviews in the second data governance deliverable. The Gantt chart below is our top-level (tentative) activity schedule.

Activities	Start date	End date	Q2 2024	Q3 2024	Q4 2024	Q1 2025	Q2 2025	Q3 2025	Q4 2025	Q1 2026	Q2 2026	Q3 2026
Co-creation workshops	Apr-24	Mar-26										
Semi-Structured interviews	Sep-24	Mar-26										
Report containing roadmaps and guidelines	Apr-26	Sep-26										

The report containing roadmaps and guidelines will be submitted in September 2026. The following section will discuss the expected results in the second deliverable in September 2026.

[6] NVIVO is a software for qualitative data analysis from interviews or surveys.

2.1.6 Expected results.

The second report of this task in September 2026 will offer the following insights:

- Guidelines for decision-makers on designing robust data governance framework for AV and AV integrated in MaaS among public and private sector stakeholders in a mutually beneficial partnership while preserving the private sector and general interests.
- Context-specific roadmaps on data governance for AV and AV integrated in MaaS innovations to achieve sustainable business models.
- Insights on the governance framework to strike a balance between privacy and the Intellectual Property Rights (IPR) of ULTIMO partners in accordance with the Consortium Agreement (CA).
- Insight on practitioners' views on themes related to collaboration around open data and open data for AV integrated in MaaS and their relevance to practice.
- Insights on how to avoid a closed data ecosystem and prevent a dominant market position of some stakeholders or mitigate a winner-takes-all situation.

2.1.7 Conclusion

More access to data for innovative reuse is essential for the EU to achieve its data economy potential. Therefore, to support data access and sharing, there is a need for more coherent data governance frameworks. We explain data governance as a system of decision rights for data-related processes that describe who can take what actions with what data, when and under what circumstances. Despite the recently enacted Data Act and Data Governance Act, there are still apparent data governance challenges in the EU. We discuss that AV requires a workable data governance framework, considering the vast amount of data it produces. Then, we discuss that in-vehicle AV data can be analysed to generate economically valuable insights for stakeholders. Nonetheless, in-vehicle AV data has to be accessible to maximise its benefits, and the decision on its access depends on the specific economic and technological context.

From an economic viewpoint, we discuss the debate on AV in-vehicle data access, which hinges on market failure issues and how to address them. The market failure issues are competition problems, lock-in problems and quasi-monopolistic markets, information asymmetry, behavioural issues, externalities, low levels of interoperability and standardisation, and innovation problems. From the technical viewpoint, we discuss that the fundamental debate hinges on whether AV in-vehicle data should be 'closed' or 'open' and to what extent. We discuss three technical solutions for in-vehicle data access in a closed system: (i.) On-board application platform, (ii.) an internal or external applications programming interface (API) to access in-vehicle data, and (iii.) an external data server to manage third-party applications and data access, which offers possibilities with (i.) extended vehicle concept, (ii.) shared/neutral server and (iii.) B2B marketplace. Besides, we discuss the open AV data ecosystem that involves co-creation and collaboration to harness innovation potential from data and manage costs. Moreover, we discuss that open API and open data are essential to realise interoperability and coordination of all the stakeholders in the AV ecosystem. Open data and open APIs are paramount to facilitating CCAM and enabling access to all means of transportation, which is required for Mobility-as-a-Service (MaaS). Therefore, open data and open API are required for AV integrated in MaaS innovation. Thus, we argue that a standardised and harmonised open data and open API could be promising when AV is integrated in the MaaS ecosystem.

Then, we discuss the objectives of the European Commission for open data and open API ecosystem and the ULTIMO project's context under three scenarios: (i.) AV without MaaS (ii.) AV integrated in MaaS and (iii.) AV replacing traditional bus lines. Building upon theoretical insights, we argue that a scenario where public and private transportation entities would make their data available on an open data and open API platform and serve as integrators could address AV integrated in MaaS data governance issues. The open data platform would be set up by a public authority or a neutral party with rules that apply to both parties. The open data platform would be a back end for private and public MaaS providers to build their systems and source data. We argue that this scenario could facilitate AV integrated in MaaS innovation and enable the sharing of mobility data, avoid competition between private and public transport, and facilitate MaaS that includes integrating societal goals. We explain that the ULTIMO project will work on this scenario to contribute to the harmonised and standardised open data and open API objectives of the European Commission.

We discuss that achieving the standardised open API objectives will require collaboration among ULTIMO consortium partners. Therefore, it is paramount to develop a data governance framework that helps facilitate partners' cooperation, breaks technical barriers, addresses market failure issues, and that is workable within the scope of the intellectual property rights of the consortium partners. Then, we propose an analytical framework from the EU CCAM project knowledge base that ULTIMO partners could apply in co-creation workshops to deliberate on data governance issues. The analytical framework could serve as a decision support tool to address the technical and some economic challenges for the open data and open API governance framework in the ULTIMO project. Furthermore, we propose to conduct semi-structured interviews with stakeholders to investigate how the benefits of data sharing could outweigh the costs and risks for the ULTIMO project partners. That is, the interviews will address the data governance techno-economic challenges.

Finally, we discuss our work plan for the second deliverable, due for submission in September 2026, and explain the insights we will offer: (i.) Guidelines for decision-makers on designing robust data governance framework for AV and AV integrated in MaaS while preserving the general interests. (ii.) Context-specific roadmaps and guidelines to overcome techno-economic data governance challenges for AV and AV integrated in MaaS innovations to achieve sustainable business models. (iii.) Insights on the governance framework to balance privacy and the Intellectual Property Rights (IPR) of ULTIMO partners (iv.) Insights on how to avoid a closed data ecosystem and prevent a dominant market position of some stakeholders or mitigate a winner-takes-all situation.

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2.2 Regulatory Impact Assessment

2.2.1 Introduction

Automated Vehicle (AV) is one of the inventions in the digital age, with the potential to drastically change the structure of cities in the future (Tran and Quoc Le, 2022; Rashidi et al., 2020). AV could have positive and negative impacts on the urban transport system. On one hand, AV could reduce private vehicle ownership and parking demand, thereby contributing to safety, congestion reduction and environmental sustainability (Singh et al., 2023; Othman, 2021; Lee and Hess, 2020). It could also offer a potential solution to close gaps in transportation services for first and last-mile transit trips. It could improve transportation services in sparsely populated areas that cannot support the high cost of a fixed-route service (Nesheli et al., 2021). On the other hand, AV may have adverse environmental impacts such as sprawling land use, increased vehicle miles travelled associated with congestion, and increased travel time consequences (Schepis et al., 2023; Nikitas et al., 2021; Freemark et al., 2020). Thus, appropriate governance frameworks are required to capture the potential benefits, minimise possible negative impacts, and support the integration of AV in the urban transport system (Docherty et al., 2018). This deliverable will contribute to the AV governance debate, focusing on 'regulation' from the 'polity' dimension of governance (Treib et al., 2007).

Regulation is a critical issue to consider in preparing a society for AV adoption (Chen et al., 2020). Given that the term ‘regulation’ is used for many purposes and means different things to different people in diverse fields of expertise, we clarify that this deliverable addresses ‘regulation’ from an institutional economics perspective as a constitutive element (Levi-Faur, 2011) of the AV and MaaS markets to serve the general interest. The challenge of regulating AVs highlights the need for a regulatory framework with effective corrections to apparent problems and anticipatory capacities to identify and address new, continuously evolving, and complex challenges (Taeihagh et al., 2021; Shladover et al., 2019). Regulating AVs is also challenging due to the high level of risks and uncertainty associated with them. Moreover, the stakeholders may not bear the costs of their risks, transferring them instead to the society and reducing societal welfare.

The burgeoning AV ecosystem epitomises the tendency of technological advancement to eclipse regulatory oversight (Mordue et al., 2020). Therefore, achieving a robust regulatory framework incorporating AV integrated in MaaS innovations is difficult because it is challenging for policymakers to keep up with the rapidly evolving innovation pace (Schepis et al., 2023). Understandably, innovations have to be present in some way before enacting regulations. Then, regulations could play a pivotal role in governing innovation. Therefore, regulation typically lags behind technological innovation (Docherty et al., 2018). Regulatory problems are likely if AV and MaaS market players establish a market for their products before market regulation; that is when regulation lags marketplace changes (Suck et al., 2023). Thus, there is a ‘pacing problem’ or the lag between regulatory responses and technological innovation (Bernstein, 1955; Mordue et al., 2020; Taeihagh, 2021).

If the market is very open before regulation, prominent market players may foreclose the market, which could lead to a winner-takes-all situation[7] (Shapiro and Varian, 1999). Thus supporting the need for ex-ante regulation. It is worth noting that an industry may seek regulation for itself, or regulation may be thrust upon it (Stigler, 1971). Notwithstanding, ex-ante regulation may also impede innovation as regulations may serve as a barrier to entry for some market players. While regulation may be instituted primarily for the general interest, regulation could impede market entry and entrepreneurship and favour the parochial interests of small groups rather than the public interest (Stigler, 1971). Given the rapid development of AV technology, regulatory approaches should also anticipate unfolding risk scenarios while providing a robust framework for innovators to operate rather than lag. Regulatory hurdles have implications for the progress of AV innovation and are challenging to address. Thus, there is a need to understand the feedback loop of the impact of transport regulations on the development of AV innovation and vice-versa (Schepis et al., 2023). The balance between innovation and regulatory oversight may be difficult to establish; too little regulation and too much regulation may be counterproductive (Goyal et al., 2021).

At the international level, the Geneva (UN, 1949) and Vienna (UNECE, 1968) conventions are the basic international traffic regulations for road traffic, drivers, and vehicles in many countries (Hansson, 2020; Attias et al., 2018; Busquet et al., 2019). The EU has ratified these conventions. It is noteworthy that Article 8 of the Vienna Convention necessitating the presence of a driver in a vehicle or combination of vehicles was amended in 2016 to pave the way for the inclusion of AVs in road transport (Busquet et al., 2019). Article 8 is amended to 'system which influences how vehicles are driven and other systems which can be overridden or switched off by the driver. Also, the United Nations established the Working Party on Automated and Connected Vehicles (GRVA)[8] in 2018. GRVA achieved the adoption of amendments to UN Regulation No. 79 that the driver should not necessarily be in primary control of the vehicle steering (UNECE, 2018; Attias et al., 2018; Bonnardel et al., 2021). Therefore, at the international level, there has been some acceptance of AV in the transport system within the last ten years, which could support market development.

At the EU level, major regulations impacting AV have been enacted. For example, the Data Act (European Commission, 2022a) in November 2023, the Data Governance Act (European Commission, 2022b) in May 2022, the Digital Markets Act in November 2022 (European Commission, 2022c), General Data Protection Regulation (European Commission, 2016) in May 2016, and the Directive on the Security of Network and Information Systems (NIS2) in December 2022 (European Commission, 2022d). These regulations impact AV because it is a data-driven innovation. At the EU level, the regulations appear to focus on standardisation, competition, and safety issues, among others. At the national and local levels within the EU Member States, the regulations vary from country to country and appear to focus on licensing issues and infrastructure access (European Commission, 2021). Thus, it is challenging to harmonise regulations because of the different and specific national and local contexts among the EU countries.

[7] Shapiro and Varian (1999) describe positive feedback based on demand-side economies of scale and network externalities leading to extreme outcomes - for example, a situation where market dominance by a single firm results in a winner-take-all market. A winner-take-all market occurs when a single firm or technology vanquishes all others because of the strong desire of users to choose the network that has (or will have) the most users.

[8] GRVA is a subsidiary of the World Forum for Harmonization of Vehicle Regulations (WP.29) that prepares regulatory proposals on active safety, Advanced Driver Assistance Systems, Automated Driving Systems and Connected Vehicles (UNECE, 2018).

Another challenge is the coordination problem among different regulators at the national and local levels. For example, transport sector regulators may be unable to coordinate with other regulatory agencies, such as competition authorities, since they may be outside their sectoral or geographical jurisdiction (Pande and Taeihagh, 2023). There is also a need for alignment between sector regulators and competition authorities to manage regulatory silos in different countries. In addition, regulatory barriers could play a crucial role in AV adoption. Disparate state regulations could create inconsistencies and complexities in the regulatory framework for AV deployment. Insufficient standards and regulations could also hinder the market development of AV technology (Fagerholt et al., 2023). To reduce complexity, disruptive innovation such as AV integrated in MaaS may require a uniform or intermodal regulation encompassing different modes of transportation instead of mode-by-mode regulation. However, merging different transport modes could be challenging for stakeholders with diverse interests.

Further complicating regulatory challenges are the misaligned interests across different levels of government, the private sector, and public stakeholders at local, national, and international levels (Schepis et al., 2023). For example, AV integrated in MaaS innovation could impact stakeholders differently. For a public transport authority or operator, their interest could be in changing citizens' travel behaviour towards more sustainable modes of transport for the general interest. For citizens, affordability, reliability, and accessibility are essential. Commercial market players may be more concerned with financial returns (Suck et al., 2023). Also, stakeholder interaction creates dependencies, tensions, and opportunities for regulatory conflicts to arise (Suck et al., 2023). Comprehending regulatory challenges and offering workable solutions for AV integrated in MaaS innovation is challenging. Therefore, there is a need for a robust regulatory framework to mitigate market foreclosure to competitors, facilitate procedural transparency (for market access and operations) and ensure collaboration and competition among stakeholders to ensure maximum societal benefits from AV integrated in MaaS innovation.

In the following section, starting from the AVENUE project (ULTIMO's predecessor), we will discuss the key insights from other regulation-related deliverables from other EU CCAM projects to complement the scientific literature. Then, we will discuss the knowledge gaps and the potential contribution of this task to the ULTIMO project.

2.2.2 Learnings from related EU CCAM project

The table below summarises the key findings from 'regulation' related deliverables from other EU CCAM projects.

Table 2: Key findings from 'regulation' related deliverables from other EU CCAM projects

EU CCAM projects	Key findings

AVENUE
Regulatory Requirements and Compliance Plan
(Attias et al., 2018);
(Bonnardel and Couzineau, 2020);
(Bonnardel and Couzineau, 2021).
	• Mapped regulatory requirements in France, Switzerland, Luxembourg, and Denmark at the national and local levels.
	• Proposed some criteria to measure the regulatory framework's openness to automated mobility:
	  ○ National industrial policy strength.
	  ○ Local territory's autonomy

	○ Public transport governance ○ National Sustainable Development Policy • The regulatory frameworks (from a PTO's perspective) in Copenhagen, Lyon, Luxembourg, and Geneva are open to automated driving and can facilitate the integration of automated buses into the existing network.
SHOW (Fürdös et al. 2021) ; Staelens et al, 2023)	Reviewed the EU vehicle general safety regulation, type approval regulation (European Commission, 2022e), and the national regulatory frameworks in 11 European countries[9] to enable AV transport services. *At the EU level* • There is a limited scope of the EU type-approval regulation for AV. *At the national level* • Lack of harmonised requirements for testing and deployment of AVs. • National frameworks are structured differently among EU countries, and the requirements and prerequisites vary. • The different authorities' roles in the approval processes are not harmonised. • National regulation is limited to defining approval and exemption procedures for testing on public roads. • Every country has its peculiar obstacles and barriers. For example, regarding AV testing permits. *At the local level* • Limited legal competence to maximise the benefits of shared AVs.
AWARD (Zotos et al., 2023)	Discussed the status of regulations for on-road testing and deployment of AVs in France, Norway, and Austria. • Current regulations for on-road testing and operation of AVs vary by country. • Proposed some 'best' practices to support reviewing existing and future regulations: ○ Ensure that safety performance requirements are met across all Operational Design Domains (ODD). ○ consider adverse weather conditions to reflect real-life environments for AV operation ○ Update regulations to provide some degree of flexibility with restrictions to enable future development and deployment of AVs.

[9] The countries are France, Germany, Austria, Sweden, Spain, the Netherlands, the Czech Republic, Denmark, Finland, Greece, and Italy.

GECKO (Busquet et al., 2019); (Busquet et al., 2020).	Developed a regulatory matrix to assess the regulation readiness level for AV. Argue that norms and standards should be defined for AVs. Several approaches are adopted to deploy new regulatory frameworks at different levels. *At the EU level* • Collaborative approach for coordinating efforts and co-designing appropriate regulatory framework. *At the national level* • Binding rules set amendments to define conditions of use and tests that regulate the AV market through authorisations. *At the regional/local level* • Experimentations with public/private cooperation through regulatory sandboxes for AVs with subsidies and incentives.

The key findings from the EU CCAM projects seem to corroborate some findings in the scientific literature. For example, Schepis et al. (2023) argue that the government's AV policies and their approach to innovation vary, given different economic, technological, social, and political environmental contexts. Some countries take more authoritative and nationally coordinated 'top-down' approaches, while others make decisions at the local levels.
The EU CCAM projects have analysed the regulation of AVs in urban transport systems at the EU, national, and local levels. However, to the best of our knowledge, no project has explored the regulatory impact of AV integrated in MaaS innovation at the national and local levels for Switzerland, Norway, and Germany. ULTIMO will attempt to bridge this knowledge gap. In addition, building upon insights from collaborative governance theory, ULTIMO will attempt to bridge the knowledge gaps on overcoming context-specific regulatory barriers at the national and local levels for AV integrated in MaaS innovation in Switzerland, Norway, and Germany. The following section discusses the ULTIMO project's hypothesis.

2.2.3 The Ultimo Regulatory Impact Hypothesis

We develop the ULTIMO hypothesis based on theory (Fagerheit et al., 2023). Building upon the works of (Suck et al., 2023) and adapting insights from the influential work of (Ansell and Gash, 2008), we hypothesise that public institutions (focusing on PTO and PTA) could play a central role in fostering AV integrated in MaaS innovation from a regulatory viewpoint. The goal is to achieve stronger co-creation and cooperation within the stakeholders' network while balancing private and general interests. In other words, we hypothesise a case where PTO/PTAs could play a decisive role in creating a regulatory framework that enhances the appeal of AV integrated in MaaS innovation in the urban transport system. Our hypothesis is called ‘collaborative governance’ (Ansell and Gash, 2008) or collaborative regulation[10] (Busquet et al., 2020).

Collaborative governance is a governing arrangement where one or more public institutions directly engage non-state stakeholders in a collective decision-making process that is formal, consensus-oriented, and deliberative to make or implement public policy (Ansell and Gash, 2008). Collaborative governance brings public and private stakeholders together in collective forums with public institutions to engage in consensus-oriented decision-making. Crucial factors in the collaborative process include face-to-face dialogue, trust-building, and the development of commitment and shared understanding (Ansell and Gash, 2008). Busquet et al. (2020) defined collaborative governance or regulation as the deployment of a new regulatory framework, co-designed by public and private stakeholders, to ensure safety and security for road users while incentivising innovation. Adapting to the ULTIMO case, collaborative regulation for AV could entail the design of a robust regulatory framework, co-designed by public and private stakeholders, that ensures safety and security for road users while incentivising AV integrated in MaaS innovation market development.

Some recent literature for MaaS also seems to support the need for public-private collaboration. For example, Audouin and Finger (2019) argue that a governance structure (governing-by-enabling) involving both public and private sectors is needed for MaaS schemes to unfold successfully in Helsinki, Finland. The authors argue that governing by enabling, facilitating, and encouraging actions with non-public actors through partnerships and incentive development is a key feature of initiating public-private interactions. Fagerheit et al. (2023) argue that the collaborative approach recognises the limitations of disciplinary boundaries in addressing the transport system’s socio-technical complexities. The authors also argue that there is a need for interdisciplinary and cross-sectoral collaboration with experts from diverse fields to provide new insights and foster mutual learning.

Adapting the theoretical framework of collaborative governance to the ULTIMO project, we intend to bring together the PTA/PTOs, non-governmental organisations and research institutions (state and non-state actors - public stakeholders) with the technology service providers and OEMs (private sector stakeholders) in forums (co-creation workshops) to achieve consensus-oriented decision-making to overcome national and local regulatory barriers to AV integrated in MaaS in the ULTIMO project countries (Norway, Switzerland, and Germany).
Table 3 describes the ‘collaborative governance’ theoretical framework and the adaptation to the ULTIMO project.

Table 3: Adaptation of collaborative governance framework to the Ultimo project.

Collaborative governance criteria	**Adaptation to the ULTIMO case**
Public institutions initiate the forum.	DB, Ruter and TPG (PTA/PTOs), and the Republic and Canton of Geneva (Switzerland) could lead the co-creation workshops.

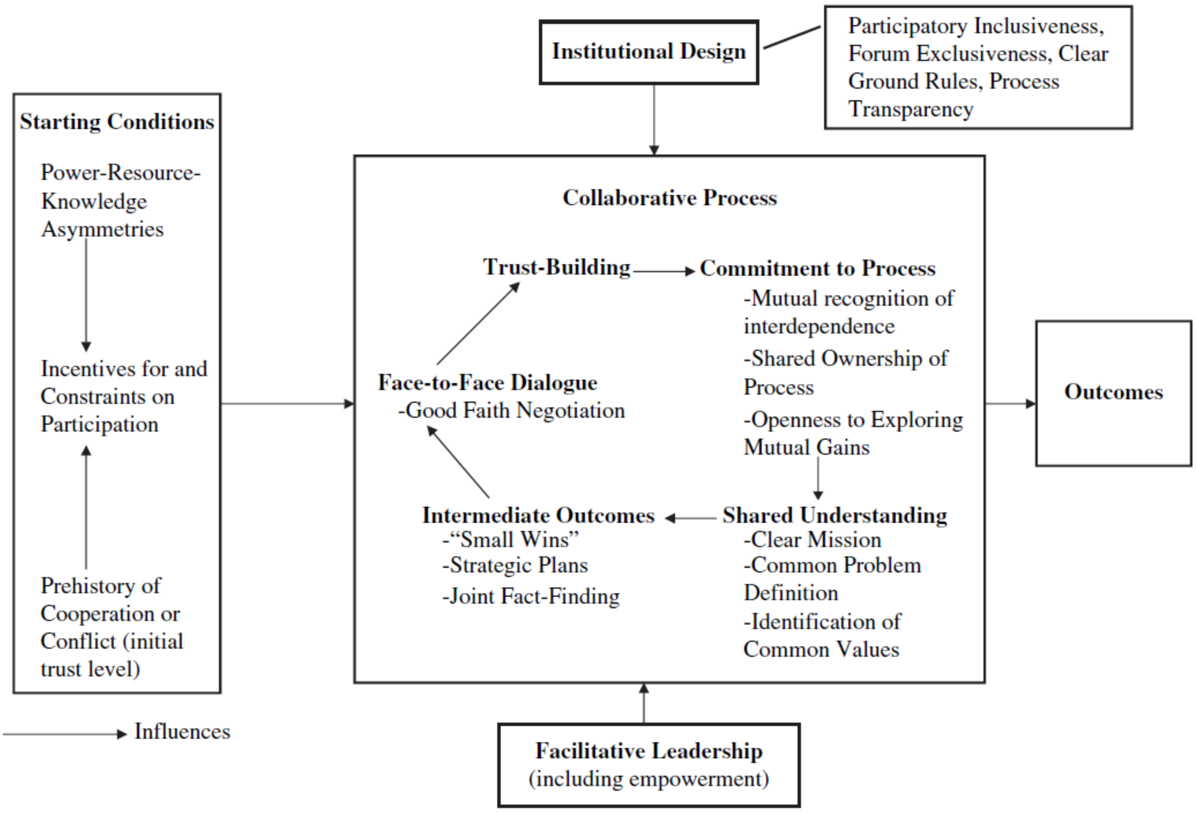
[10] Collaborative governance and collaborative regulation are used interchangeably in this deliverable.

Participants in the forum include non-state actors (private stakeholders)	GAMA (formally NAVYA), Trapeze, Padam Mobility, Siemens, Capgemini Engineering, Bax & Company, MobileThinking, ZF, SAAM, Arthur legal strategies, ArgYou.
Participants in the forum include non-state actors (public stakeholders).	CentraleSupélec, Pforzheim University, University of Geneva, CERTH (research institutions); International Association of Public Transport (UITP), Open Geneva.
Participants engage directly in decision-making.	Participants will be physically present in the co-creation workshops to engage in decision-making formally.
The forum is formally organised and meets collectively	The co-creation workshops could hold in the ULTIMO bi-annual General Assembly (GA)
The forum strives for consensus decision-making or to discover areas of agreement.	The ULTIMO co-creation workshop would aim for consensus-oriented decision-making.
The focus of collaboration is on public policy.	The co-creation workshops will address regulatory barriers of AV integrated in MaaS innovation.

Source: Ansell and Gash (2008)

Also, some variables could influence whether the collaborative process would produce successful collaboration. These are the starting conditions, institutional design, and leadership. Starting conditions set the basic level of trust, conflict, and social capital that become resources or liabilities during collaboration. The starting conditions are a prior history of stakeholder conflict or cooperation, stakeholder incentives to participate, and power and resource asymmetries. Institutional design sets the basic ground rules under which the collaboration would take place. Leadership provides the essential mediation and facilitation for the collaborative process (Ansell and Gash, 2008). Figure 6 shows the collaborative governance model.

Figure 6: Collaborative governance model



Source: Ansell and Gash (2008)

A related stream of literature worth noting is the logic of collective action from the pioneering work (Olson, 1965). In large groups, unless there is coercion or some incentive to make members of the group act in their common interest, rational, self-interested members will not work to achieve their common or group interests. In other words, even if the members in a large group are rational and self-interested and would gain if, as a group, they acted to achieve their common objective, they will still not voluntarily act to achieve that common or group interest (Olson,1965). Over the last decades, scholarly works have focused on four preconditions for a successful collective action: homogeneity of interest, clarity about the distribution of the costs and benefits of collective action, the limit of the extent to which individuals free ride on the effort of others, and sufficient communication (or reducing information asymmetries) among members to allow for coordinated action (Keefer, 2018).
In the following section, we will discuss our methodology.

2.2.4 Methodology

This task on regulatory analysis will analyse AV integrated in MaaS innovation regulatory barriers in Norway, Switzerland, and Germany (the deployment sites of the ULTIMO project) at the EU, national, and local levels. We will combine three data collection and analysis methods: machine learning techniques, semi-structured interviews, and co-creation workshops. We describe the methodologies in the following sub-section.

Machine learning techniques

The availability of digitised data for textual analysis has provided an opportunity for new ways (Allen, 2018) of conducting inductive analysis. We will use natural language processing with supervised learning (text mining and web data scraping) and unsupervised learning (clustering) for text analytics. Using Python[11], we will scrape or mine information from the Internet from arbitrary text data on AV integrated in MaaS regulation-related insights from scholarly articles, discussions, news, and social media in English, French, Norwegian and German. This inductive, data-driven approach will provide insight into the key variables of interest to understand the main factors that could influence AV integrated in MaaS regulations from the vast resource of unstructured text data available on the Internet. We will extract and analyse the text data using sentiment analysis or opinion mining. Then, with the help of visualisation techniques, we can observe clusters within that information and present the results of our data analyses (Prufer and Prufer, 2018).

Our data analysis using sentiment analysis and clustering will complement semi-structured expert interviews with stakeholders in the ULTIMO project to investigate how regulations on AV and MaaS innovations at the EU, national and local levels impact their operations or business models. The semi-structured expert interviews will allow us to better understand underlying issues from the stakeholders' perspective on the past, present and expected future regulatory developments (Schepis et al., 2023). Qualitative research through interviews is suitable for uncovering and understanding the diversity of opinions (Suck et al., 2023). We anticipate that our data-driven text mining and web data scraping research will also contribute to revealing other vital issues to include in the semi-structured interviews, thus improving our research.
We provide below some (tentative) interview questions:

- Which regulatory interventions should be considered locally to accelerate the market development of Level 4 AV integrated in MaaS innovation?
- How do we regulate to avoid a winner-takes-all situation for AV integrated in MaaS innovation at the local level?
- What are the regulatory barriers to the diffusion of AV integrated in MaaS at the local level in Oslo, Geneva, and Herford?
- What are the potential expectations regarding regulatory evolutions?

We will use the NVIVO tool for transcription (see section 2.1.5, page 33). We will code and analyse the interviews to gain insights on addressing AV integrated in MaaS regulatory issues. Then, we will organise expert co-creation workshops with public transport authorities, operators, and technical partners applying the collaborative governance model (Ansell and Gash, 2008) discussed above. The focus would be to create a shared understanding and address the regulatory issues (Suck et al., 2023) of AV integrated in MaaS innovation to foster its potential to promote sustainable mobility. Workshops are suitable for addressing the uncertainties and complexities of AV deployment, which requires continued efforts, strategic coordination, and the involvement of multiple stakeholders (Fagerholt et al., 2023).

We hypothesise that the collaborative governance model could facilitate collaboration among stakeholders. Therefore, we will strive to address the regulatory challenges and identify potential bottlenecks and expectations regarding regulatory evolutions in the co-creation workshops. Also, we hypothesise that the role of the PTA/PTOs could go beyond

[11] Python is a computer programming language.

administration and include collaborative governance/regulation to maximise societal benefits and the general interest. We will attempt to test the following hypothesis:

- A collaborative governance model may be successful for AV integrated in MaaS innovation, considering the applicable EU, national and local level regulations in Norway, Germany, and Switzerland.
- A collaborative governance forum could provide an adaptable regulatory framework that keeps up with the fast evolution of AV and MaaS innovations.
- Collaborative governance/regulation could help serve the general interest and avoid the winner-takes-all phenomenon if the critical starting condition variables are satisfied.

Insights from the stakeholder interviews will also be elaborated in the co-creation workshops while maintaining the anonymity of the interviewees. We shall analyse the results to gain insights and test our collaborative governance hypothesis for AV integrated in MaaS innovation. In sum, our methodology will combine epistemologically inductive and deductive approaches in a complementary manner to provide a rich knowledge base to investigate granular questions (Mahmoodi et al., 2017) for AV integrated in MaaS regulatory issues.
The following section discusses the link between this deliverable and the other Ultimo project tasks.

2.2.5 Link between regulatory analysis and other tasks in the Ultimo project

This task will provide insights into Task 6.2 on the business strategies, models, and cases for future intelligent citizen-centric transport and sustainable business model design for AV integrated in MaaS. It will contribute to the conceptual design of a mobility business ecosystem and support the strategy design or transformation concept towards a future intelligent citizen-centric transport ITS/CCAM ecosystem for persons and goods. It will identify regulatory obstacles to the diffusion of AV and AV in MaaS innovations and offer policy recommendations for cities, public transport operators and authorities.
This task is linked to WP 1 (Task 1.5) on the ethics of connected and automated driving led by Deutsche Bahn (DB). Task 1.5 will provide an overview of the critical ethical and legal considerations. This task is also linked to the WP2 (Task 2.1) on the passengers, PTO needs, and use cases led by Siemens. The use cases are based on the insights from the three pilot sites (WP 5) in Herford, Germany; Oslo, Norway; and Geneva, Switzerland.

This deliverable will contribute to a holistic impact assessment of AV integrated in MaaS in urban transport systems (Task 6.1). It will also provide insight into the impact of regulations on the mobility ecosystem stakeholders and contribute to developing and validating innovative cross-sectoral business models (Task 6.2) for private and public stakeholders (ULTIMO's key objective 6). It will also provide insights into achieving realistic, long-term transition planning and design for integrating AVs in MaaS (Task 6.3) with context-specific governance frameworks to balance stakeholder interests in the urban transport system to serve the general interest (ULTIMO's key objective 8).
The following section discusses our proposed work plan for the second deliverable, due for submission in September 2026.

2.2.6 Proposed Work Plan

Following the submission of this deliverable in March 2024, we will proceed with the data-driven inductive analysis of regulatory barriers for AV integrated in MaaS innovation at the EU, national, and local levels for Switzerland, Norway, and Germany. We will then complement our research with semi-structured interviews and co-creation workshops (to test our collaborative governance hypothesis). We intend to use two general assembly meetings of the Ultimo project for the co-creation workshops in September 2025 and March 2026. A final report with our findings will be submitted to the European Commission in September 2026. See the Gantt chart below.

Activities	Start date	End date	Q2 2024	Q3 2024	Q4 2024	Q1 2025	Q2 2025	Q3 2025	Q4 2025	Q1 2026	Q2 2026	Q3 2026
Data-driven analytics of AV integrated in MaaS regulatory barriers for Germany, Norway and Switzerland	Apr-24	Sep-24										
Semi-Structured expert interviews	Oct-24	Sep-25										
Co-creation workshops	Oct-25	Mar-26										
Report containing roadmaps and guidelines	Apr-26	Sep-26										

2.2.7 Expected results.

The final report of this task in September 2026 will offer the following insights:

- Context-specific guidelines and roadmaps to adopt collaborative governance for AV integrated in MaaS innovation to support sustainable business models in Norway, Switzerland, and Germany at the national and local levels.
- Context-specific recommendations for PTA/PTOs on collaborative regulation to foster the integration of all transport modes that contribute to safer, sustainable, inclusive, and efficient mobility in the urban transport system.
- Guidelines for policymakers to design adaptable and fit-for-purpose regulatory governance to support AV and MaaS innovations.
- Guidelines for collaborative governance among regulatory institutions at the national and local levels in Norway, Switzerland, and Germany.
- Insights on how to align regulations with industry requirements to meet the needs of local and national innovators, build mutually beneficial partnerships and preserve the private sector and general interests.

2.2.8 Conclusion

Given that AVs could positively or negatively impact the urban transport system, appropriate governance frameworks are required to capture the potential benefits and mitigate adverse impacts to enhance the general interest or societal welfare. This deliverable contributes to the AV integrated in MaaS governance debate from the regulatory viewpoint. We focus on how AV and MaaS regulations (at the EU, national and local levels) can support market development and serve the general interest. First, we discuss the hydra-headed regulatory issues such as the tendency for technological advancement to eclipse regulatory oversight, regulation lagging behind technological innovation, regulation lagging behind marketplace changes, the winner-takes-all market problem, decision making challenge on whether to use ex-ante or ex-post regulation, regulations favouring particular interest group(s), regulatory silos at the national and local levels, and the intriguing challenge of balancing stakeholders' diverse interests.

Second, we review learnings from related EU CCAM projects that have analysed AV regulation in urban transport systems at the EU, national, and local levels, namely, AVENUE, SHOW, AWARD, and a related project (GECKO). We find that (i.) there is a lack of harmonised regulations for testing and deploying AVs. (ii.) there is a challenge to harmonise regulations because of the different and specific national and local contexts among the EU countries (iii.) there are diverse regulatory barriers for AV among EU countries, and (iv.) national frameworks are structured differently among EU countries. Furthermore, there seems to be no project or scientific literature that has explored the regulatory impact of AV integrated in MaaS innovation at the EU, national and local levels for Switzerland, Norway, and Germany. Therefore, we propose to bridge this knowledge gap in the ULTIMO project.

Third, we propose to adapt the collaborative governance model to address context-specific regulatory barriers at the national and local levels for AV integrated in MaaS innovation in Switzerland, Norway, and Germany. That is, for public institutions (focusing on PTOs and PTAs) to play a central role in fostering AV integrated in MaaS innovation from a regulatory viewpoint. We hypothesise that insights from the collaborative governance model could be helpful to bridge the knowledge gaps and overcome context-specific regulatory barriers at the national and local levels for AV integrated in MaaS innovation in Switzerland, Norway, and Germany.

Fourth, we propose and discuss our methodology for the second deliverable due for submission in September 2026. We propose to combine three data collection and analysis methods: machine learning (text mining/analytics and clustering), semi-structured interviews, and co-creation workshops (to test our collaborative governance hypotheses). We argue that combining epistemologically inductive and deductive research approaches in a complementary manner could offer invaluable insights to address AV integrated in MaaS regulatory issues. Finally, we propose to provide key results to support policymakers' decision-making for AV integrated in MaaS innovation in the second deliverable as follows: (i.) context-specific guidelines and roadmaps to adopt collaborative regulation for AV integrated in MaaS innovation at the national and local levels (ii.) recommendations for designing new regulatory frameworks to support AV integrated in MaaS innovation. (iii.) recommendations for PTA/PTOs on collaborative regulation, (iv.) guidelines for collaborative governance among regulatory institutions at the national and local levels, and (iv.) insights on how to align regulations with industry requirements while preserving the general interests.

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3 Economic Impact Assessment

On-demand automated vehicles (AVs) present an opportunity for public transport authorities and operators to enhance public transport systems. AVs could offer a personalised and, possibly, efficient solution for urban mobility (Andrews, 2023). For instance, the possibility of individuals hailing an AV from their homes to the nearest subway station and sharing the ride with others along the route could address a fundamental limitation of traditional public transport - its rigidity. This innovation could persuade more individuals to opt out of private car usage (Mohammadzadeh, 2021). As European cities strive to replace private cars with more sustainable transport solutions, integrating AVs into Mobility as a Service (MaaS) could be a possible strategy to reduce urban traffic congestion. Despite efforts to make public transport more appealing, the persistence of high car traffic in European cities signifies the need for more tailored transport options. Fournier et al. (2023) argue that AV in MaaS systems could be a game-changer. AV in MaaS could bridge the first and last-mile gap by focusing on user-centric services, enhancing the overall public transport experience through increased reliability and accessibility (Butler et al., 2022; Fournier et al., 2023). The success of this integration hinges on many factors, including technical, social, economic, and environmental factors.

This task focuses on the economic factor, and its objective is to assess the economic viability of integrating on-demand AV in public transport systems, specifically focusing on evaluating appropriate innovative pricing models for value creation to serve the general interest of citizens, PTOs, PTAs and city governments. While the potential benefits of AV in terms of efficiency, environmental impact, and traffic management are widely acknowledged, existing studies such as Fagnant & Kockelman (2014) and Fagnant et al. (2015) work on these services' social and environmental impacts overlook its economic viability, leading to a possible biased and overly optimistic results. Thus, it is crucial to assess the economic viability of this integration to ensure its sustainability (see T.6.2. for more details). Moreover, developing sustainable business models for AVs in MaaS, among other factors, requires optimising revenue strategies, exploring different revenue streams, such as subscription models, pay-per-use, or advertising, and ensuring that the service is economically viable for operators and consumers.

The economic assessment of AV services in ULTIMO evolves around the key research question: *“How can we conceptualise and conduct a proper economic evaluation for stakeholders in the MaaS and LaaS ecosystem, considering their stakes and issues?”.*

This question underscores the commitment to provide practical solutions for stakeholders, navigating the complexities of economic evaluation in the evolving field of CCAM. By tapping into insights of AVENUE and other EU CCAM projects, ULTIMO will contribute valuable perspectives and methodologies, fostering a more informed and suitable approach to economic evaluation. This research's central hypothesis revolves around utilising the Total Cost of Mobility (TCM) approach, a field that has not been extensively explored in existing research. By comprehending value creation and capture mechanisms, a basis is built for conducting a thorough and holistic economic evaluation of AV services integrated in MaaS and LaaS. Thus, we also assume that the Total Cost of Ownership (TCO) approach alone for an economic assessment of AV services is insufficient when considering different areas of consideration, such as impacts on the PTO, the citizens, and the city. In the underlying context,

the TCO is a financial metric that evaluates the comprehensive expenses of owning and operating an AV over its entire life cycle. It includes various factors such as acquisition costs, maintenance costs and possible resale values (Mitropoulos et al. 2022b; Ongel et al. 2019). Unlike the TCO approach, the Total Cost of Mobility (TCM) strongly emphasises the demand perspective, incorporating multiple transport means and services into a single intermodal journey tailored to specific passenger needs. (Nemoto et al. 2021).
The economic evaluation aims to quantify the various expected impacts (costs and benefits). It seeks to give a monetary translation to assess the overall benefit that the community will derive from the project. We will proceed in two stages.

In the first part, we will present a cost-benefit analysis to understand the costs of an AV service integrated into a MaaS. This part will explain how to calculate the Total Cost of Mobility (TCM), which is helpful for a fleet manager or a MaaS operator. Secondly, we will focus on the revenue that PTOs/PTAs must maximise to guarantee the AV in MaaS service over time. To do this, we will propose to simulate pricing strategies that vary over time based on multiple variables. These two parts could be a determining factor for PTOs/PTAs and OEMs in their decision to invest in such projects and serve users in the best conditions.

3.1 Economic Cost Analysis

The use of automated vehicles has considerable potential to change the current mobility paradigm by transforming urban and rural regions and creating transportation systems with a common economic approach that benefits the entire population of the region (C. Legacy et al. 2019). By making automated vehicles available (especially connected ones), the technology can offer passengers the opportunity to circumvent the elevated costs associated with driving only with their personal cars (Clements und Kockelman 2017). However, understanding the overall costs of automated mobility services involves considering various cost factors. Fixed costs include purchasing vehicles, which is considered a significant upstream investment (Turoń und Kubik 2020). Additionally, fixed costs may include expenses for shipping and registration of the vehicles (Mitropoulos et al., 2022). Variable costs, on the other hand, are associated with the day-to-day operations of the service, comprising expenses for charging and maintaining electric vehicles, salaries or wages for employees, and energy costs, which are linked to the type and duration of services (Loeb und Kockelman 2019).

The AVENUE deliverables and contributions from other EU CCAM projects could provide valuable insights. While their findings and approaches have been considered in our initial benchmark, the full extent of their value in informing ULTIMO's goal of developing economically viable solutions for deploying automated mobility services is yet to be fully explored. Automated vehicle systems will be tested with a large-scale, on-demand, door-to-door, inclusive and user-oriented development. Regarding the project’s framework, a holistic approach should be adopted, considering all elements in a cross-sectoral business environment. This holistic approach aims to ensure that the economic cost-benefit analysis integrates user-centricity. We applied this basic model to the Ultimo’s cases to consider new developments. However, offering an AV service in MaaS does not imply the exact costs and benefits as offering an AV product.

3.1.1 Learnings from AVENUE and other CCAM Projects

This section summarises the key learnings from ULTIMO's predecessor project, AVENUE, specifically focusing on the economic cost benefit analysis in the context of AV deployment in public transportation. The AVENUE project highlighted the significance of public transportation in regional economic development and the overall well-being of citizens. It highlighted the emergence of on-demand transport as a solution to efficiently address widespread and diverse transportation needs, tackling the inefficiency of certain regular transport services. By building upon the economic implications of the AVENUE project, we aim to create a practical basis for directing the actions in the economic cost benefit analysis of AV services in ULTIMO. In the context of AVENUE, the ecosystem of AV services was described, encompassing two key areas: (1) relations between AVENUE business "champions" customers and operational users and (2) an extended focus on the relationships between AVENUE business customers and end-users, respectively the passengers. To understand the final balance of costs and gains for all analysed stakeholders, a developed economic assessment tool was used to simulate the economic impact of AV deployment. Simulating the economic impact of AVs at a local level can help local policymakers in decision-making.

3.1.1.1. Micro-Data Calculator

The AVENUE project's economic assessment included a micro-data calculator as part of the Total Cost of Ownership (TCO) analysis. The tool focused on the detailed economic framework, identifying cost drivers, and evaluating investment costs (CAPEX) and operational costs (OPEX) for various stakeholders, including public transport operators and users. The Micro-Data calculator included direct and indirect costs, potential savings and 'hidden costs' related to the deployment of AVs within a specific area, were considered. This comprehensive analysis served as a foundational step for (1) understanding the cost breakdown and (2) assessing the economic viability of integrating AVs within a public transport system. Integral to the economic assessment was the fleet size dimensioning. This analysis was crucial for determining the number of shuttles required for efficient service delivery. It addresses fixed-route and on-demand services, offering estimation options through supply push (where service demand is unknown) and demand-pull (where existing public transport is known). While the supply-push and demand-pull options for fixed-route services have been tested and validated within the cost calculator (EASI-AV ©) developed for the AVENUE project, algorithms for on-demand fleet size were not developed (Antonialli et al. 2021).

3.1.1.2 Macro-Data Calculator: Scenario simulations and analysis of externalities

Building on the Micro-Data analysis, the AVENUE project used a macro-data calculator to simulate scenarios for the widespread adoption of AVs. By considering fleet size, user acceptance, energy consumption, emission of particulate matter, nitrogen oxides, and carbon footprint of different classes of vehicles. The calculations included the valuation of externalities in monetary terms. This approach underlined impacts such as sustainability, congestion, accidents and parking costs (spatial optimisation). The macro-data Calculator was important in evaluating the broader implications and potential societal and environmental benefits of adopting AVs. To understand the final balance of costs and gains for all analysed stakeholders, a developed economic assessment tool was used to simulate the economic impact of AV deployment. Simulating the economic impact of AVs at a local level can help local policymakers in decision-making. Other CCAM projects dealt with questions of economic evaluation, even if the determinants of the impacts have not always been defined. Table 4 presents the contribution of other EU CCAM projects concerning the economic assessment of AV services. It provides a brief overview of selected EU CCAM projects, from which valuable insights can be gained for the economic assessment in ULTIMO.

Table 4: Key findings on economic assessment from other EU CCAM projects

Project	**Contributions to Economic Assessment of AV Services**	**Cost components identified**
MOVE 2 CCAM	• Developed a system dynamic model to assess the potential economic impacts of CCAM solutions. • Highlighted the importance of considering economic factors in deploying CCAM solutions.	CAPEX and OPEX Maintenance cost Costs of AI Costs of automated delivery service Costs savings Costs platform management, Apps
SHOW	• Analysed the economic benefits of implementing automated and electric shuttle buses. • Analysed the potential cost savings of AV services • Highlighted the importance of developing economically viable business models for CCAM solutions	Operative costs/km Travel time savings Impact areas with three levels (CCAM)
URBANE	• Discussed the importance of considering economic factors in implementing urban logistics solutions. • Analysed the economic viability of microhubs for last-mile delivery. • Identified the need for economic incentives to promote adopting CCAM solutions for last-mile delivery.	LaaS Transportation cost structure for different stakeholders (administrative flat, infrastructure, market regulated)
WISE	• Analysed the economic potential of autonomous and connected transport (ACT) (Business Challenges of Autonomous and Connected Transport). • Assessed the economic impacts of AV deployment using simulation tools (Autonomous and Connected Transport scenarios evaluation based on simulation analysis).	Value of travel time Equity impacts

Project	Contributions to Economic Assessment of AV Services	Cost components identified
LEVITATE	• Developed a methodology for estimating the monetary valuation of the impacts of connected and automated vehicles (CAVs) • The methodology has been applied to case studies assessing the economic impacts of CAVs on urban mobility and evaluating the cost-effectiveness of CAVs for freight transport.	Direct impacts (OPEX and CAPEX, others monetarised) Systemic impacts (congestion, infrastructure, split of travel, shared mobility, parking and monetarisation) Wider impacts (public health, commuting distances, land use, inequality and monetarisation)
MOMENTUM	• Developed an extended transport simulation framework for emerging mobility solutions, including shared mobility services. • The framework integrates activity-based, agent-based, and system dynamics modelling approaches to model the demand for and supply of new mobility services	Operating costs for the operator Costs for the user (as a function of the minutes a passenger has to work to pay the route)

Our economic assessment will incorporate key findings from other EU CCAM projects to enhance our analysis. Specifically, we will integrate identified cost components from these projects into our framework and conduct a cross-avenue methodology comparison with other European projects to elucidate any disparities and provide explanations for such differences. While our analysis draws insights from the AVENUE methodology, it's essential to note differences in approach. For instance, while AVENUE's economic assessment includes a micro-data calculator focusing on Total Cost of Ownership (TCO) analysis, other projects such as MOVE2CCAM emphasise system dynamic modelling to assess potential economic impacts. Additionally, AVENUE's consideration of fleet size dimensioning and supply-push and demand-pull options for fixed-route services may differ from approaches like those of URBANE, which focuses on transportation cost structures and economic incentives for last-mile delivery solutions. Furthermore, while AVENUE's macro-data calculator simulates scenarios for widespread AV adoption, other projects like WISE analyse the economic potential of autonomous and connected transport (ACT) through simulation tools and assessment of equity impacts. These methodological differences highlight the diverse approaches used across European CCAM projects, underscoring the need for a comparative analysis to refine our economic assessment framework.

The concept of TCM (in combination with MaaS) implies the calculation and analysis of all costs associated with a particular mode of transportation or bundle of services (On-demand or PT mobility packages) that could facilitate mobility for an individual or community (Kuhnimhof und Eisenmann 2023b). With the integration of automated vehicles in urban areas, new mobility services may emerge, improving accessibility for people with reduced mobility (Bagloee et al. 2016).

Beyond AVs, Logistics-as-a-Service (LaaS) also contributes to the ongoing rethink of mobility systems, aligning with the integrative character of MaaS. In this context, the literature suggests that utilising autonomous technologies in last-mile logistics has the potential to optimise costs and contribute significantly to environmental sustainability (Alverhed et al. 2024; Lemardelé et al. 2023). To understand the potential economic impact of AVs in LaaS, it is crucial to analyse related costs and evaluate AV services that complement MaaS-integrated ones. This comprehensive approach underscores the necessity for an extended method for economically assessing AV services in a broader mobility context.

In this evolving landscape, from a business perspective, the continuous development of transportation systems, especially with digital technologies, requires a redefinition of the ownership of mobility services (Gong et al.,2022).

3.1.1.3 Cost considerations of AV services

In a broader perspective, AV services have different typologies, such as carsharing, ridesharing and mixed systems, which refer to hybrid models combining car- and ridesharing elements. Integrating AVs with public transport and promoting ridesharing is proposed to bolster sustainable transportation systems (Narayanan et al., 2020). However, the potential for increased fleet usage in a ridesharing scenario introduces a challenge, as it can decrease service use, particularly with a larger fleet size. Optimising AV operation becomes complex in addressing this issue, as increasing fleet size alone encounters a trade-off between revenue and expenditures (Vosooghi et al. 2019). Several factors must be considered when calculating fleet sizes for automated vehicle services, such as demand patterns, service coverage, and operational efficiency. These are factors to determine the optimal number of vehicles required to meet users' needs effectively while minimising operating costs and maximising the overall system performance. While certain approaches differentiate between fixed line and door-to-door AV service for a specific area with its dimensions (Badia und Jenelius 2021), others perform fleet sizing with a presumed dynamic ridesharing scheme (Fagnant und Kockelman 2018). However, the operations of AV fleets may require certain strategies to optimise vehicle assignment based on a requested demand, with which the travelled vehicle distances and waiting times for a potential customer can be reduced (Hyland und Mahmassani 2018).

Implementing on-demand mobility services and what service type is considered - such as ridesharing or vehicle sharing - may also positively impact the overall cost of operating automated transport systems (Kuhnimhof and Eisenand, 2023a; Gurumurthy et al., 2019). Moreover, vehicle automation must be considered as well as it can mitigate the costs of shared mobility systems, which are designed on an on-demand basis (Militão und Tirachini 2021). Regarding TCM, externalities (for example, congestion) can be integrated into cost calculations, although they might be constrained due to low public acceptance (Gu et al., 2018; Liljamo et al., 2020). As the customer respectively the citizen perspective is highlighted within the TCM approach, the willingness to pay for unlimited access to public transport or other specific options (e.g., carsharing or bus services) is a decisive factor for a mode of choice particularly covered in MaaS subscriptions (Liljamo et al. 2020).

Another key aspect of the deployment of automated vehicles is certain effects that come with electrical propulsion. Implementing automated electrical vehicles in urban areas might positively affect the costs per passenger-kilometre for AV services (cost reduction), although it might initially augment the hardware acquisition costs (Becker et al. 2020). Effects of electrification and automation are related to mobility costs and potential changes in certain cost areas, such as maintenance, repair, battery costs and energy consumption (Ryosuke Abe 2019; Alonso Raposo et al. 2022; Bhatti et al. 2021; Muratori et al. 2021). Regarding service performance, the amount of kilometres travelled by the vehicle can also be influenced by electrification and automation (Beza und Zefreh 2019; Clements und Kockelman 2017).

The cost considerations for AVs in Public Transport (PT) are multifaceted and complex for these given implications. Contemporary research addresses this issue from various angles, including the initial investment required for purchasing and implementing AV technology, the operational costs of maintaining and operating the vehicles, the potential reduction in labour costs due to the reduced need for human drivers and the potential impact on ridership demand (Bösch et al. 2018; Winter et al. 2018; Sipetas et al. 2023).

3.1.2 Methodology for the economic assessment

A two-sided approach is chosen to support the development of the economic evaluation methodology for automated vehicle services within the ULTIMO project. The approach strategically identifies further knowledge gaps from two key areas: the existing literature and relevant European projects. The first step in the methodology is to analyse the state-of-the-art from the scientific literature. Besides diverse considerations, covering fixed and variable components in AV services (initial investments and day-to-day operations), the following is essential: to underline challenges and opportunities for more sustainable and seamless transport by integrating AVs in MaaS (Narayanan et al. 2020; Ambrosino et al. 2016), emphasising the need for a balanced approach in fleet optimisation (Vosooghi et al. 2019), and possible positive effects (for example, less congestion) of shared mobility systems (Beza et al. 2022). Analysing the literature through a review can inform our methodology for designing a comprehensive economic assessment framework for AV services in the ULTIMO project. Based on findings from the literature, additional European projects will be analysed to refer to other projects' experiences and successes. These projects serve as valuable benchmarks and provide additional scenarios and practical implications for the economic assessment.

3.1.2.1 Pathways to introducing the comprehensive economic assessment.

In working to create an economic assessment model for AV services, we outline three different approaches, each offering a strategy to handle the complexities of economic evaluations. Whether building on existing calculators, combining their strengths, or innovating with a new tool, these pathways aim to improve the understanding and assessment of the economic implications of AV services. Figure 7 represents the different pathways and their transitions.

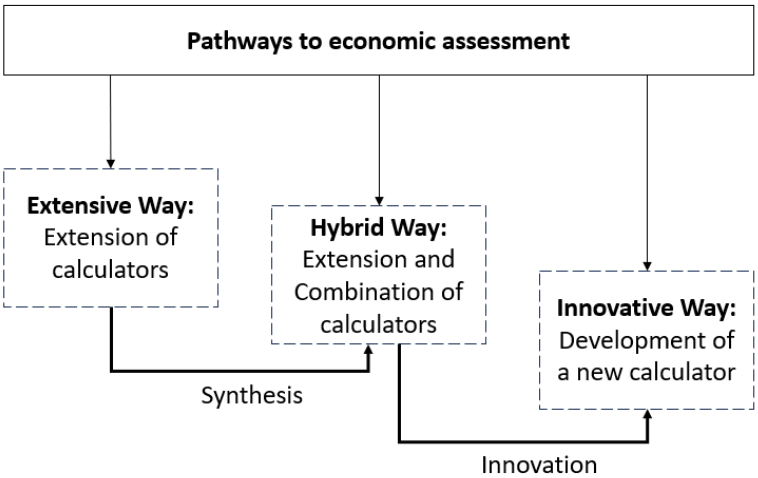


Figure 7: Pathways to economic assessment

Extensive Way: Extension of calculators

The **Extensive Way** involves building upon the foundation laid by existing calculators, particularly those used in the AVENUE project. This pathway focuses on expanding and refining the current tools, leveraging their methodologies to incorporate additional variables and wide-ranging scenario simulations. By extending the capabilities of established calculators, ULTIMO aims to enhance the accuracy and comprehensiveness of economic assessments, providing a more detailed understanding of the implications of AV services.

Hybrid Way: Extension and Combination of Calculators

The **Hybrid Way** represents a synthesis of Extensive and Combinatoric pathways. It would aim to extend existing calculators while integrating them to form a hybrid model. This approach maximises the benefits of refinement and combination, offering a strategy that could draw on the strengths of individual calculators. By extending and combining tools, the economic assessment model aspires to provide a robust and adaptable framework for evaluating the economic dimensions of AV services.

Innovative Way: Development of a new calculator

The **Innovative Way** focuses on developing a new calculator tailored to the project's specific needs. Notably, the Innovative Way does not operate in isolation. It acknowledges the value of insights and knowledge gained from existing calculators, leveraging this collective knowledge to accelerate the development processes. It is important to note that this approach does not suggest the other pathways "lack" innovation; instead, it builds upon and integrates innovative elements from various approaches.

3.1.2.2 Development of a comprehensive economic assessment framework

A comprehensive economic assessment of autonomous vehicle (AV) services within a Mobility as a Service (MaaS) ecosystem necessitates a detailed understanding of the cost structure associated with these services. This cost structure encompasses, in particular, various expenses incurred throughout the lifecycle of an AV fleet, from vehicle acquisition and operation to maintenance and infrastructure investments, as previously outlined in the cost considerations for AV services. The cost structure should be validated by various stakeholders, including Public Transport Operators, Public Transport Authorities, MaaS providers and possibly policymakers. Once the cost structure is finalised, the data collection can be initiated. Moreover, the analysis should also consider the influence of demand patterns on costs and the economic dynamics among the different stakeholders within the respective ecosystem. Additionally, various business cases of AV services should be analysed to understand the specific cost implications of different operation models.

3.1.2.3 Data Collection and Analysis

To understand the cost structure and economic viability of automated vehicles within the MaaS (and LaaS) ecosystem, we aim to better conceptualise the financial implications of AVs by collecting data on vehicle acquisition costs, operating and maintenance expenses and infrastructure investments. This data will be collected from PTOs and PTAs or reports, which have to undergo a validation process (with PTOs or PTAs). Furthermore, economic data can be found in the literature and other EU projects. Existing surveys and studies, particularly on user preferences and willingness to pay, could provide insights into potential demand and revenue streams for AV services. In order to further show the economic interactions between various stakeholders (operators, MaaS providers), interviews or focus groups can be a suitable data collection method. This would provide valuable insights into the economic dynamics that shape the AV ecosystem, allowing us to understand the perspectives and motivations of different stakeholders.

We aim to combine different methods to extract insights from the collected data. First, In order to gain a more comprehensive understanding of cost structures and economic viability of AVs, in-depth case studies will be conducted for three locations: Herford (Germany), Oslo (Groruddalen) and Geneva (Switzerland). Second, by applying a Cost-Benefit Analysis (CBA), a quantitative evaluation of the economic potential of AVs can be conducted, which in turn allows a comparison of the potential economic outcomes of AV deployment. CBA has been, in particular, conducted by Carreyre et al. (2023) and Österle et al. (2022) in order to contrast the benefits and costs of AV services. Third, we aim to examine the economic impact of various scenarios of AV deployment, aligned with the case studies. A comparative analysis of different scenarios across demonstration sites could provide a broader understanding of the factors that influence the economic viability of AVs in MaaS and LaaS contexts.

3.1.2.4 Research design

We derived diverse mobility scenarios from being potentially applied in the respective demonstration site by reviewing different cost factors for AV services and for using AVs in Public Transport (for example, ridesharing). With the specifics “Ridesharing vs Vehicle Sharing” and “Unimodal vs. Intermodal” (Fig. 8), we derived the classification for the AV mobility scenarios. It was important in our framework to identify how MaaS could seamlessly combine different means of transport.

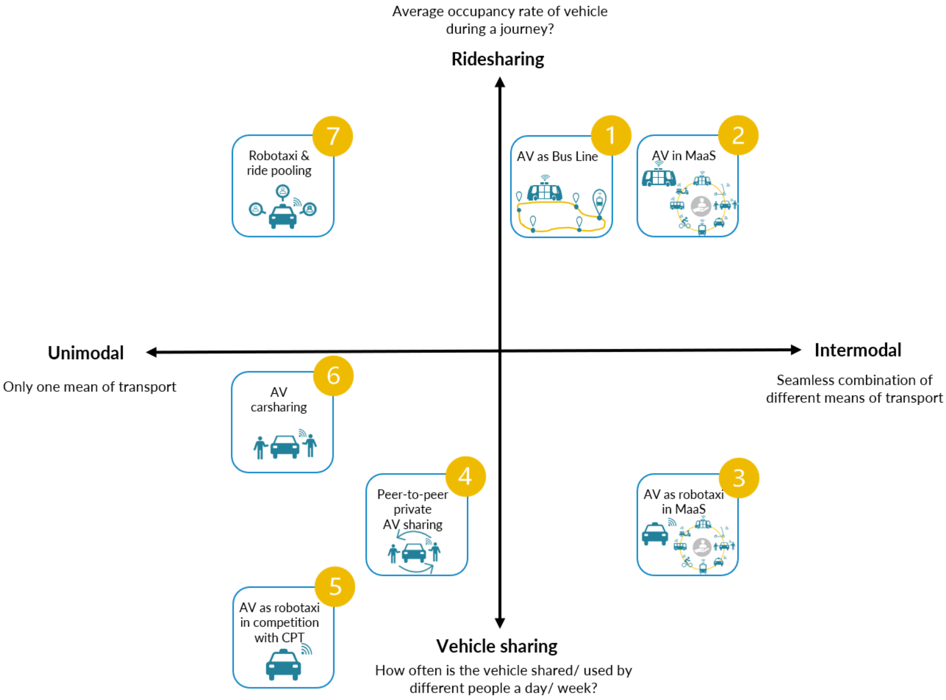


Figure 8: Derived Mobility Scenarios

Based on the horizontal axis, “Unimodal” means that only one means of transport is used, and “Intermodal” describes the seamless combination of different means of transport. Regarding the vertical axis, “Vehicle Sharing” implies how often a vehicle is shared and used by different people in a given usage time period. “Ridesharing” – as the opposing aspect – focuses on the average occupancy rate of a vehicle during a journey. The development of the scenarios (also in terms of dimensioning) was refined several times through consultation with the local PTA. Additionally, the scenarios were refined by further describing them by their temporal and spatial characteristics. The temporal aspect determines how flexible the related service is, ranging from fixed schedules to on-demand options. The spatial aspect provides information on the use of AVs in a specific ODD, ranging from serving AV services with fixed lines to more flexible AV services provided on a larger scale in an area. The scenarios were numbered from one to six within the classification matrix, depending on the certain criteria they are fulfilling. In the second step of the framework, fleet size has to be dimensioned. Some algorithms are developed. In the third step, all costs are defined: capital expenditures (CAPEX), operational expenditures (OPEX), external costs, and costs of shared mobility. As a primary test, we calculated the costs for automated mobility services in the suburban area of Oslo-Groruddalen in Norway (one of the demonstration sites of ULTIMO) based on two selected mobility scenarios and through a developed Fleet and Cost Calculator (FCC).

3.1.3 Preliminary Results: AV service costs in demonstration site Groruddalen, Oslo

To date, we have only tested the first two scenarios at the Oslo demonstration site. Scenario 3, already tested on Groruddalen, will be the subject of in-depth analysis. Our idea is to test the method on the first two scenarios because we have access to the data, and we aim to make the method more robust before rolling it out to other scenarios and experiment sites.

The examined AV mobility scenarios are described in detail below.

3.1.3.1. Scenario 1: AV as bus line

This scenario implies the substitution of conventional internal combustion engine buses with automated minibuses. These minibuses have a passenger capacity of up to 16 passengers in contrast to the 130-passenger capacity of the prevalent diesel-fueled buses. The intended application of AVs (automated minibuses) involves their deployment as shuttle services along a circular bus route that currently traverses the ODD Groruddalen[12] (see Figure 9).

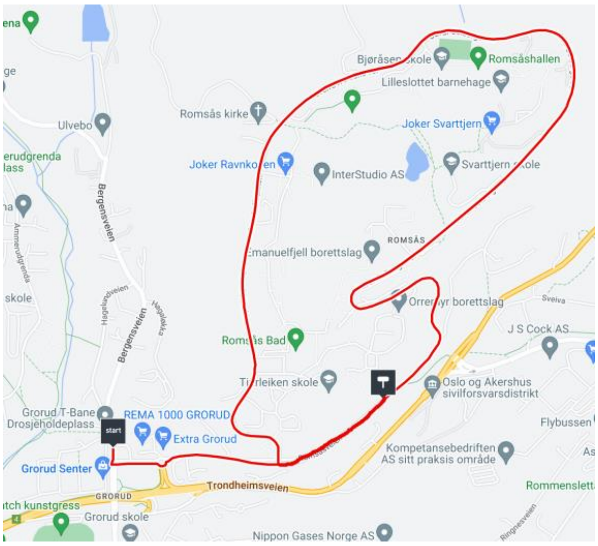


Figure 9: Route of existing ring bus in Oslo-Groruddalen

This particular scenario is positioned within the "Ridesharing-Intermodal" quadrant of the scenario matrix. This categorisation signifies the utilisation of AVs for shared journeys, accommodating multiple passengers simultaneously, especially for trips that seamlessly integrate various modes of transportation. In a specific context, these AVs could facilitate commuter access to the metro station to particularly follow a subsequent journey towards Oslo's city centre.

Concerning the temporal aspect, the AV shuttle will only serve a fixed schedule without on-demand options. Regarding the spatial dimension, the AV shuttle will only follow a specific route. The route length is 5.2 km, including 13 stops (concerning the configuration of the existing ring bus service).

3.1.3.2. Scenario 2: AV in MaaS

The primary objective of Scenario 2 is the seamless integration of AVs into the existing Public Transport (PT) infrastructure by implementing a comprehensive Mobility-as-a-Service (MaaS) framework. Providing seamless journeys for local residents is important, thus including the potential to support an Intelligent Transportation System (ITS). Positioned in the "Ridesharing-Intermodal" quadrant of the scenario matrix, this scenario is characterised by its multimodality and forms a part of a broader itinerary, including diverse PT modes. Concerning the temporal aspect, the AVs (specifically automated minibuses) will operate on-demand, giving potential passengers the flexibility to book and take a ride at their desired time to their desired destination without any specific schedule, also acting as a feeder service. In the scope of this

[12] Ruter 2022.

scenario, a door-to-door service without fixed bus stops is offered to serve the area of Groruddalen, which represents the spatial structure. The ownership of the vehicle belongs to the PTA of Oslo, as the AVs are part of the PT system.

For both scenarios, we assumed a daily demand (evenly distributed) of 10.000 passengers, a vehicle speed of 25 $\frac{km}{h}$ and a vehicle capacity of 15 passengers. The other individual specifics are explained in the results of each scenario. Important aspects in relation to the costs on which the focus is placed are the CAPEX and OPEX values, total costs in different time periods, and the key performance indicator (e.g., cost per passenger kilometre). The sensitivity analyses examine the influences of the adaptation variables (e.g. reduction of energy costs) on the KPIs. These variables are set individually, while the remaining settings in the calculator are retained. First, the results of scenario 1 are indicated. The baseline always considers no adaptations, a cleaning cycle of 1 time per month and vehicle and the necessity of an onboard driver.
We applied the following conceptual framework:

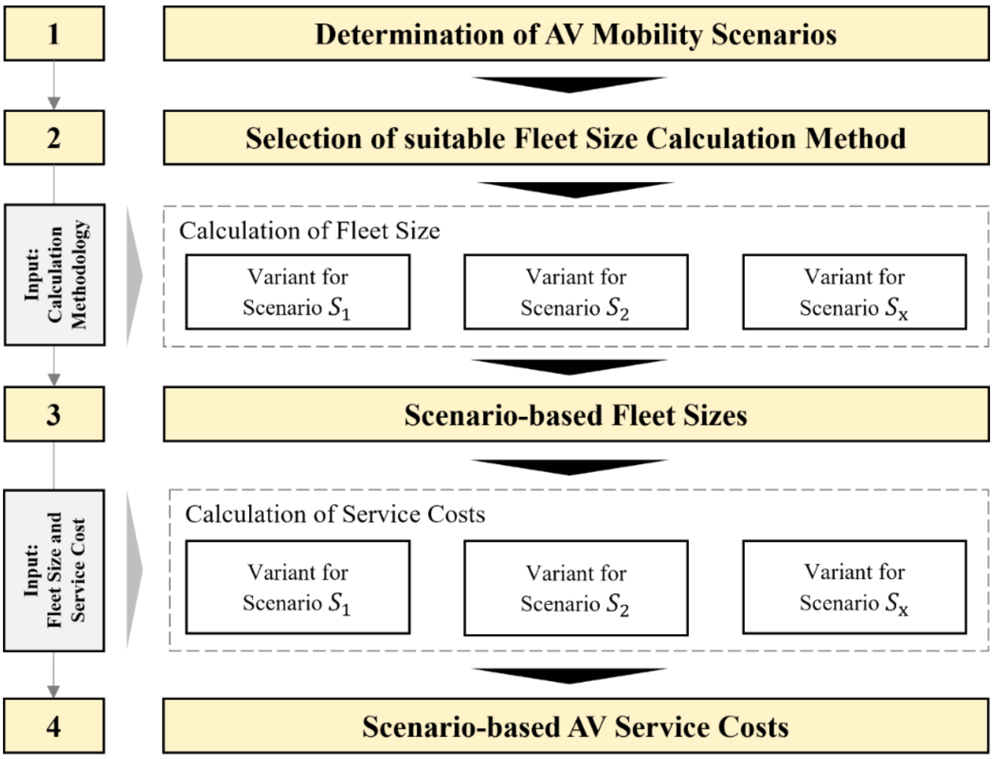


Figure 10: General conceptual framework for AV service cost calculation

The key difference from AVENUE lies in customising the calculator to suit the specific requirements and scenarios related to the analysis. Unlike AVENUE, where fleet size determination was conducted under varying demand assumptions, our methodology adopts a tailored approach. Specifically, we selected fleet size calculation methods that align with the characteristics and demands inherent to our chosen scenarios. This strategic selection ensures the applicability and relevance of the calculated fleet sizes, optimising the accuracy of cost estimations for the respective AV services.
Building upon these customised fleet size calculations, our methodology determines the costs associated with the envisioned AV services. Utilising the selected fleet size as a foundational basis, we undertake comprehensive cost assessments encompassing various operational,

maintenance, and infrastructure factors. These cost determinations are integral to understanding the economic feasibility and viability of implementing AV services within the specified scenarios. Moreover, to operationalise the entire methodology seamlessly, we developed an RStudio Application.

3.1.3.3. Applied Cost Classification

A cost classification for this FCC was developed. In addition to the conducted literature review on cost factors, other cost criteria (CAPEX and OPEX) were added to the classification after consultation with the local PTA. Additional cost aspects were also included through this process. In conclusion, the cost classification for automated vehicles contains three parts: (1) CAPEX, the initial purchase price of the automated vehicle, including any additional equipment or technology required for automation (and also other factors); (2) OPEX, the ongoing operational costs associated with the automated vehicle, such as energy consumption and maintenance costs and (3) Additional costs: Sunk Costs[13] or External Costs that are not directly related to the purchase or operation of the automated vehicle, but still might impact its total cost of ownership. The specific cost figures are summarised in the following Table 5

Table 5: Cost Specifications

Cost factor	**Figure**	**Unit**[14]	**Base**[15]
CAPEX (C)			
C1: Vehicle Acquisition[16]	250.000	$\frac{€}{veh}$	o.t
C2: Commissioning cost[17]	22.500	$\frac{€}{veh}$	o.t
C3: Infrastructure Works[18]	Not applicable	-	-
C4: Insurance premium[19]	560	$\frac{€}{veh}$	y

[13] Sunk Costs = money that a business or organization has already spent and cannot get back. Source: Cambridge Dictionary (https://dictionary.cambridge.org/dictionary/english/sunk-cost)
[14] Abbreviations: veh = vehicle; km = kilometer; SV = Supervisor;
[15] Abbreviations: o.t = one time (expense); h = hourly; d = daily; m = monthly; y = yearly
[16] Estimated vehicle costs. Source: https://www.electricmotorengineering.com/the-electric-bus-without-driver-is-arriving-in-bari/
[17] Based on assumption. The value was taken from the predecessor calculator from the AVENUE project (see Chapter 5.1). The value was about 22420 € per vehicle and was rounded up to 22500 €.
[18] No specific data could be found to take as a calculation basis. The PTA just stated the necessity of high-capacity pick-up and drop-off points.
[19] Statista 2021. Due to lack of available data about insurance premiums of EVs/AVs, it is assumed that the value is equivalent to the average insurance premium price for private car in Norway by 2020 (6600 NOK per year). The values was also converted to €.

Cost factor	Figure	Unit[14]	Base[15]
C5: Certification and Standardisation	No data found	$\frac{€}{veh}$	o.t
OPEX (O)			
O2: Maintenance Costs[20]	0,17	$\frac{€}{km}$	h
O3: Fees (whole fleet)	10.000	€	y
O4: Salaries (General)			
O4.1: Salary On-board Driver[21]	18,50	$\frac{€}{h} * veh$	h
O4.2: Salary Off-board supervisor(s)[22]	18,50	$\left(\frac{1}{SPV}\right) * \frac{€}{h} * veh$	h
O5: Energy Costs[23]	0,083	$\frac{€}{kWh}$	h
O6: Cleaning (General)[24]	15	$\frac{€}{h} * veh$	m
O7: Tax[25]	48	$\frac{€}{veh}$	y
O8: Fleet Management System	No data found	-	y
O9: Cost of Sales (e.g. Advertising)	Not applicable	-	-
ADDITIONAL (A)			

[20] Assumption for electric buses according to Thorne et al. 2021.
[21] Based on average salary for bus drivers in Norway. The same goes for CAPEX C3.2 (assumption). The values were converted from NOK to EUR based on an exchange rate of about 0,085322 NOK / EUR (course date: 02.07.2023). Source: https://www.erieri.com/salary/job/bus-driver/norway
[22] 1 / SPV = Ratio of one off-board supervisor to the number of supervised vehicles.
[23] From statistics published by Statista Research Department (as of May 4th, 2023). Values were converted from €/MWh to €/kWh. Source: https://www.statista.com/statistics/1271469/norway-monthly-wholesale-electricity-price/
[24] Eurostat 2022 The assumption is based on the monthly average minimum wage in the EU (approx.. 877 €). Considering 120 working hours per month, this would result in 7.3 € per hour. However it is assumed, that the hourly cleaning costs are twice this value (and rounded up). Therefore the hourly cleaning costs are assumed to be 15 € per hour.
[25] Annual road tax for fully electric vehicles and plug-in hybrids.
Source: https://alternative-fuels-observatory.ec.europa.eu/transport-mode/road/norway/incentives-legislations

Cost factor	Figure	Unit[14]	Base[15]
A1: Overhead Costs	Not included yet	$\frac{€}{veh}$	d
A4: External Costs	To be included later	$\frac{€}{veh}$ or $\frac{€}{km}$	-

To facilitate the calculation of the AV costs, the cost factors with known values that are not already related to an hourly base are broken down into hourly values. If an adaptation to the number of kilometres travelled was necessary, it was coherently related to the travelled distance to it. Regarding both scenarios, 16 hours of operation are considered per day. A month is considered to have 30 days (480h). A year is assumed to have 360 operational days (5760 h). Since the vehicle acquisition and commissioning costs are one-time expenses for the whole vehicle lifetime, they were first converted to present values[26], with a discount rate of 3% (Norway),[27] before breaking them down to hourly values. The daily operational hours are also designated as t_O with 16 hours. To calculate the price per passenger km, the following formula was applied:

$$P_{pkm} = \frac{c_{pkm}}{(1-r)\cdot(1-p)} * (1+VAT)$$

c_{pkm} is the cost per passenger-kilometer

Here it is assumed that the transaction fee is $p = 1\%$, the expected profit margin for the services is $r = 20\%$ and the Value Added Tax $VAT = 20\%$.

3.1.3.4. Results for Scenario 1: AV as a bus line

The scenario "AV as bus line" considers the operation of the vehicle on a fixed route, as depicted in Fig. 5. D_x designates the distances between stations (in total 5,2 km for this scenario).

[26] Fagnant und Kockelman 2018.

[27] Source: https://tradingeconomics.com/norway/interest-rate; The actual interest rate as of 23.03.2023 was taken in order to calculate the present value. The rate is about 3%.

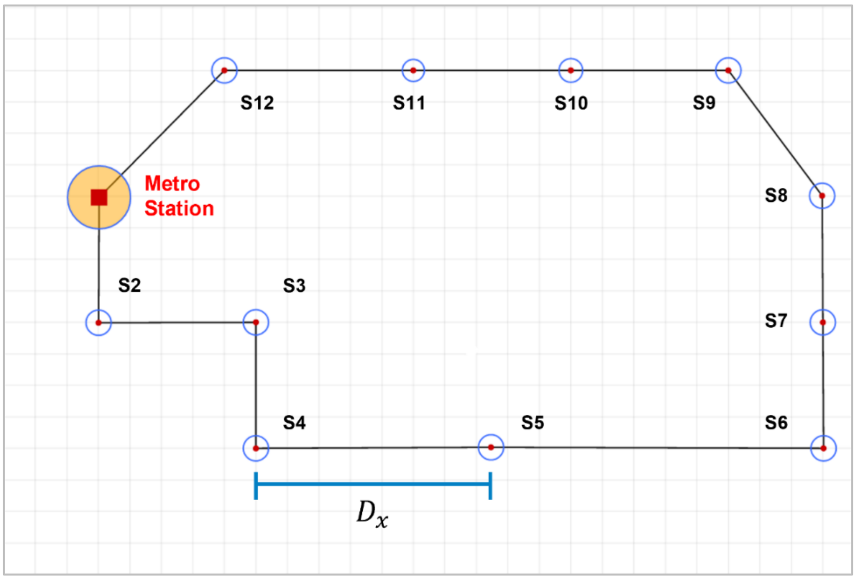


Figure 11: Graphical sketch of scenario 1 - AV as a bus line

Cost Calculations:
Regarding the costs, this service constellation results in daily aggregated costs of 5282 €. Monthly, this value amounts to 158460 €. The cost breakdown of CAPEX and OPEX in this base case shows the following values (Figures 12 and 13):

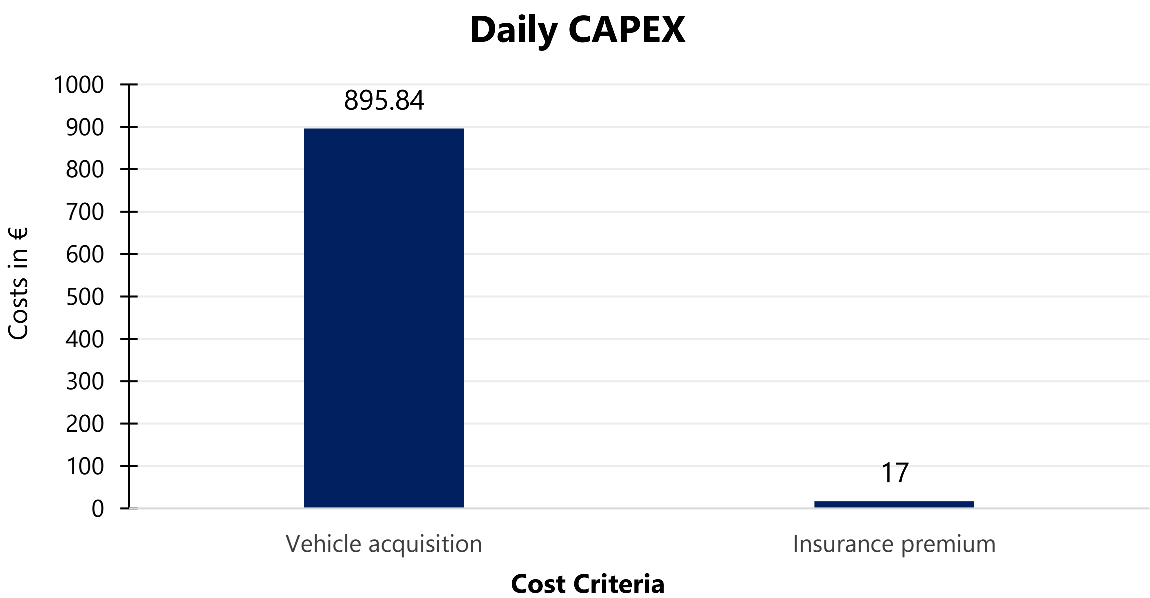


Figure 12: Daily CAPEX of Scenario 1 - AV as bus line

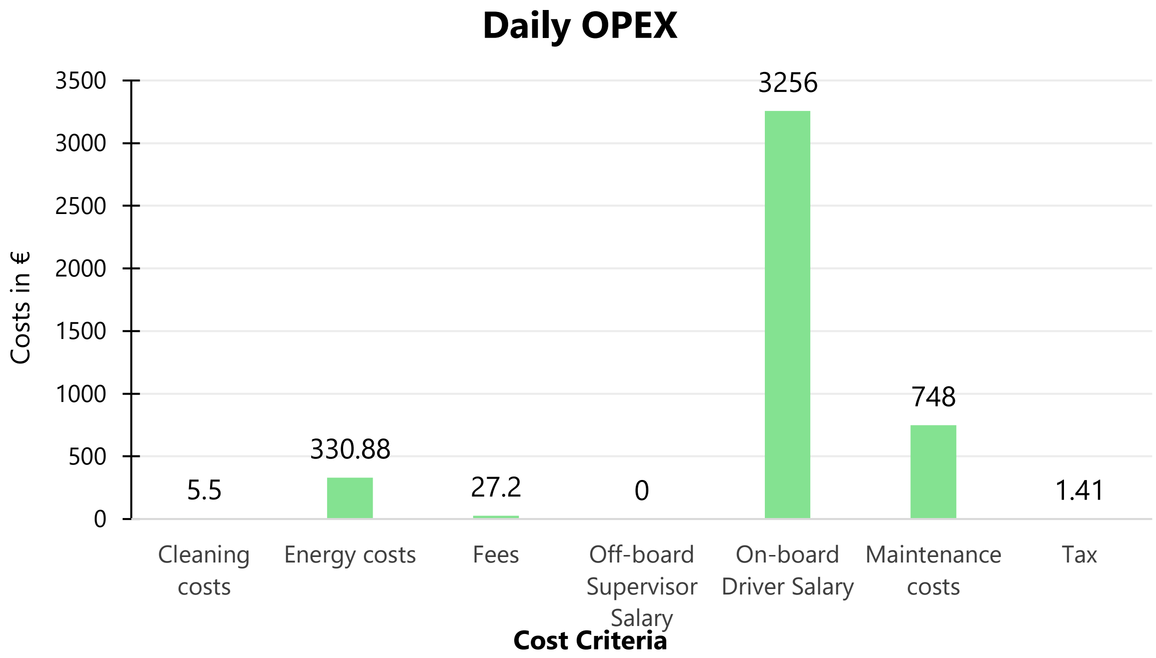


Figure 13: Daily OPEX of Scenario 1 - AV as bus line

As presented in Figure 12, on the CAPEX side, the acquisition is the cost-driving factor, with 895.84€. The importance of labour costs becomes apparent here, as they represent more than half of the daily costs. On the OPEX side (Figure 13), the highest costs are energy and maintenance costs and the salary for the onboard driver, with cost values of 330.88€, 748€ and 3256€, respectively, while cleaning costs and taxes do not significantly impact under these conditions. Considering the acquisition costs, the on-board driver salary, the energy costs, and the maintenance costs (in total 5230,72€), it is clear that they make up mostly the same amount as the total daily costs.

Key Performance Indicator:
The cost per kilometre driven is 1.2 €, and the price in relation to the same base is 1.82 €. For each kilometre driven, the acquisition cost is about 0.20 € (17% of the total cost per kilometre), and the salary cost of the onboard driver is 0.74€ (about 61.67% of the total cost per kilometre). For the energy costs, the value calculated on the kilometres driven is about 0.08€ (a percentage of 6.3%). For each service hour, the cost is 330,12€, which is 30,01€ for each vehicle required.

Sensitivity Analysis
When considering the impact of energy cost reduction, there is a price and cost decline of about 3.3% between the minimum and maximum case. The low price drop can most likely be explained by the fact that the share of energy costs in the total daily costs was insignificant (in this scenario). Figure 14 graphically shows the cost change, focusing on the values for r_{EN1} and r_{EN10}.

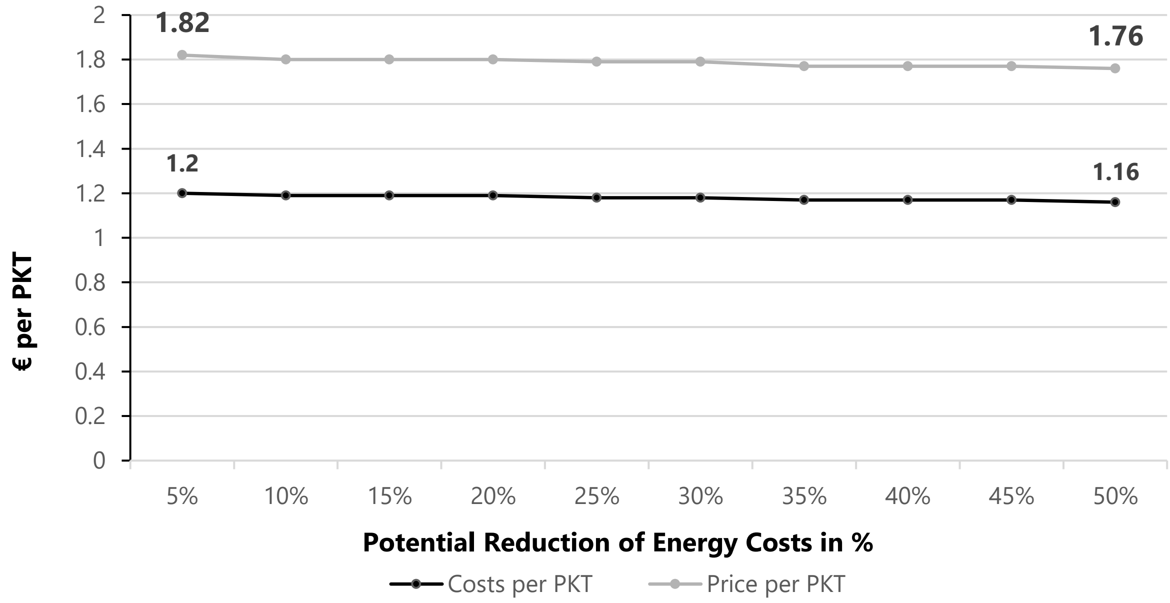


Figure 14: Scenario 1 - Impact of Potential Energy Cost Reduction (Graph)

When considering the impact of maintenance cost reduction, the average cost and price drop is approximately 4.17%, even though maintenance costs accounted for a higher percentage of total daily costs than the energy costs, for instance. Figure 15 shows the cost change.

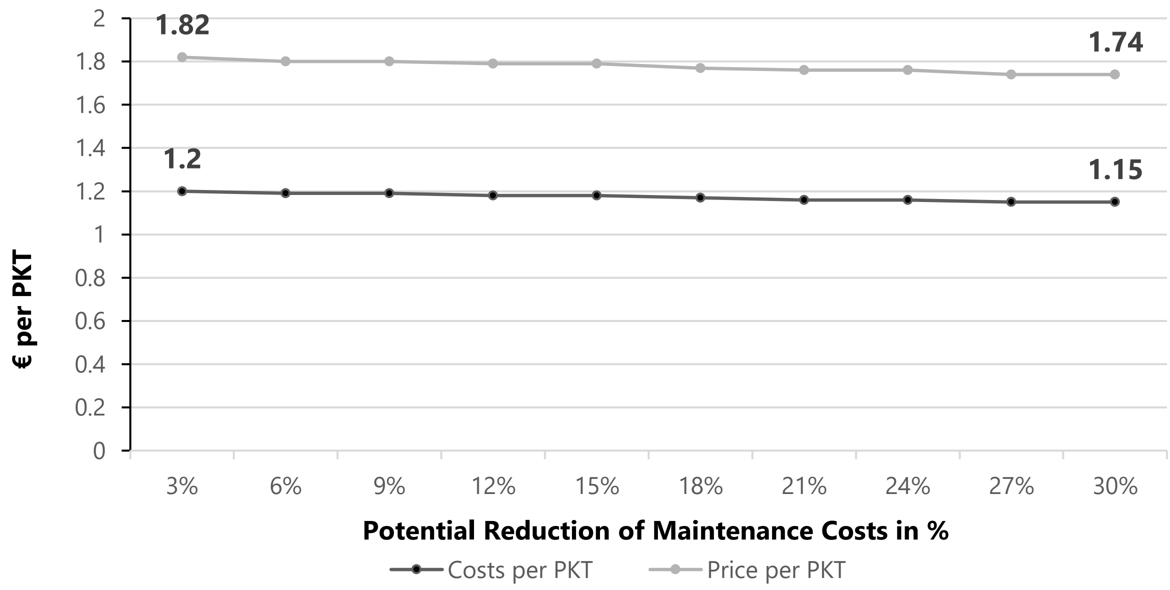


Figure 15: Scenario 1 - Impact of potential Maintenance Cost Reduction

There are hardly any increases with increasing cleaning frequencies on a per kilometre basis. Nevertheless, it may be that these values change with different long cleaning times and possibly individually defined cleaning durations with, for example, other cleanness conditions of the vehicle. The cost change is graphically shown in Figure 16, focusing on q_{cl1} and q_{cl10}.

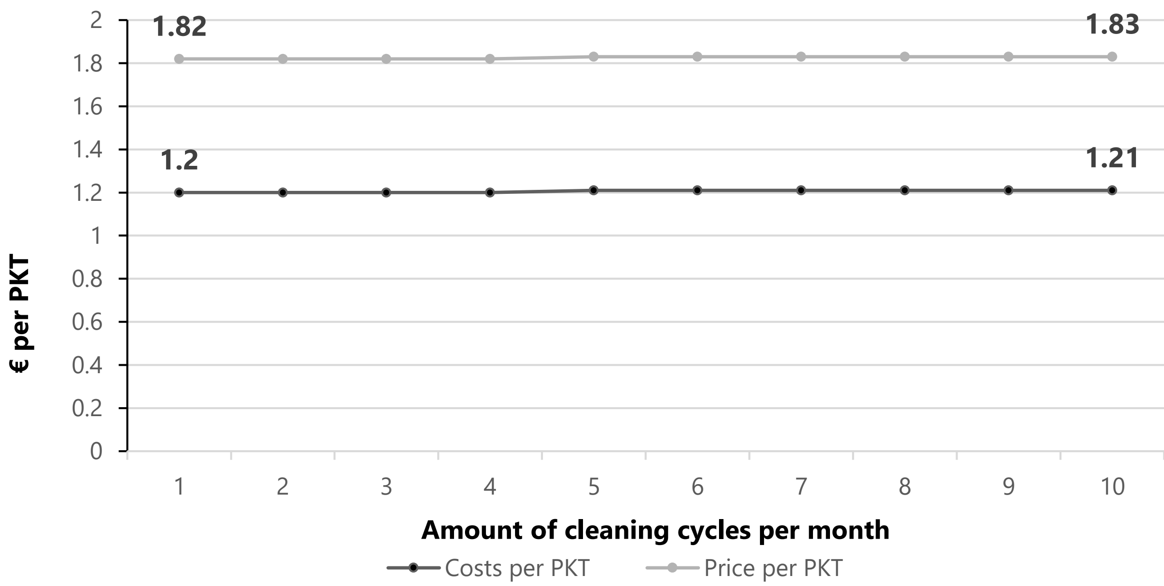


Figure 16: Scenario 1 - Impact of Cleaning Frequency (Graph)

Looking at the distinction between on-board and off-board drivers, the following changes in costs emerge: It is apparent that there are significant differences in the cost structures compared to the base case. In this constellation, the daily costs drop from 5282€ to 3654 €, initially considering that an off-board supervisor can monitor two (2) vehicles. The costs per kilometre decreased by 30,8% compared to the base case (from 1.2€ to 0.83€), which includes the most significant cost reduction. The cost value for the off-board supervisor in this setting is 1628€, representing about a 44,5% share of the total daily cost. The salary costs have decreased by 50% compared to the base case (with an on-board driver). With the resulting fleet size of eleven (11) automated vehicles, the following cost changes occur when the number of vehicles to be monitored per 'Off-Board Supervisor' is set from the minimum to the maximum: The kilometre-based costs and prices decrease by approximately 36,8%, considering the minimum and maximum number of supervised vehicles per off-board supervisor. In the most extreme case, t SPV_{11}, the reduction compared to the base is about 55,83 %. Figure 17 shows the cost change focusing on the values for SPV_2 and SPV_{11}.

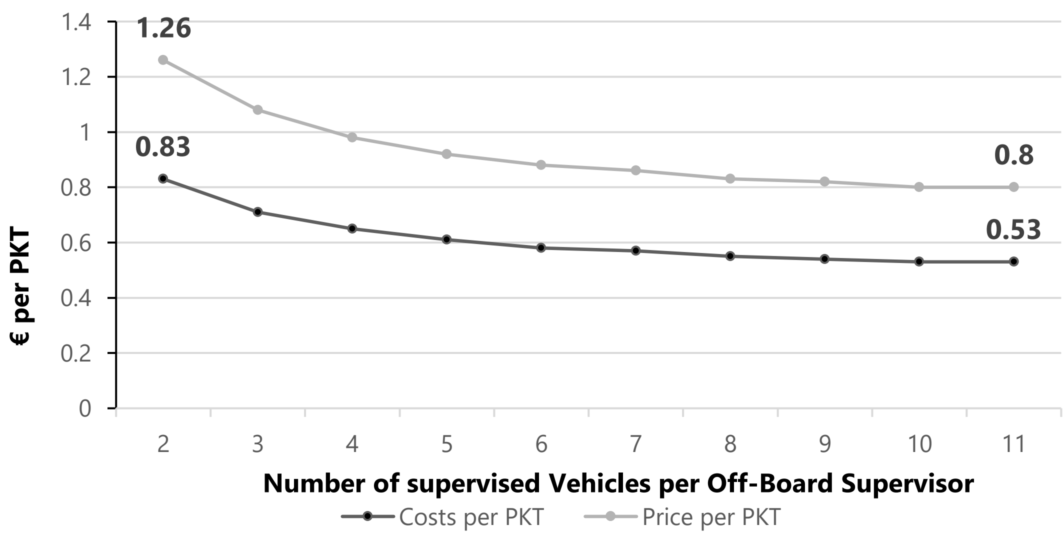


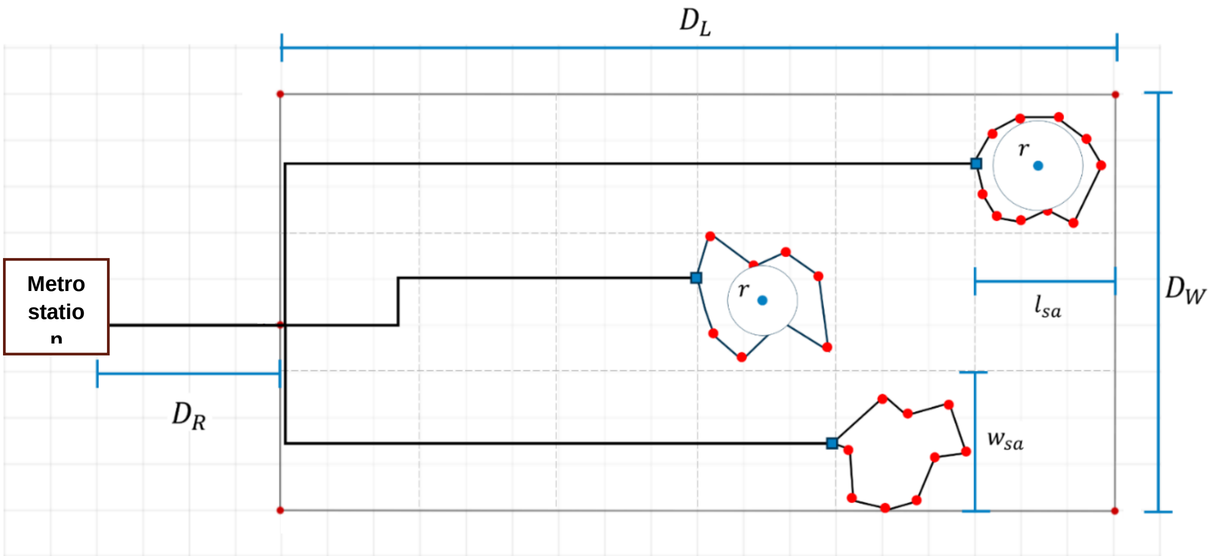
Figure 17: Scenario 1 - Impact of the number of supervised vehicles per off-board supervisor

While the cost decline is considerable between SPV_2 and SPV_5, the costs per kilometre only further decreases slightly for a value of more than 5 supervised vehicles per Off-board Supervisor (see Figure 16). However, the graph shows more significant changes in kilometre-based costs when adjusting this adaptive factor in contrast to the previously described ones.

3.1.3.5. Results for Scenario 2: AV in MaaS (door-to-door feeder service)

The second mobility scenario considered describes an on-demand service without a fixed timetable to enable flexible booking of the automated vehicle. The applied method for fleet size calculation can be used for feeder services (Fig. 18). By considering a connection to other means of transport in order to have a possible seamless connection, a main characteristic of the MaaS concept is fulfilled. In contrast to scenario 1, no fixed route to be replaced is considered, but a larger service area where the automated vehicles operate flexibly between an intermodal hub (in the case of Metro Station) and sub-areas. In this scenario, the operation of an on-demand bus service commences at a station (in this case considered as an intermodal hub, serving people travelling towards a specific subarea allocated to that bus. Once the bus reaches the assigned subarea, it follows a route defined by requested origins and destinations, allowing the passenger pickups and drop-offs along the road. The passengers to be dropped are individuals arriving at the station during the period between two successive buses. On the other hand, the passengers to be picked up are individuals within the subarea who are heading to the station. The cycle is concluded when internal route r within the specific subarea (with $l_{sa=}1\ km$ and $w_{sa=}1\ km$) is completed, and the bus returns to the station (Badia und Jenelius 2021). The distance to station D_R was set to 0km. We considered an area of 19,25 km^2 , with the dimensions D_L of 3,5km and D_W of 5,5 km.

Figure 18: Graphical Sketch of Scenario 2 - AV in MaaS



(Author's presentation based on Badia und Jenelius 2021)

Cost Calculations

Regarding the costs, this service constellation results in daily aggregated costs of 950 €. Monthly, this value amounts to 28500 €. The cost breakdown of CAPEX and OPEX in this base case shows the following values (Figures 19 and 20):

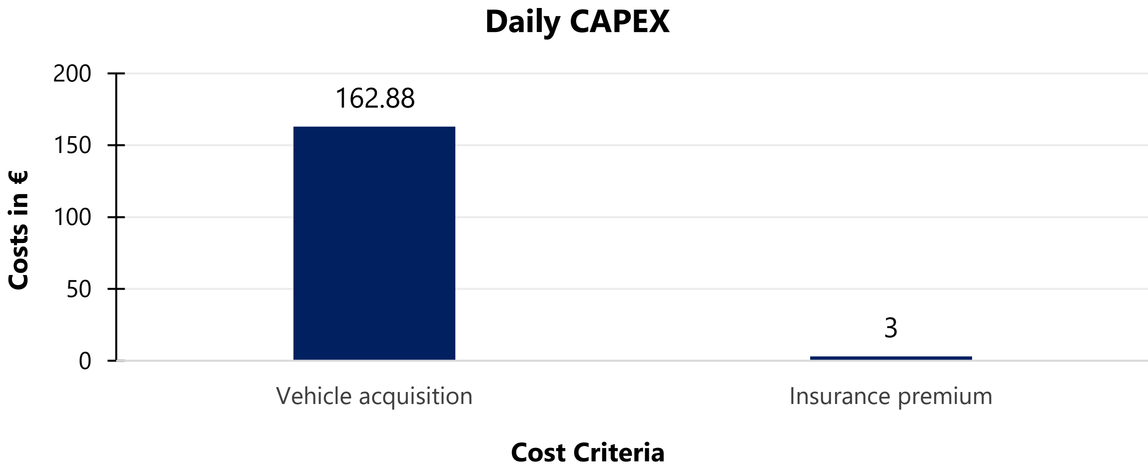


Figure 19: Daily CAPEX of Scenario 2 - AV in MaaS

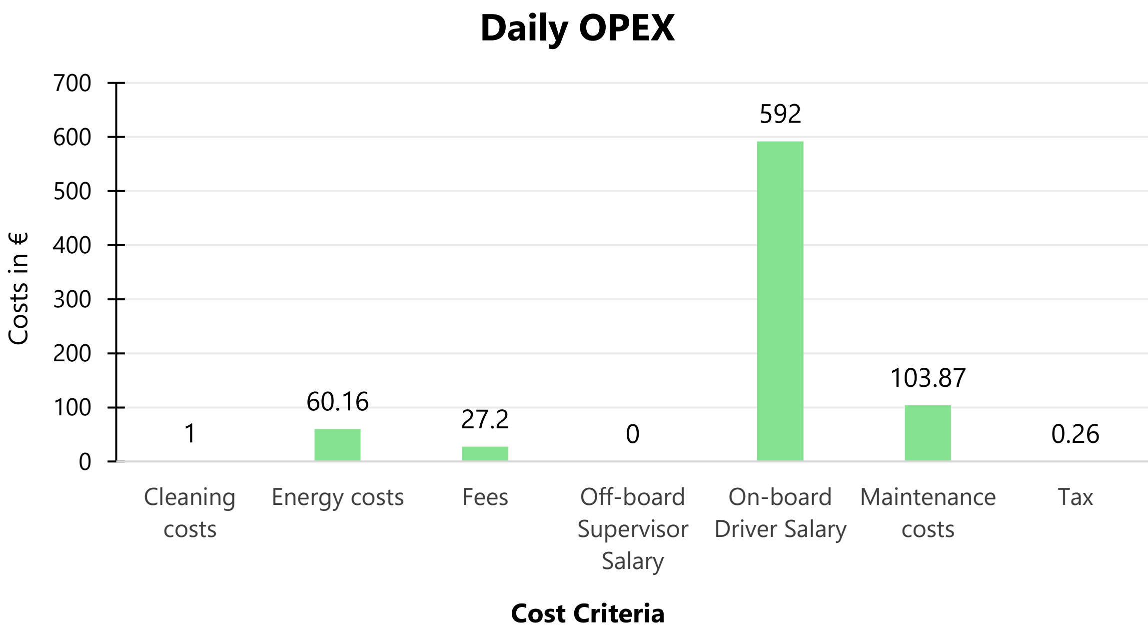


Figure 20: Daily OPEX of Scenario 2 - AV in MaaS

Due to the lower required fleet size for this scenario, the aggregated total costs per day are lower compared to scenario 1, resulting in lower values for the cost criteria on both the daily CAPEX (Figure 18) and OPEX (Figure 19). For this scenario, the acquisition costs are 162,88€. On the daily OPEX side, the energy costs are 60,16€, the maintenance costs are 103,87€ and the onboard supervisor's salary is about 592€. In comparison to that, the values for the remaining cost criteria are very low. Like scenario 1, the importance of labour costs is underlined too. Considering the acquisition costs, the onboard driver salary, the energy costs, and the maintenance costs (in total, 918,91€), it is clear that they make up mostly the same amount as the total daily costs.

Key Performance Indicators

The cost per kilometre driven is 1.55 €, and the price related to the same base is 2,35 €. For each kilometre driven, the acquisition cost is about 0.27 € (17,2% of the total cost per kilometre), and the salary cost of the onboard driver is 0.74€ (about 62.5% of the total cost per kilometre). For the energy costs, the value calculated on the kilometres driven is approximately 0.1€ (a percentage of 6.4%). For each service hour, the cost is 59,38€, which is 29,69€ for each vehicle required.

Sensitivity Analysis

When considering the impact of energy cost reduction, there is a price and cost decline of about 2,58% between the minimum and maximum cases. The aggregated total costs (daily) decrease to 920€. Concerning the kilometer-based costs, Figure 21 depicts the cost change, focusing on the values for r_{EN1} and r_{EN10}.

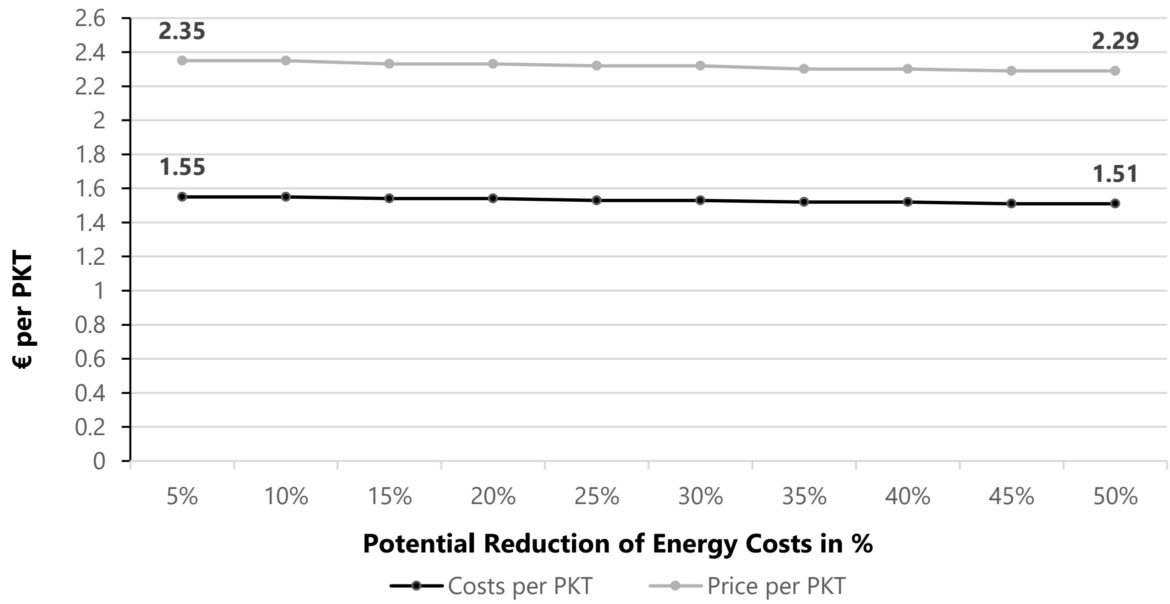


Figure 21: Scenario 2 - Impact of potential Energy Cost Reduction (Graph)

When considering the impact of maintenance cost reduction, the average cost and price drop is approximately 3.8%, even though maintenance costs accounted for a higher percentage of total daily costs than energy costs. The cost change is depicted in Figure 22.

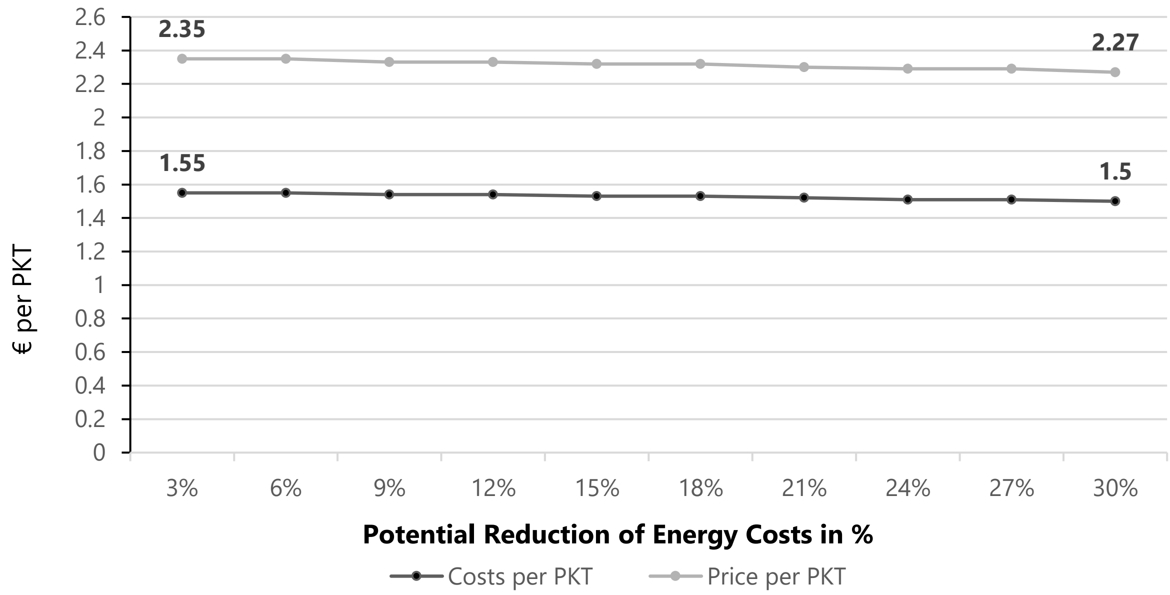


Figure 22: Scenario 2 - Impact of potential Maintenance Cost Reduction (Graph)

Similar to scenario 1, changes in the amount of monthly cleaning cycles do not significantly affect the kilometre-based costs of the underlying AV service. However, in this scenario, factors that are difficult to assess (e.g., duration of each cleaning cycle) could substantially impact the overall costs. Nevertheless, the cost change is graphically shown in Figure 23, focusing on q_{cl1} and q_{cl10}.

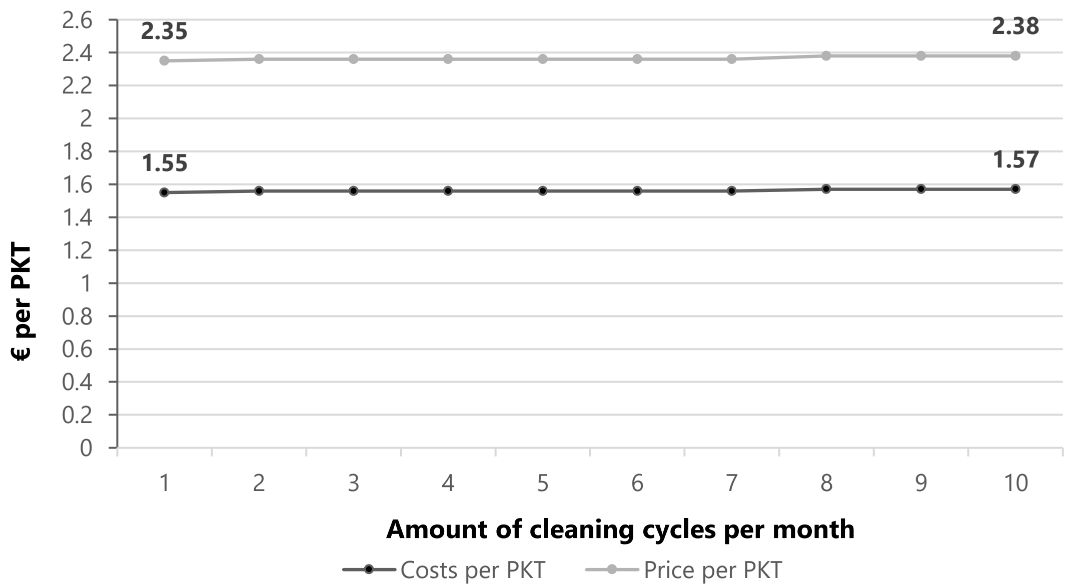


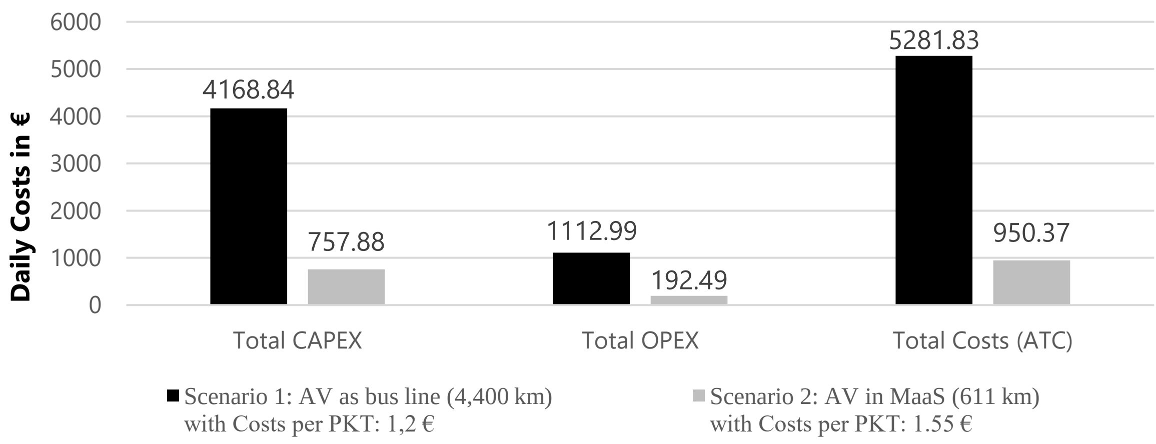
Figure 23: Scenario 2 - Impact of Cleaning Frequency (Graph)

Looking at the distinction between on-board and off-board drivers, the following changes in costs emerge: It is apparent that there are significant differences in the cost structures compared to the base case. In this constellation, the daily costs drop from 950€ to 654€, considering that an off-board supervisor can monitor two (2) vehicles. As the resulting fleet size for this scenario comprises two automated vehicles, the kilometre-based costs are only compared between setting (1), which is the base and setting (2), where one off-board supervisor supervises the 2 vehicles. Introducing off-board supervisors in Scenario 2 has led to a significant reduction in costs per kilometre driven, as in Scenario 1. The costs per kilometre have decreased by approximately 30,9% compared to the base case, resulting in a new cost per kilometre of 1,07€ instead of the initial 1,55€. Moreover, the off-board supervisor's cost in this setting amounts to 296€, representing approximately 45,25% of the total daily costs.

3.1.3.6. Summary

Scenario 1, "AV as a bus line", and Scenario 2 ", AV in MaaS", consider a daily demand of 10.000 passengers with even distribution. In both scenarios, the labour costs, including the onboard driver and off-board supervisor's salary, significantly contribute to total daily costs. Under the set assumptions, the impact of energy and maintenance cost reduction leads to a slight decline in overall kilometer-based costs. The fleet size and total daily distance covered differ between scenarios, with scenario 1 having lower costs per kilometre than scenario 2. Additionally, the contribution of each criterion to the total daily cost varies between the two scenarios. Scenario 1, with a larger fleet size and a greater distance to cover, exhibits higher daily, monthly, and annual costs compared to Scenario 2. In the initial case of Scenario 2, without any adjustments, the cost breakdown of the daily CAPEX shows that the acquisition costs are the highest, at 162,88€. On the daily OPEX side, the energy costs are 60,16€, and the maintenance costs are 103,87€. The on-board supervisor's salary is about 592€. Regarding Scenario 1, the cost breakdown of the daily CAPEX shows that the acquisition costs amount to 895,84€. For this scenario, the daily OPEX side energy and maintenance costs are 330,88€ and 748€, respectively. The salary for the onboard driver is 3256€.

In the initial case of scenario 1, the costs per vehicle-hour are 30,01€, while for scenario 2, this value amounts to 26,29€. The importance of labour costs is evident in both scenarios, highlighting the potential cost reduction by implementing off-board supervisors. Despite the different fleet sizes and daily travelled distances, the costs per kilometre for scenario 2 are about 29,2 % higher than for scenario 1 but represent the more flexible service. In the most extreme case, scenario 1, where one off-board supervisor can monitor all the AVs of the fleet, the costs per kilometre considerably decline to 0,53€, representing a cost decrease of more than 50% compared to the initial values. This significant cost decline might indicate that AV service costs can decrease despite larger fleet sizes. However, with a minimum number of two (2) supervised vehicles per off-board supervisor, the costs per kilometre declined by approximately 30% for both scenarios, compared to having on-board drivers. The adjustment factor "cleaning frequency" only had the lowest impact on the costs in both scenarios. In both mobility scenarios, taxes and insurance costs do not account for a significant share of the total costs. The summary of the AV service cost calculations and sensitivity analysis are depicted in Fig. 24.



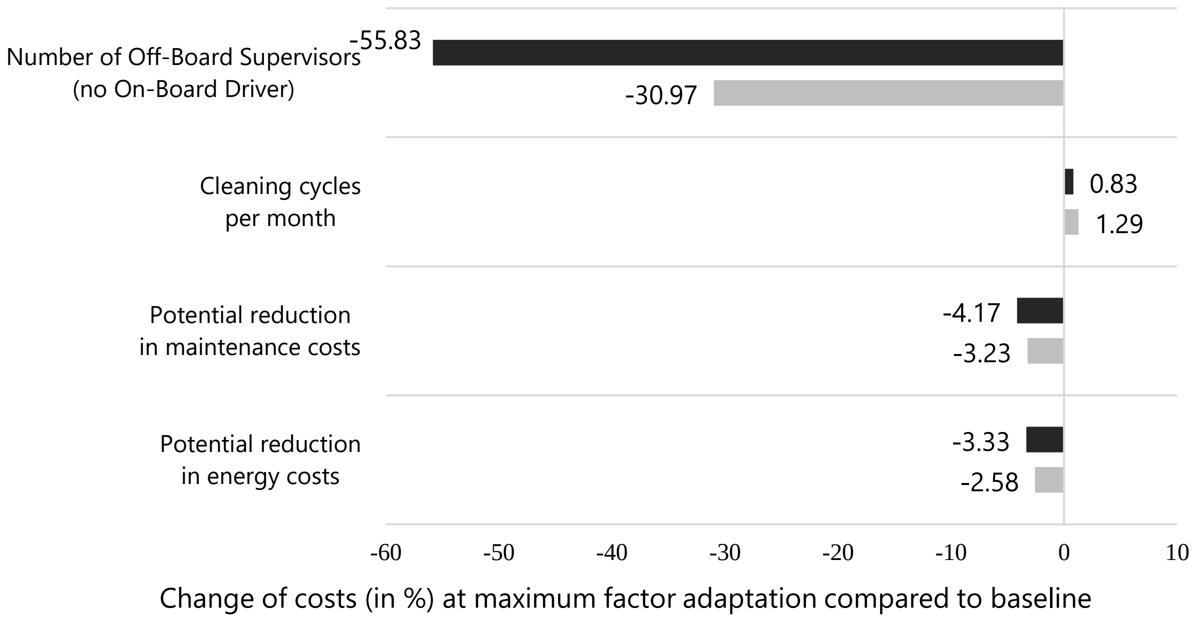


Figure 24: Summary of AV service cost calculation and sensitivity analysis

3.1.4 User Interface of the Fleet Cost Calculator for AV Services

In this section, the Fleet Cost Calculator's User Interface (UI) is presented according to the conceptual framework and the specific items that belong to the calculation model. As a differentiation between two mobility scenarios was drawn, there is a certain page on the user interface (UI) for the respective scenario. In this sense, the user can clearly see for which scenario the calculations are conducted and which adjustments have to be made.

AV as bus line user interface

Figure 25 shows the interface of the "AV as a bus line" scenario with the respective placement of the settings and the results.

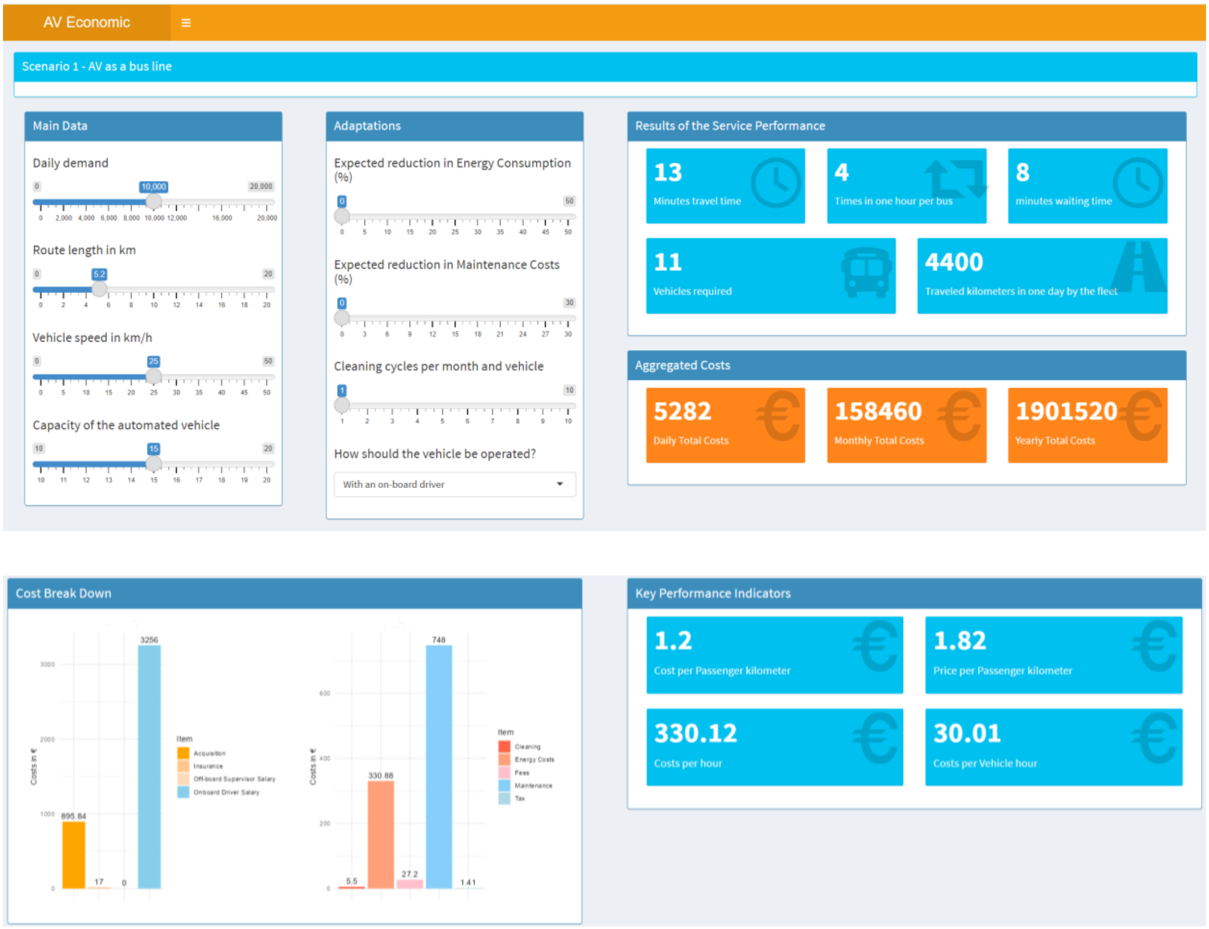


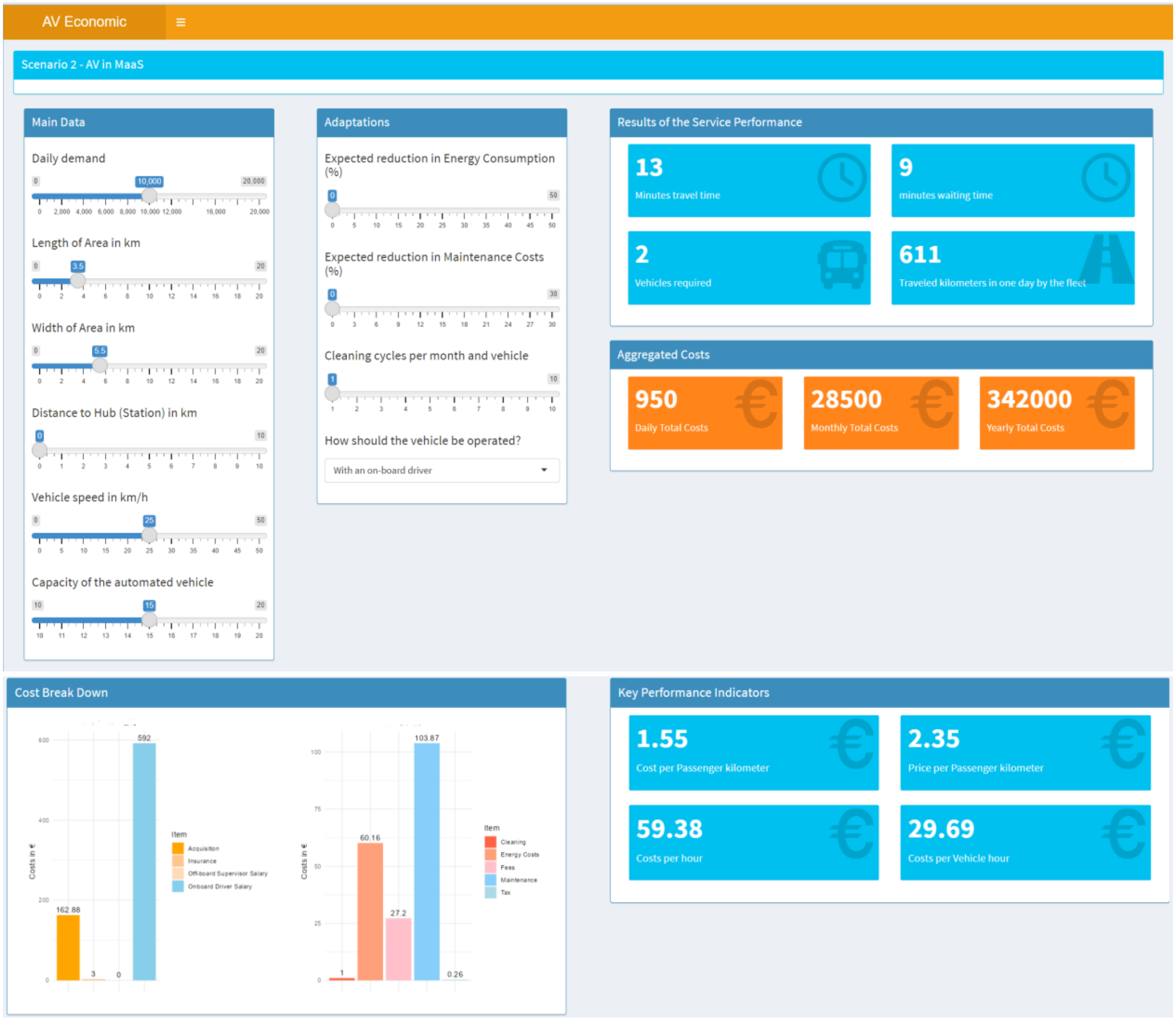
Figure 25: AV as a bus line" user interface

The user can conduct the main crucial settings on the upper left side for this scenario. These settings include daily passenger demand, route length, vehicle speed and capacity. Directly to the right, adaptation can be assumed (effects of electrification and automation recognised from the literature or additional adjustments), which could affect the cost structures for the mobility service. In the interface's right and lower areas, the service's performance and cost results are shown (total costs, cost breakdowns, and specific indicators). In the cost breakdown, differentiation between daily CAPEX and OPEX values is drawn to see which cost factors are the most significant ones for the service in terms of fixed and variable costs directly related to the service performance.

AV in MaaS user interface

Figure 26 shows the interface of the "AV in MaaS" scenario with the respective placement of the settings and the results.

Figure 26: "AV in MaaS" user interface



Equivalent to the "AV as a bus line" page, the main settings can be seen on the upper left side, while the results (related to service performance and costs) are placed on the upper right side and on the lower part of the interface. In contrast to scenario 1, as already outlined, the user must adjust more main settings, due to differences in fleet size calculation. The FCC of this work will be further developed during the project, considering the other demonstration sites and the incorporation of external costs within the calculation procedures so that the results can more accurately reflect the economic efficiency of AV mobility services in various contexts and locations. In conclusion, further developing the calculator can help develop business models for sustainable, citizen-centric AV mobility solutions.

3.1.5 Research Gaps

Based on the previous elaborations, we identified three research gaps:

- Limited empirical data on AV service costs and economic impacts: Despite ongoing research, empirical data on AV service costs and economic impacts remain limited. This is mainly due to AV technology's emergent development and evolving transformative potential. As AV technology matures and AV services become more widely adopted, empirical data can be expected to be better available. However, it remains necessary to refine economic assessment methods for AV services and explore innovative modelling and simulation.

- Lack of systemic economic assessments of AV services within MaaS and LaaS: Current economic assessments of AV services primarily focus on financial metrics and neglect broader economic dynamics within a MaaS and LaaS ecosystem. To effectively understand the economic impact of AV services, system-level assessments are necessary that consider:
  - ✓ User-related factors (such as user preferences and willingness to pay).
  - ✓ Interactions between various stakeholders involved in the MaaS and LaaS ecosystems.
- Neglect of broader social and environmental impacts of AV services: Economic assessments of AV services often overlook broader social (for example, improved accessibility) and environmental impacts (for example, congestion). A more comprehensive economic assessment should consider these broader social and environmental impacts and the direct costs and benefits of AV services.

3.1.6 Proposed work plan and expected results

Sequel to the research gaps, we identified further sub-research questions as follows:

- What are the variables of LaaS influencing the economic implications of AV services?
- How can we account for social and environmental impacts in an economic assessment of AV services?

The proposed workplan for the economic assessment within the ULTIMO project encompasses different steps for developing a robust framework for calculating the Total Cost of Mobility of AV services, particularly in the context of MaaS and LaaS. The first decision involves selecting the most suitable pathway (Fig. 26), which will subsequently guide the development of the economic assessment model. Currently, we focus on developing an integrated (holistic) cost structure, specifically emphasising operational costs associated with AV services. This process is in progress and includes discussions with Public Transport Operators (PTOs) and Public Transport Authorities (PTAs) to ensure applicability to the operational context. This empirical aspect adds a practical perspective and real-world validation to the elaborated framework and improves its applicability and reliability. The proposed work plan represents a structured approach ranging from selecting pathways to developing a comprehensive economic assessment framework and its subsequent application at three demonstration sites. This process aligns with the overarching research question of ULTIMO, which aims to create a detailed understanding cost-benefit analysis of mobility for AV services in the evolving landscape of connected and cooperative automated mobility (integrated in T.6.2. for designing sustainable business model).

3.1.6.1 Link with other tasks and WP

This task will contribute to a holistic impact assessment of AV and AV integrated in MaaS in urban transport systems (Task 6.1). This task will provide insight into Task 6.2 on the business strategies, models, and cases for future intelligent citizen-centric transport and sustainable business model design for AV integrated in MaaS. This task will contribute to designing a mobility business ecosystem and support the strategy design or transformation concept towards a future intelligent citizen-centric transport ITS/CCAM ecosystem for persons and goods. This task will also contribute to developing and validating innovative cross-sectoral business models (Task 6.2) for private and public stakeholders (ULTIMO's key objective 6). It will also provide insights into achieving realistic, long-term transition planning and design for integrating AVs in MaaS (Task 6.3) to serve the general interest (ULTIMO's key objective 8).

Examining economic dynamics within the automated shuttle ecosystem reveals the significant roles played by key stakeholders. Beginning with the AV (shuttle) manufacturers, their strategic decisions to sell or lease automated shuttles to transport initiate a primary financial transaction. Transport operators take possession of shuttles and deliver transportation services. These services may involve serving client cities, enabling better access to mobility to end users like commuters, or catering to client firms under transport contracts to commute employees. Additionally, transport operators may collaborate with digital service providers, aiming to improve user experience through personalised mobility services. Hereby, the digital service provider assumes the role of a platform operator overseeing the mobility services. Local transport authorities have the ask to ensure regulatory compliance and harmonised operations within the ecosystem.

The ecosystem involves different participants such as passengers, municipalities, software providers, mobility platforms, telecommunication companies, insurance companies, vehicle providers, infrastructure providers, maintenance/service companies, marketing intermediaries, mobility associations, data business providers, operating businesses, and technical inspection organisations. With each participants' role, the automated shuttle ecosystem is shaped and can further evolve for an efficient and user-centric future of urban mobility (Antonialli et al. 2021). It is projected that AVs might bring advantages in a triple bottom line: economic, environmental and social benefits associated with the accessibility of mobility services for specific groups of people (Camps-Aragó et al., 2022). It is imperative to extend aspects of value creation and capture to the environmental and social dimension and map the cost structures (and revenue streams) of all stakeholders involved in the entire ecosystem (Bocken et al. 2018). Within the Sustainable Business Model context, the creation of social, environmental and economic value is underlined, considering created, missed or wasted value (Bocken et al., 2013).

3.1.6.2 Expected Results

The economic cost analysis is expected to generate insights into the potential costs of AV adoption and implementation. With these insights and related real-world examples (case studies), policymakers can make informed decisions about integrating AVs in a more sustainable manner. Considering the implications of AVs and MaaS, it will be important to align with the interplay of stakeholders (Gandia, 2020), to further support the holistic view of the assessment. Additionally, we expect that AV costs can be reduced when the AV services are integrated into the MaaS and LaaS models. The ULTIMO project's goal of developing a comprehensive Total Cost of Mobility (TCM) framework for Automated Vehicle (AV) services aligns coherently with the broader discourse on sustainable business models (SBM). Therefore, the TCM framework not only provides a quantitative basis for assessing economic impact but also aligns with the larger goal of developing sustainable business models. The economic insights derived from TCM calculations will become integral to a holistic approach that considers social and environmental dimensions to support sustainable business models.

3.1.7 Conclusion

The preliminary analysis of two scenarios - "AV as a bus line" and "AV in MaaS" revealed noteworthy insights into the potential economic viability of AV services. We find that labour costs, including the salaries of on-board supervisors, contribute significantly to the total daily costs in both scenarios. In addition, energy and maintenance cost savings led to a slight decrease in the total cost per kilometre under the specified assumptions. It is worth noting that while scenario 1 had a lower cost per kilometre compared to scenario 2, the latter offered greater flexibility in service provision. Introducing offboard supervisors led to potential cost reductions, particularly in scenario 1, where the cost per kilometre decreased by over 50% in the most extreme case. We intend to build upon these preliminary findings to refine our economic assessment framework and enhance our understanding of the economic implications of AV services. Specifically, we aim to delve deeper into the factors influencing cost structures and explore scenarios for optimising the operational efficiency and cost-effectiveness of AV in MaaS and LaaS.

Moreover, sunk costs[28]as addtitional costs, could be a significant factor in the decision-making framework of PTA/PTOs because of their substantial capital infrastructure investments. Increased insights into their sunk costs could help PTOs/PTAs make informed decisions regarding future investments and resource allocation. Besides, PTOs/PTAs should consider the opportunity costs of their decisions. For example, PTOs/PTAs should consider not only the resources already invested but also the potential benefits that could be achieved by allocating resources to alternative projects or initiatives. By incorporating opportunity costs into their decision-making framework, PTOs/PTAs can be able to maximise the value of their resources and adopt strategies that offer significant overall benefit. In the subsequent phases, we will continue to implement the proposed work plan to develop the economic cost-benefit analysis framework and further refine the economic calculator, which is integral to our methodology. Through rigorous refinement and analysis, we aim to provide stakeholders with robust economic evaluation to inform strategic decision-making with the ULTIMO project.

3.1.7.1 Limitations of our preliminary research.

A limitation of our preliminary analysis is the lack of data on the infrastructure costs. The PTA is aware of this shortcoming. Moreover, discussions on the different service models such as door-to-door, door-to-hub, and corner-to-hub (including ride pooling as an extension of Fig. 18) are crucial aspects to consider in the cost analysis. These models offer varying levels of convenience and efficiency for passengers, with the choice often dependent on factors like infrastructure availability, passenger preferences, and operational feasibility. Further clarification is needed regarding where and how these service models can be included in the project's framework.

Following the analyses of the profitability conditions of two scenarios: "AV as a bus line" and "AV in MaaS" in this section, the next section discusses how pricing strategies could be adapted to maximise PTO/PTA revenues.

[28] Sunk Costs = money that a business or organisation has already spent and cannot get back. Source: Cambridge Dictionary (https://dictionary.cambridge.org/dictionary/english/sunk-cost)

3.2 Dynamic Price Modelling of AV integrated in MaaS innovation.

3.2.1 Introduction

An approach to optimise revenues is through dynamic pricing. Dynamic pricing, also referred to as surge pricing, demand pricing, or time-based pricing, is a revenue management pricing strategy in which businesses vary the price for a product or service to reflect changing market conditions (Ferrara, 2018). Dynamic pricing models could maximise efficiency and profitability (Turan et al., 2020). Prices can be adjusted based on demand, time, and other factors to optimise service use and revenue. Assessing the economic viability of integrating on-demand AVs into MaaS is not just a financial imperative but a critical step in ensuring that this innovative transportation model can sustainably meet urban mobility needs. A key aspect of the success of shared-use AV will be the ability to price rides in real-time. As these services become more prevalent, detecting behaviour shifts is essential to optimise the system quickly and ensure system efficiency and economic viability (Abkarian & Mahmassani, 2023). Dynamic pricing could provide insights for balancing demand, maximising revenue, optimising resource use, and influencing user behaviour (Kopalle et al., 2023), which may be useful for integrating AVs in MaaS systems. By increasing prices during peak demand periods and reducing them during low demand, businesses can effectively manage their capacity, leading to improved service quality and customer experience. This strategy could also help reduce costs as the capacity or infrastructure required to meet peak period demand is lowered, resulting in significant cost savings for businesses (Kopalle et al., 2023).

In this task, we propose to use dynamic pricing to assess the economic viability of integrating AV in MaaS. In the next section, we discuss the state-of-the-art on dynamic pricing for on-demand mobility systems, including analyses of various dynamic pricing methodologies applicable to inform the choice of our model.

3.2.2 State-of-the-art on dynamic pricing for AV integrated in MaaS.

The integration of AVs in MaaS presents a transformative potential for the future of urban transport. However, this integration poses significant challenges and opportunities to adapt pricing strategies. This section explores the implications of both pricing strategies for private transport operators, particularly in integrating AVs in Mobility as a Service (MaaS). It also discusses the current state of research on dynamic pricing for shared mobility on-demand services, the various techniques researchers employ to optimise pricing strategies, and their strengths and weaknesses.

3.2.2.1 Dynamic vs Static Pricing Strategies

The debate between dynamic and static pricing strategies becomes increasingly significant in the rapidly evolving landscape of shared automated on-demand mobility services, including ride-sharing and autonomous vehicle (AV) fleets. Traditional static pricing models offer simplicity and predictability but lack the flexibility to adapt to the dynamic nature of demand and supply in transportation networks. Conversely, dynamic pricing strategies, which adjust fares in real-time based on varying conditions, present a promising solution to these challenges. This section examines the comparative advantages of dynamic versus static pricing strategies for private transport operators in the context of MaaS, advocating for a strategic shift towards dynamic pricing to fully leverage AVs' capabilities.

Theoretical foundation of dynamic and static pricing

Hörcher & Graham (2020) seminal work on pricing in a MaaS context underscores the efficiency and equity benefits of dynamic pricing over static models. By adjusting prices according to demand, time, and externalities such as congestion and pollution, dynamic pricing aligns closer with the societal costs and benefits of travel, fostering a more sustainable transport ecosystem. In contrast, Tervo (2020) study on Finnish taxi dispatch centres post-liberalisation highlights the challenges of dynamic pricing, pointing to technological, regulatory, and market acceptance barriers. Despite these challenges, the study acknowledges the potential advantages of dynamic pricing in enhancing market responsiveness and operational efficiency.

Riquelme et al. (2015) present a comprehensive study on applying queueing theory to dynamic and static pricing strategies in ride-sharing platforms. The authors explore how these pricing strategies impact the equilibrium between supply (drivers) and demand (riders), utilising a model that considers driver and passenger incentives, system throughput, and revenue optimisation. The methodology includes a combination of theoretical modelling and equilibrium analysis, focusing significantly on threshold dynamic pricing policies and their robustness compared to static pricing. The results indicate that while dynamic pricing may not consistently outperform the optimal static pricing in terms of performance, it offers greater robustness to fluctuations in system parameters, making it a preferable strategy for managing real-time supply-demand imbalances in ride-sharing platforms.

Chen & Sheldon (2016) examination of surge pricing on the Uber platform further supports the argument for dynamic pricing by demonstrating its positive impact on labour supply elasticity, thereby increasing service availability during peak demand periods. Shatanawi et al. (2022) analysis of road pricing strategies in the context of AVs in Budapest reveals that dynamic pricing strategies outperform static ones in scenarios involving AVs, enhancing network performance and social welfare. The studies provide a theoretical and empirical foundation for advocating dynamic pricing strategies in the MaaS ecosystem, especially with the inclusion of AVs. The evidence suggests that dynamic pricing more effectively addresses the economic principles of supply and demand and promotes a more efficient, equitable, and environmentally friendly transportation system. Integrating AVs in MaaS requires reevaluating traditional pricing strategies to account for the unique operational characteristics and potential of automated technology. Dynamic pricing offers several key advantages in this context:

- Enhanced operational efficiency: Dynamic pricing allows for the real-time adjustment of fares based on demand and supply conditions, optimising fleet utilisation and reducing wait times.
- Increased customer satisfaction: By aligning pricing with demand, customers benefit from potentially lower prices during off-peak times and guaranteed service availability during peak periods.
- Revenue optimisation: Dynamic pricing can maximise revenue through demand-responsive pricing, ensuring that prices reflect the value of the service provided at any given time.

- Adaptability to market conditions: The flexibility of dynamic pricing models enables operators to swiftly adapt to changing market dynamics, regulatory environments, and technological advancements.

Despite the arguments in favour of a dynamic pricing strategy for integrating AV in MaaS, it is not without limitations. The subsequent tabular comparison between the two pricing strategies highlights some of its limitations.

Table 6: Comparison of dynamic vs static pricing in the transport sector

Feature	Dynamic Pricing	Static Pricing
Definition	Prices change in real-time based on demand, supply, and other factors.	Prices are fixed and do not change with demand or other immediate market conditions.
Flexibility	High flexibility to adjust prices based on current market conditions.	No flexibility; prices remain constant regardless of demand or supply changes.
Customer Perception	Can be perceived as unfair or exploitative during peak times due to higher prices.	Seen as more transparent and reliable, as customers know the cost upfront.
Revenue Optimization	Helps maximise revenue during peak demand periods by adjusting prices upwards.	May miss out on potential revenue during high demand periods as prices remain fixed.
Utilisation Efficiency	Encourages higher utilisation during off-peak times through lower prices and maximises profit during peak times.	Does not inherently encourage off-peak utilisation, possibly leading to inefficiencies in asset use.
Complexity	Requires sophisticated algorithms and real-time data analytics to adjust prices accurately.	Simpler to implement and manage as prices do not change based on external factors.
Predictability	Less predictable for customers, which can affect their decision to use the service.	High predictability makes it easier for customers to plan and decide on using the service.
Customer Loyalty	Risk of losing customer loyalty if prices are frequently perceived as too high.	Easier to build customer loyalty with a consistent pricing approach.
Market Competition	Can provide a competitive edge by allowing for rapid response to market changes and competitor pricing.	May result in losing out to competitors who use dynamic pricing to attract more customers during certain times.
Adaptability	Better suited to adapt to sudden changes in demand or supply, such as special events or natural disasters.	Less adaptable to sudden market changes can result in overcharging or undercharging relative to demand.

Source: Authors' compilation from synthesising information from the studies referenced above.

Considering the insights from various studies on the impact of dynamic and static pricing strategies in the transport sector, it's evident that dynamic pricing offers a strategic advantage for private transport operators integrating AVs into MaaS. Dynamic pricing maximises efficiency and resource utilisation by aligning prices with real-time demand and enhances customer satisfaction and accessibility, leading to a more sustainable and equitable transportation ecosystem. Therefore, embracing dynamic pricing strategies is essential for operators aiming to leverage the full potential of AV technology within the MaaS ecosystem, ensuring a competitive edge in the evolving transport landscape.

Dynamic pricing for AVs integrated in MaaS involves developing real-time pricing algorithms that respond to varying factors like demand, traffic conditions, and operational costs. The goal is to optimise revenue for service providers while ensuring affordability and accessibility for users, thus making AV integration in MaaS systems more sustainable and effective. The study of dynamic pricing has grown in the last decades thanks to the scientific advances in statistics, economics and information technology. Current research on dynamic pricing for AV in MaaS primarily focuses on optimising pricing strategies to balance supply and demand, enhance operational efficiency, and improve user experience. Studies, including Turan et al. (2020) and Qiu et al. (2018), explore how dynamic pricing can influence user behaviour, such as encouraging off-peak travel to reduce congestion. Additionally, a study by Müller et al. (2023) also explored integrating real-time data analytics for more responsive and adaptive pricing models. Key challenges with dynamic pricing of rides include ensuring equitable service access and aligning pricing models with broader transportation policy goals. This area of research is evolving rapidly with the rise of mobility matching platforms.

The implementation of dynamic pricing strategies is also heavily reliant on technology and data analytics. Modern dynamic pricing software uses advanced algorithms and real-time data integration to automate price adjustments, ensuring businesses can quickly respond to market changes and maintain a competitive edge. These tools analyse a wide range of data points to predict market trends and automatically adjust prices in real-time, thereby enhancing the efficiency and effectiveness of dynamic pricing strategies. Estimating customers' sensitivity to different prices while also considering market uncertainty is one of the difficult steps in designing an efficient dynamic pricing strategy. Ferrara (2018) suggests that machine learning techniques such as reinforcement learning could possibly perform such a task, adding that these techniques also consider the uncertainty of the market.

3.2.2.2 Dynamic pricing methods

The dynamic pricing of Shared Mobility on-Demand Services (SMoDS) has emerged as a critical area of research aimed at enhancing operational efficiency, customer satisfaction, and profitability. This section delves into the myriad approaches employed by researchers to address this complex issue, focusing on their strengths and weaknesses. By reviewing several pivotal studies, we aim to shed light on the diverse strategies developed to navigate the challenges of dynamic pricing in shared mobility contexts. This review highlights the innovative methodologies and findings that have significantly contributed to the field. The studies discussed herein demonstrate the breadth of research and underscore the multifaceted nature of dynamic pricing mechanisms and their implications for shared mobility services.
We analysed this literature by highlighting these methods' techniques, advantages, and limits. These elements are evaluated in the light of Ultimo's constraints in terms of availability and

accessibility of data relating to the supply and demand of the AV in MaaS service, the needs of the PTO/PTA over time for territories different, and finally, the costs associated with the deployment of services. Finally, regulatory conditions are considered because pricing conditions are sometimes constrained on operational sites (for example, setting a minimum price). After a short presentation of each method and its stakes we propose a summary table (Table 7) presenting their techniques, used variables, strengths and limits.

3.2.2.2.1 Machine Learning Algorithms

Machine learning algorithms play a pivotal role in dynamic pricing. The algorithms continuously learn from new data, adjusting the pricing strategy to accommodate changing market conditions, customer behaviour, and other external factors. These models could provide insights to forecast demand with high accuracy, identify optimal pricing in real-time, and even personalise prices for individual customers or customer segments. They also help in understanding the elasticity of demand – how sensitive customers are to price changes under different conditions. Machine learning algorithms could also provide insights for understanding and predicting customer behaviour, optimising fleet usage, and adapting to rapidly changing urban transportation landscapes (Jiang et al., 2023). These algorithms leverage various techniques and consider many variables, discussed below, to optimise pricing in real-time. Key machine learning techniques offer powerful tools for developing dynamic pricing models in automated on-demand mobility, capable of processing complex data sets to optimise pricing strategies effectively. However, their success depends on the quality of the data, the interpretability of the models and ethical considerations.

3.2.2.2.2 Price Optimisation Algorithms

In dynamic pricing, price optimisation algorithms adjust prices in real-time or near-real-time based on changing market conditions, competitor actions, inventory levels, and customer behaviour. The goal is to find the optimal balance between demand and pricing to maximise or minimise a specified objective, often revenue or cost respectively, subject to some constraints. Advanced price optimisation models might also include machine learning components to predict how these variables will change and adjust the pricing strategy accordingly. The model's sophistication often depends on the industry, the nature of the products or services, and the quality and quantity of the available data. These techniques are particularly relevant to on-demand automated mobility services, such as self-driving taxis, automated ride-sharing, or delivery services.

Researchers have extensively used price optimisation techniques to study pricing strategies for on-demand shared autonomous vehicles (Müller et al. (2023), Hörl et al. (2021)). Price optimisation techniques have emerged as a cornerstone for developing effective pricing strategies, offering a nuanced approach to balancing the complexities of supply and demand dynamics. We review recent literature that employs price optimisation techniques and various computational and modelling approaches to explore pricing strategies tailored to on-demand shared automated vehicles (Qiu et al. (2018); Castillo (2018)). By examining studies ranging from customer-centric dynamic pricing models to the impacts of surge pricing in ride-hailing services, we aim to highlight the diverse methodologies and findings contributing to the broader understanding of pricing in shared mobility.

Reviewing price optimisation techniques in the context of on-demand shared automated vehicles reveals a complex interplay between technological innovation, consumer behaviour, and urban transportation dynamics. The studies discussed herein demonstrate a range of approaches, from computational studies and stochastic dynamic programming to agent-based transport simulations, each offering valuable insights into developing pricing strategies that can enhance profitability, service efficiency, and customer satisfaction. These findings underscore the potential of dynamic pricing to address the unique challenges of shared mobility systems, such as balancing demand and supply, reducing congestion, and improving system-wide efficiency. However, they also highlight the need to carefully consider the broader impacts on urban mobility, including the effects on congestion, service capacity, and the equitable distribution of benefits among stakeholders. Next, we will discuss Bayesian Models and Markov Chains, another common technique employed in the literature to optimise pricing strategies for AMoD systems.

3.2.2.2.3 Bayesian Models and Markov Chains

Bayesian Models and Markov Chains are statistical approaches often used in dynamic pricing strategies, particularly in complex and uncertain environments like on-demand automated mobility. These methodologies appear to handle uncertainty and probabilistic scenarios well, making them well-suited for predicting and adjusting to fluctuating demands and operational conditions. For instance, during peak hours or in high-demand zones, the system might predict a higher probability of demand outstripping supply and adjust prices upward to balance demand and supply. Similarly, prices might be adjusted downward in low demand to attract more users. By continuously updating their predictions and decisions based on new data, Bayesian models and Markov chains can help automated mobility services optimise pricing, enhance revenue management, improve customer satisfaction, and efficiently manage their fleets. However, the success of these models heavily relies on the quality and granularity of the data they are fed and the accuracy of the assumptions underlying their probabilistic frameworks. In the following sub-section, we discuss the various techniques, their strengths and limitations, and the variables for developing Bayesian Models and Markov Chains algorithms.

Scholarly examination of dynamic pricing mechanisms for Shared Mobility on-demand services (SMoDS) has significantly advanced through applying Bayesian Models and Markov Chains techniques. This literature review synthesises key findings from recent studies, demonstrating the multifaceted approach to understanding and optimising the economics of shared mobility platforms. For example, a dynamic pricing strategy can be formulated aiming at regulating Estimated Waiting Time (Guan et al. 2020).

Building upon the work of Guan et al., Wang & Xie (2021) introduce a nuanced approach to dynamic pricing that takes into account the intricate dynamics of demand, supply, and network externalities. This study enriches the discourse by emphasising the impact of network externalities on pricing strategies, thereby broadening the understanding of pricing mechanisms in ridesharing platforms (and it could be relevant with the question raised by Task 6.1 on environmental assessment). Zhong et al. (2023) explore the environmental and energy implications of Shared Automated Vehicles (SAVs) under different pricing strategies. Their research reveals a nonlinear relationship between SAV fares and their effects on energy consumption and $PM_{2.5}$ emissions, advocating for optimal pricing strategies to achieve significant environmental benefits.

Exploring dynamic pricing strategies for Shared Mobility on-demand services reveals a complex landscape where Bayesian Models and Markov Chains techniques have played a role (Mahavir et al., 2020; Banerjee et al. (2017)). The studies reviewed herein, spanning from operational efficiency and customer satisfaction to environmental sustainability, demonstrate the depth and diversity of research efforts in this area. These methodologies have provided valuable insights into balancing demand and supply, optimising revenue, and achieving social and environmental goals. However, challenges such as the optimal balance between operational objectives and the practical implementation of these strategies in real-world scenarios remain.

3.2.2.2.4 Game Theory Techniques

Game Theory in the context of dynamic pricing for on-demand autonomous mobility involves strategic decision-making based on the anticipated reactions and interactions of various market participants. This approach is particularly relevant in competitive environments, where the actions of one service provider can significantly influence others. Applying Game Theory to dynamic pricing involves carefully considering the actions and potential reactions of competitors, regulatory bodies, and consumers. It can provide valuable insights into how pricing strategies could unfold in a competitive landscape and how best to position a service in the market. However, the success of such applications depends on the accuracy of the models, the quality of the data available, and the ability to adapt to changing market conditions and players' behaviour. It is also important to balance strategic competitive pricing with fair and ethical business practices, ensuring that such strategies are beneficial in the long term and align with broader market regulations and consumer expectations.

Game theory has enabled researchers and practitioners to model and predict how service providers adjust their pricing in response to varying market conditions. Some studies highlight how integrating game theory provides insights into optimising pricing, enhancing service efficiency, and improving user experiences in the face of direct competition. For example, Luo & Peng (2007) and Yan et al. (2020) demonstrate the potency of combining game theory with stochastic control theory and equilibrium analysis to devise pricing strategies that maximise revenue and competitive positioning and improve service efficiency and user satisfaction.
The exploration of game theory in the context of dynamic pricing within the on-demand automated mobility sector uncovers the intricate interplay between competitive strategies and market dynamics. The application of game theory allows for a nuanced understanding of the Nash equilibrium in competitive pricing scenarios, enabling service providers to optimise their pricing strategies in real-time. However, the literature also suggests that while dynamic pricing and matching algorithms offer significant benefits, their effectiveness can be contingent upon specific market conditions and operational parameters.

3.2.2.2.5 Elasticity Model

Elasticity models in the context of dynamic pricing are essential for understanding how changes in pricing affect the demand for services. Price elasticity of demand is a crucial concept here, referring to consumers' responsiveness or sensitivity to a price change. Elasticity models help set prices sensitive to customer demand and market conditions. For instance, during peak demand periods, prices might be increased if the demand is relatively inelastic, maximising revenue without significantly reducing demand. Conversely, in times of low demand, reducing prices might stimulate demand if the elasticity is high.

However, these models must be applied with a nuanced market understanding. Overreliance on elastic pricing can lead to customer dissatisfaction, especially if prices fluctuate widely and unpredictably. Moreover, these models require accurate and comprehensive data for precise estimation. In on-demand shared mobility, where market dynamics are rapidly evolving, elasticity models must be regularly updated to reflect current conditions. Additionally, ethical considerations and regulatory compliance must be factored in, especially in scenarios where dynamic pricing might lead to excessively high prices during emergencies or peak times. Effective use of elasticity models in dynamic pricing can lead to optimised revenue, better service utilisation, and maintained customer satisfaction.

3.2.2.3 Discussion

The methods discussed demonstrate a shift towards leveraging advanced computational models like Markov Decision Processes, Game Theory, Machine learning techniques, Price Optimisation Techniques and Approximation Frameworks to address complex, real-time decision-making in dynamic environments. Common themes include balancing supply and demand, improving service efficiency, and optimising operational costs. Insights drawn highlight the importance of data-driven, computationally sophisticated approaches to dynamic pricing. This suggests that the future of on-demand automated mobility will increasingly rely on these advanced models to enhance system performance, user experience, and profitability. Table 7 below summarises the various techniques employed by researchers for optimising pricing strategies for shared mobility-on-demand services.

Table 7: Summary of various techniques employed in the literature for dynamic pricing.

Category	Technique/Models	Parameter	Strengths	Limitations
Machine Learning Algorithms	Regression analysis, decision trees, Neural networks, and Support vector machines, Reinforcement learning	Historical Price Data: Past pricing information is often used to train the model. Sales Volume Data: Historical sales data at different price points. Competitor Pricing: Information on competitor prices, which can influence optimal pricing strategies.	Adaptability: Can handle a wide range of data types and adapt to new patterns in the data. Predictive Power: Capable of making accurate predictions based on large and complex datasets. Automation: Allows for automated decision-making, reducing the need for manual intervention.	Data Dependency: Requires large and high-quality datasets; performance is limited by data availability and quality. Complexity: Can be complex to implement and require significant data science and machine learning expertise. Opaque Decision Making: Often termed as "black boxes," making it difficult to understand how decisions are made.
Demand Estimation Models	Econometric models: Linear regression, Logistic regression, or Time-series analysis	Price and Demand History: Historical data showing how demand varies with price. Market Conditions: Information on economic conditions, seasonality, or other market factors. Customer Segmentation Data: Information about different customer segments and their price sensitivity.	Intuitive understanding: Based on established economic theories, making the results interpretable and intuitive. Simplicity: Generally simpler and easier to implement compared to complex machine learning models. Data Efficiency: Can work effectively with smaller datasets.	Limited Complexity Handling: May not capture complex nonlinear relationships as effectively as machine learning models. Data Sensitivity: Sensitive to inaccuracies in data; small changes can significantly impact predictions. Static Nature: Often assumes static conditions and may not adapt well to rapidly changing market conditions.

Price Optimisation Algorithms	Linear programming, Dynamic programming, Heuristic methods, Stochastic Optimisation, Integer Programming, Non-Linear Programming	Cost Data: Information on the costs associated with the product or service. Demand Curves: Data or estimations on how demand varies with price. Capacity Constraints: For service-based industries, information on capacity limits.	Optimal Solutions: Designed to find the best solution based on the given objective (e.g., maximising profit). Quantitative Analysis: Provides a clear quantitative framework for decision-making. Scalability: Can handle large-scale problems involving numerous variables.	Computational Complexity: Some algorithms can be computationally intensive, especially for large-scale problems. Data Requirements: Needs accurate and comprehensive data to produce reliable results. Rigidity: May not adapt well to changes in market conditions without reconfiguration.
Game Theory and Auction Models	Auction models: dynamic and sealed-bid auctions	Competitor Strategy Information: Data or assumptions about how competitors set prices. Market Demand Data: Overall market demand information. Bid History: In auction models, historical data on bids for similar products or services.	Competitive strategy analysis: Excellent for analysing and predicting competitive behaviours in the market. Dynamic pricing mechanisms: Useful in real-time pricing environments like auctions. Theoretical rigour: offers a solid theoretical foundation for understanding market dynamics.	Assumption-dependent: Often relies on specific assumptions about market conditions and behaviours. Complexity: Can be complex and challenging to implement in practical scenarios. Limited Applicability: Best suited for markets with clear competitive interactions and auction-like settings.

Agent-Based Modeling	This involves simulating the actions and interactions of automated agents (like customers and competitors) to assess their effects on the system as a whole. It can be particularly useful in complex, dynamic environments.	Agent Characteristics: Information about the agents (consumers, competitors), including their behaviours and decision rules. Market structure data: Information about the market environment in which agents operate. Interaction Rules: Rules governing how agents interact within the model.	Good for understanding how individual behaviours impact the overall market.Flexibility: Can be customised to simulate a wide variety of market scenarios.Interactivity Analysis: Useful for analysing the effects of interactions between different market participants.	Computational Demand: Can be computationally expensive, especially for large-scale simulations. Modeling Complexity: Building accurate agent-based models can be complex and time-consuming. Data Calibration: Requires extensive data to accurately calibrate the model.
Bayesian Models and Markov Chains	These probabilistic models can handle uncertainty and the dynamic nature of markets. They are useful in scenarios where the pricing model needs to adapt to new information over time.	Prior Information: Previous knowledge or data about pricing and demand, used as the 'prior' in Bayesian models. Transition Probabilities: In Markov Chains, probabilities represent the likelihood of moving from one state (price level) to another. Demand Uncertainty Data: Data on the uncertainty or variability in demand.	Handling Uncertainty: Effective in dealing with uncertainty and probabilistic scenarios. Dynamic Nature: Well-suited for dynamic environments where conditions change over time. Sequential Decision Making: Useful when pricing decisions are interdependent over time.	Mathematical complexity: Can be mathematically complex and require specialised knowledge. Computational intensity: Some models can be computationally intensive, especially for large state spaces. Data requirements: Like other models, their effectiveness is contingent on the quality and availability of data.

Elasticity Models	Price elasticity of demand is a key concept in dynamic pricing. Models that estimate the elasticity of products can help businesses understand how price changes might affect demand.	Price Elasticity Coefficients: Measures of how sensitive demand is to price changes. Cross-Price Elasticity Data: Information on how the price of one product affects the demand for another. Income Elasticity Data: Data on how demand changes with consumer income levels.	Economic Rationality: Based on well-established economic principles. Simplicity and Practicality: Relatively simple to understand and implement. Direct Focus on Price-Demand Relationship: Specifically focuses on the relationship between price and demand, which is central to pricing strategies.	Assumption of Constant Elasticity: Often assumes elasticity is constant, which may not hold in real-world scenarios. Over-Simplification: Can oversimplify complex market dynamics. Static Analysis: Typically does not account for changes over time or feedback loops.
Segmentation and Personalization Strategies	Using customer data to segment the market and personalise prices. Data mining and clustering techniques can identify customer segments with different price sensitivities.	Customer Demographic Data: Information on customer age, gender, income level, etc. Purchase History Data: Individual customer's historical purchase data. Customer Preferences: Data on customer preferences and behaviours.	Customer-Centric: Focuses on understanding and catering to different customer segments. Increased Relevance and Effectiveness: Can lead to more effective pricing by aligning with specific customer needs and preferences. Enhanced Customer Relationships: Can improve customer satisfaction and loyalty by offering personalised experiences.	Data Privacy Concerns: Requires careful customer data handling to avoid privacy breaches. Implementation Complexity: Implementing personalised pricing strategies can be complex and resource-intensive. Risk of Discrimination: There is a risk of perceived or actual discrimination if not managed properly.

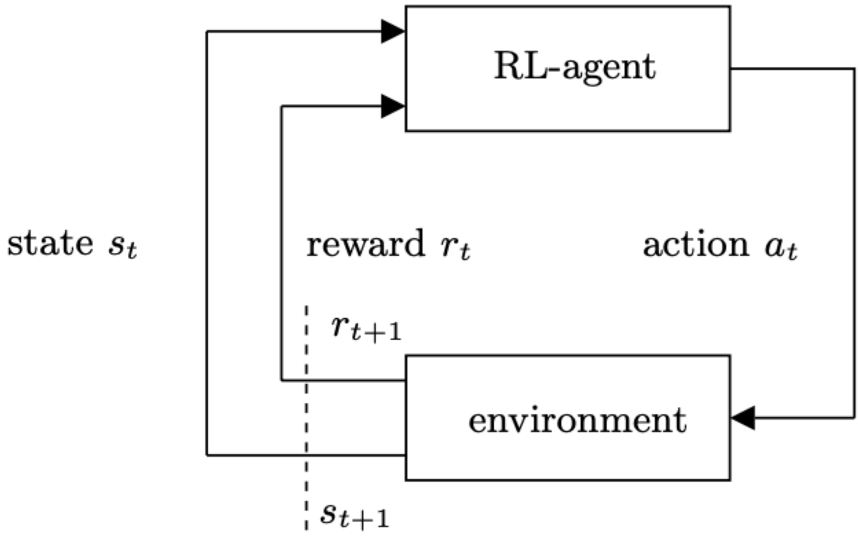
Developing a dynamic pricing model for on-demand automated mobility requires an approach or a model that can adapt to changing conditions in real-time, handle complex interactions between variables, and predict prices that balance demand and supply efficiently. In particular, pricing algorithms should be able to set fares based on intricate demand functions that vary in sensitivity (Abkarian & Mahmassani, 2023). Furthermore, these algorithms should possess the ability to identify non-stationary patterns—meaning, when the true value of actions changes over time, such as due to changes in customers' willingness to pay—and adjust their pricing strategies based on what they have learned from past decisions (Sutton & Barto, 2017). No single "best" technique exists, as the optimal choice depends on the specific characteristics of the service, the data available, and the goals of the pricing strategy.
However, compared to the other techniques discussed earlier, Reinforcement Learning (RL), discussed in detail below, is more commonly used and well-suited due to its ability to adapt to changing market conditions and user behaviours and learn optimal strategies in complex, uncertain environments.

3.2.2.4 Reinforcement Learning

Reinforcement Learning (RL) is a machine learning technique that focuses on how an agent should take actions in an environment to maximise some notion of cumulative reward. It is distinct from supervised learning, where learning occurs from a labelled training set provided by an external supervisor, and unsupervised learning, which involves uncovering hidden structures in unlabelled data. Unlike supervised learning, which focuses on extrapolating correct actions from labelled examples to act correctly in new situations, RL learns from the consequences of actions in an interactive environment to maximise a reward signal. This makes relying solely on supervised learning in interactive problems impractical, as obtaining correct and representative examples of desired behaviour for all possible situations is often infeasible. Unsupervised learning's focus on discovering data structures does not address RL's goal of reward maximisation.

Therefore, RL is considered a third paradigm in machine learning, distinct for its focus on learning through interaction and experience to achieve optimal outcomes rather than just identifying patterns or making predictions based on provided data (Sutton & Barto, 2017). In addition, the main challenge that distinguishes reinforcement learning from other kinds of learning is to find the trade-off between exploration and exploitation – balancing the act of exploring new actions to find out their rewards (exploration) and using known actions that yield high rewards (exploitation) (Sutton & Barto, 2017). The agent should use what it already knows to get a reward, but it should also explore to make a better choice of action in the future (Ferrara, 2018). The challenge is not to perform each task individually but simultaneously to achieve its goal. A key advantage of RL over other AI approaches, such as DPS, is that there is no need to specify how the task will be achieved (Kaelbling et al., 1996). Below is the reinforcement learning loop and a breakdown of its key components:

Figure 27: The reinforcement learning loop



Source: Schredelseker & Hauser (2008)

- The reinforcement learning agent (RL-agent) is connected to its environment via sensors.
- In every step of interaction, the agent receives feedback about the state of the environment s_t+1 and the reward r_t+1 for its latest action.
- The agent chooses an action a_t+1 representing the output function, which changes the state s_t+1 of the environment and thus leads to state s_t+2.
- The agent receives new feedback from the reinforcement signal r_t+2.
- The agent's objective is to optimise the sum of the reinforcement signals in the long run.

Reinforcement learning (RL) provides a framework through which agents learn to make decisions by interacting with their environment. This process is guided by the goal of maximising cumulative rewards over time. The theoretical foundations of RL are deeply rooted in the principles of dynamic programming, optimal control, and Markov decision process (MDP) theory. A MDP is defined by a set of states (S), a set of actions (A), a transition function (T), and a reward function (R). The transition function describes the probability of moving from state s to state s′ after performing action a. The reward function explains the immediate reward received after moving from s to s′ through action a. The Markov property asserts that the future is independent of the past, given the present state, thus simplifying the decision process based only on the current state and action. It is then a question of imagining a policy, denoted π, which maximises the cumulative reward over time.

The value function, Vπ(s), measures the expected cumulative reward to the state S under policy π, thus providing a means of assessing the quality of a policy.
The definition of success for "quality of a policy" in RL transcends simple financial metrics to encompass customer satisfaction. Too much emphasis on revenue or profits can lead to market fragility and customer alienation. A more balanced approach, therefore, is to adjust prices to cater to a broader customer base, thereby striking a balance between financial success and customer satisfaction. This balance is essential for sustainable business operations, as demonstrated by the detrimental effects of neglecting customer satisfaction in favour of short-term financial gains (these results will be inserted in Task 6.2.'s reflections).

RL has been successfully applied in various fields, including gaming (e.g. AlphaGo), automated vehicles, robotics, resource management… In terms of optimising pricing strategies for self-driving mobility systems shared, we will rely on recent studies to propose our specific simulation model for Ultimo. For example, Turan et al. (2020) highlights the integration of dynamic pricing with fleet management in an AV context, using advanced machine-learning techniques for real-time decision-making. Chen et al. (2021) addresses the challenge of determining optimal spatial and temporal pricing in ride-sourcing platforms, a complex task due to the dynamic and multifaceted nature of demand and supply in transportation. Finally, Abkarian & Mahmassani (2023) question how reinforcement learning can be used for dynamic pricing in shared-use autonomous mobility systems (SAMSs), considering the behaviours of heterogeneous users.

Reinforcement learning also has some limitations and challenges. RL algorithms often require numerous interactions with the environment to learn an effective policy (Riccio et al., 2021). They are usually tested in simulated environments rather than real environments. Thus, their application to real-world contexts might be limited, which could raise questions about their effectiveness in complex real-world scenarios. Balancing exploration and exploitation is a fundamental challenge with RL (Fruit, 2020). A fundamental challenge in RL is balancing exploration and exploitation. Exploration involves gathering more information about the environment and potentially discovering new strategies leading to higher rewards. Conversely, exploitation focuses on using currently known information to maximise immediate reward. Effective RL algorithms must navigate this trade-off, exploring sufficiently to find optimal policies while exploiting known strategies to accumulate rewards.

In many real-world problems, the design of the reward structure is crucial in RL. Poorly designed reward functions can lead to unintended behaviours, in which the agent learns to exploit the reward system in unexpected ways that do not correspond to the desired outcome (Kattepur, 2022). In complex environments with delayed rewards, it can be difficult to determine which actions are responsible for eventual outcomes, making it difficult for the agent to learn effective strategies. Additionally, environments with rare or misleading rewards can make it difficult for the agent to learn effective policies (Dai, et al., 2022). In such cases, the agent receives little or no feedback on his actions for long periods of time or may receive misleading feedback.

RL offers a robust framework for decision-making in complex environments, though it is not without its computational and conceptual challenges. Balancing computational feasibility and pursuing optimal policies necessitates a nuanced approach to model representation and learning dynamics, highlighting the intricate interplay between algorithmic efficiency, financial success, and customer satisfaction (Chen et al. (2023); Riccio et al. (2021)).
In the Ultimo project, we plan to develop a specific RL model that considers the experiments' constraints and opportunities, the diversity of issues, and territorial diagnoses. Simulations, depending on the data we can collect, will allow us to consider different simulations of pricing strategies for AV in MaaS services. For example, to solve the exploration/exploitation dilemma, we will test different exploration methods (to increase the exploration ability of agents to obtain various experience samples), redistribution (for the delayed reward problem, or modeling environmental rewards)

3.2.3 Data Requirements

Data quality is pivotal in designing and training Reinforcement Learning (RL) algorithms for dynamic pricing strategies, especially in the context of AV integrated in MaaS. Various studies, including Turan et al. (2020) and Chen et al. (2021), demonstrate the application of reinforcement learning and other machine learning techniques to optimise pricing strategies, highlighting the importance of real-time data analysis in adapting to market conditions and user behaviours. High-quality data ensures that RL algorithms can accurately learn and adapt to the complexities of real-world market dynamics, customer behaviours, and demand patterns. Without quality data, RL models may not effectively capture the nuances of pricing strategies, leading to suboptimal decisions and outcomes. Thus, acquiring quality data forms the foundation upon which efficient, adaptive, and intelligent pricing algorithms are built, enabling tailored, responsive pricing strategies that maximise operational efficiency and customer satisfaction in the evolving landscape of automated mobility services.
Table 8 details the data types scholars use in developing pricing algorithms for on-demand automated mobility services. This table not only categorises the data types employed in the existing literature but also proposes additional data types that may enhance the performance of Reinforcement Learning (RL) models based on insights derived from our review.

Table 8: Data type required for dynamic pricing algorithms.

Data type	Description
Demand Data	Historical booking data (time, location, duration, distance) Time-based demand patterns (peak hours, off-peak hours, special events) Predicted future demand based on trends or special events
Supply Data	Availability and location of vehicles Status (idle, en-route, occupied), and operational hours. Maintenance schedules Vehicle types and their capacities
Utility	The average revenue generated per vehicle
Pricing Data	Historical pricing data: Competitor pricing, the cost paid by the users, Price elasticity of demand
Revenue	Total revenue generated from ticket sales Income from other revenue streams, such as advertisement
Customer Data	Customer segmentation (regular users, occasional users) Historical usage patterns and preferences. Demographics, previous booking history, customer feedback, Sensitivity to price changes
Operational Costs	Fuel or energy costs, labour costs (if applicable), vehicle maintenance and depreciation, insurance costs
Geographic and traffic data	Real-time traffic conditions; Road closures and detours Average travel times and distances; Geographic demand hotspots and typical trip origins/destinations.
Competitor Information	Pricing strategies of competitors, market share, and service offerings.
External factors	Weather conditions, Local events (concerts, sports events, etc.) Economic indicators (inflation rates, economic downturns)

Regulatory data	Local transportation regulations and restrictions (data on any legal constraints or regulations that might impact pricing strategies, such as maximum or minimum fare limits.) Surge pricing regulations
Technological data	Vehicle telemetry and diagnostics System health and performance metrics
Time-Related data	Time of the day, day of the week, and seasonal variations affecting demand and supply.
Economic Indicators	Broader economic data that might influence consumer spending and travel habits.
Social and Cultural Data	Public holidays and cultural events Social trends influencing travel behaviour
Travel time	Time taken to destination/for journey, in search of parking, to the destination in congestion/non-congested situation.
Average speed	The average speed at toll points and roads. It is mainly used to evaluate the effectiveness of congestion pricing.
Delay/waiting time	Time for passengers to wait for the vehicles to arrive. Time for which EVs wait before getting their turn for charging/discharging. Time for which vehicles wait for parking, time for which vehicles wait before crossing toll gates Time in which the journey is completed.
Number of rejected/declined customers	The count of customers who have been denied services due to its scarcity. The number of customers who have declined service usage due to their high prices.
Searching time/congestion	The time taken to search spaces in case of parking and the number of vehicles at unit place in unit time respectively.
Average flow	The number of vehicles passed through a point on the road. This parameter provides congestion status and demand at that place.

Source: Authors' compilation based on insights from the literature review.

3.2.4 Methodology

This study aims to explicitly model from the perspective of a public transport operators and authorities and provide insights into optimal pricing strategies specific to the three different use cases of the ULTIMO project. We would use qualitative and quantitative methods and scenario-based analysis to achieve the above objective.

3.2.4.1 Qualitative Analysis

Following the approach of Carrese et al. (2023), Carreyre et al. (2022), and Saharan et al. (2020), we will conduct a further literature review on dynamic pricing strategies and related literature. We would investigate various dynamic pricing models used in transportation, focusing on their application in MaaS, particularly with AVs. We would analyse the effectiveness of different pricing strategies, such as time-based, demand-based, and congestion-based pricing, in managing demand and optimising the use of on-demand mobility services. The review would also explore the challenges in implementing dynamic pricing, such as technical complexities, user acceptance, and regulatory issues. Additionally, we would assess the impact of dynamic pricing on the overall efficiency and sustainability of transport systems, drawing from case studies and empirical research.

3.2.4.2 Quantitative Analysis

Considering the methodologies explored in dynamic pricing literature, we intend to follow the approach of Abkarian & Mahmassani (2023), Turan et al. (2020) and Qiu et al. (2018) to use a reinforcement learning technique to develop an efficient algorithm for optimising pricing decisions. As discussed extensively in this review, the reinforcement learning approach is the most suitable method for optimising dynamic pricing strategies in on-demand automated vehicle services compared to other techniques due to its unique capabilities in managing complex, uncertain environments and its ability to learn and adapt in real time.

3.2.4.3 Scenario Analysis

ULTIMO will deploy fleets of automated vehicles in three sites across Europe. In all the sites, fleets of AVs will be integrated into existing (public) transport networks, aiming further to enhance mobility and logistics services in the area. Under this task, we will collaborate with the PTAs and PTOs at the three implementation sites for practical insights and data to test and train our model. We would conduct surveys and interviews to gather user feedback on dynamic pricing acceptability and preferences. We would also conduct a scenario analysis by adapting our model to the various use cases of integrating AV in MaaS at the three implementation sites.

3.2.5 Proposed Work Plan

The following table shows the timeline of the activities to be conducted.

Table 9: Proposed work plan

Year	Activity Plan
April 2024 – Sept. 2024	• Conduct a systematic literature review on the dynamic pricing of AV integrated in MaaS
Sept. 2024 – March 2025	• Build a prototype reinforcement learning model. • Train the model to compare error rates.
March 2025 – June 2026	• Build the reinforcement learning model • Continuously improve the predictive accuracy of the model.
July 2026 – Sept. 2026	Report on key findings in the second D6.1 deliverable

3.2.6 Expected results

With our reinforcement learning model, we anticipate to provide the following insights in the second D6.1 report in September 2026:

- Optimal pricing strategies specific to the three different ULTIMO use cases for PTAs and PTOs.
- Commercially viable and sustainable solution when AVs are integrated into MaaS.
- Understanding of user responses to price changes (price elasticity).
- Policy recommendations to support informed decision-making for integrating AV in MaaS in urban transport systems.

3.2.7 Conclusion

In this study of dynamic price modelling for integrating AV in MaaS, we explore the comparative advantage of dynamic pricing strategy over static pricing. The insights drawn from the literature review suggest that dynamic pricing could offer a strategic advantage for private transport operators integrating AVs in MaaS. The proposed adoption of dynamic pricing to assess the economic viability of AV integration in MaaS signifies a step towards realising a transport model that is adaptable, efficient, and aligned with the evolving transport needs of urban societies. Various methodological approaches, including statistical analysis, machine learning techniques, and simulation models, have been explored to understand which method and technique may be more suitable for developing an efficient dynamic pricing algorithm for AV into MaaS. The analysis includes an evaluation of the strengths and weaknesses of each methodological approach, alongside a discussion on the types of data or variables integral to developing dynamic pricing algorithms using these methodologies. Furthermore, applying these methodologies within existing literature is examined to enhance the understanding of the different approaches. The insight gathered from the review suggests that among these methodologies, the adoption of the RL technique for dynamic tariff design could be more suitable for the study, given its proven efficacy in refining pricing strategies to align with fluctuating market demands and operational challenges.

Reinforcement learning appears promising to drive economic viability and sustainability for AV integration in MaaS, marking a pivotal step towards realising the full potential of AV technology within the evolving transportation landscape. Exploring RL's theoretical foundations offers a robust framework for understanding decision-making in complex environments. The nuanced approach to model representation and learning dynamics highlights the intricate balance between algorithmic efficiency, financial success, and customer satisfaction. Despite RL's computational and conceptual challenges, ongoing research and development are addressing these limitations, enhancing its robustness and applicability across various domains.

The successful application of RL in dynamic pricing underscores the importance of quality data in capturing the complexities of market dynamics and customer behaviours. Collaborative efforts with ULTIMO partners will be crucial in collecting the necessary data to train RL models effectively. This approach promises not only to refine pricing strategies to align with fluctuating market demands but also to ensure the economic viability and sustainability of AV integration in MaaS, marking a pivotal advancement in transportation technology. The adoption of RL for dynamic pricing in the integration of AVs in MaaS represents a significant step forward in leveraging advanced machine learning techniques to meet the evolving needs of urban mobility. By balancing the objectives of operational efficiency, revenue maximisation, and customer satisfaction, dynamic pricing strategies powered by RL promise to play a pivotal role in the sustainable development of smart mobility solutions, offering valuable insights for policymakers, transport operators, and urban planners in the quest for more efficient, accessible, and user-friendly transportation services.

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4 Social Acceptance Assessment

4.1 Introduction

The European Commission aims to provide more secure, safe, environment-friendly, user-centric transportation. To achieve its goals, the integration of AV in the existing public transportation system is a promising mobility innovation that has the potential to reduce congestion, CO_2 emissions, increase safety, increase fuel savings (Fagnant and Kockelman 2015) and increase mobility for people with special needs (Kassens-Noor et al., 2020). Another growing innovation is Mobility as a Service (MaaS). MaaS is a citizen-centric paradigm integrating different mobility solutions in a single online platform that enables commuters to plan, book, and pay for trips based on their preferences. The shift toward MaaS solutions is associated with a change in mobility behaviour patterns, such as an increase in the use of ride-sharing services apps and a reduction in private car ownership among younger adults (MaaS Alliance, 2019). In this task, we analyse the integration of AV in MaaS (an additional service offer) from the social acceptance viewpoint. In our research context, the object analysed is the integration of AV into a MaaS, which implies a reflection in terms of an additional service offering in the MaaS defined as a disruptive innovation. The integration of AV in MaaS will form a disruptive game changer to raise the transport system to a higher level of sustainable mobility evolution.

Why is it important to understand how this game changer is implemented in a transportation system? The social acceptance assessment (or the ability to accept such an innovation) will provide insights on the determinants of the intention to use the service proposed by automated vehicles. It will provide insights on people's willingness to pay and provide insights to support the economic impact assessment (WP6, Task 6.1) to determine the best pricing strategies. The social acceptance conceptual model will help to predict the adoption rate of AV integrated in MaaS services and provide insights to support the sustainable business models to identify the fleet of vehicles that should be in service at the end of the project. The social acceptance assessment will identify in which circumstances potential users will use the service. For example, if people believe or are convinced that AV integrated in MaaS will reduce the environmental impact, then they will intend to use the service. The user-behavioural analysis will identify the perceptions and beliefs regarding automated vehicle services. In a nutshell, the expected results from this deliverable will be useful for the social impact assessment, environmental assessment, and sustainability business analysis.

Social acceptance is one of the main barriers to the widespread adoption of AV (Raj and Bansal, 2020). Social acceptance is increasingly gaining research attention. Different streams of research have been identified in the literature. However, only few studies focusing on evaluating the acceptance of advanced driving systems (Regan, Horberry and Stevens 2014) and automated vehicles (Martina et al., 2022) have explained or defined acceptance explicitly. Generally, researchers defined acceptance in several ways. Some scholars defined acceptance as the satisfaction of users' requirements and needs (or the usefulness of the system). A second category defined acceptance as the sum of all attitudes. A third category considered acceptance as the willingness or intention to use a service. The definition of the third category argues for a behavioural change based on the result of the first two categories (the usefulness of the system and the sum of all attitudes). For the third category, acceptance refers to the real usage of the service. Furthermore, some researchers use acceptance and acceptance interchangeably. According to Jamson (2010), acceptability is how much a system is liked, while acceptance is how much it would be used. In this task, we are interested in understanding the use of the service and focus on the concept of acceptance.

As AVs are not widely used in public transport yet, we define social acceptance as "the user behavioural intention to use (or intention to use) the service, if the service is available. Behavioural intention to use seems promising to analyse behavioural change and based on the theory of reasoned action (TRA) (Fishbein and Ajzen,1975) that explain the main predictor of usage behaviour. We can define behavioural intention to use as the result of evaluating the fulfilment of users' needs and the sum of all attitudes. The Avenue project was thus able to assess users' perceptions and attitudes towards autonomous mobility. (Korbee et al., 2019; Naderer et al., 2021). For example, the results of the representative survey of the AVENUE project (Korbee et al., 2023) in Lyon, Copenhagen, Luxembourg and Geneva confirm that 45% of car drivers are "willing" (22%) or even "very willing" (23%) to give up using their cars to use AV to bridge the first-last mile mobility gap.

In this task, we will focus on the definition and evaluation of behavioural intention to use; then, we will also evaluate actual user behaviour. The assessment of behavioural intention to use encompasses various psychological, economic, values, attitudes and individual factors that could better explain potential users' behaviour. This task will focus on evaluating behavioural intention to use automated vehicles integrated in MaaS at three deployment sites and representing the ULTIMO project scenarios[29]. The main objective is to evaluate potential users' intention to use the service if the service is available.

Thus, the three research questions that will be addressed in this task are the following:

- What are potential users' needs to facilitate citizen acceptance of AV in MaaS as a sustainable mobility solution?
- What are the main determinants that could change behavioural intention?
- How can we change user mobility behaviour if AV services are offered in a MaaS?

We assume that to increase social acceptance we need to raise awareness about ongoing demonstration projects and allow people to test the service to create a positive attitude towards the service.

In the next section, we will present our literature review of the theoretical frameworks to explain user acceptance and the learnings and results from other related EU CCAM projects.

4.2 Related Work

This section presents different theoretical frameworks to explain user acceptance. Furthermore, we review the key contributions of other EU CCAM projects and identify some knowledge gaps that will be addressed within this social acceptance assessment.

[29] See Preface for the explanation of the three ULTIMO project scenarios

4.2.1 Theoretical framework to explain user acceptance

Davis (1989) developed the pioneering theoretical framework to explain user acceptance of information and communication technologies: the Technology Acceptance Model (TAM). The theoretical underpinning of this framework was the Theory of Reasoned Action (TRA). The Theory of Reasoned Action (TRA) is the fundamental theory that claims that usage behaviour is explained by the behavioural intention to use. According to TRA, behavioural intention is mainly explained by two psychometric constructs: attitude toward technology and subjective norm. Building upon this theoretical framework, Davis (1989) argue that behavioural intention to use is determined by perceived usefulness (PU) and perceived ease of use (PEU). We defined perceived usefulness as the expectation of use based on what it will bring to the user in terms of improving their individual performance. And perceived ease of use is the expectation of easy use. Venkatesh and Davis (2000) extended the theoretical framework of TAM by adding some constructs related to social influence and cognitive instrumental processes in order to take into account these behavioural anticipations and perceptions. This theoretical framework became influential among scholars. Many researchers started to adapt it to different technologies. Jing et al. (2020) reviewed the theoretical frameworks that were mostly used to explain the acceptance of AV. The authors found that: Technology Acceptance Model (TAM), Theory of Planned Behaviour (TPB), Diffusion of Innovations Model (DIM), Unified Theory of Acceptance and Use of Technology (UTAUT), Theory of Reasoned Action (TRA), Socio-ecological Model (SEM), and Causal Model were the most frequently used frameworks to explain user acceptance of AV[30].

Mara and Meyer (2022) reviewed the factors that could influence the acceptance of automated vehicles. The authors reviewed the previously mentioned frameworks. Furthermore, the researchers explained two additional conceptual models, (MAVA (Multi-level model on automated vehicle acceptance), Nordhoff et al. (2019)) and AVAM (Automated Vehicles Acceptance Model, Hewitt et al. (2019)) that were mainly addressed to explain the acceptance of automated vehicles. Zhang et Kamargianni (2023) also found an additional theoretical framework comprising several conceptual pillars: socio-demographic characteristics, attitudinal preferences, travel and behaviour pattern, built environment, psychological factors, environment and weather related factors. To the best of our knowledge, the technology acceptance model is the first theoretical framework used to explain user acceptance of automated vehicles, followed by UTAUT. An extension of UTUAT, UTAUT2 was developed to explain user acceptance of e-mobile services for consumers rather than the acceptance of information and communication technologies in an organisational context. In addition, UTAUT2 explained 74% of the behavioural intention to use e-mobile services (Venkatesh et al., 2012). We discuss below a brief presentation of UTAUT.

Venkatesh et al.(2003) developed the unified theory of acceptance and use of technology (UTAUT). UTAUT model summarised eight predominant user acceptance models (Theory of

[30] The Theory of Planned Behaviour (Ajzen, 1991) postulates that attitude toward the technology, subjective norm and perceived behavioural control are the main predictors of the behavioural intention to use (BIU) and perceived behavioural control and BIU are the determinants of usage behaviour. The Innovation Diffusion Theory supposes that relative advantage, ease of use, image, visibility, compatibility, results of demonstrability and voluntariness of use are the main predictors of BIU.

Reasoned Action (TRA), Theory of Planned Behaviour (TPB), Technology acceptance model (TAM), Combined TAM – TPB (C-TAM-TPB), Motivational Model (MM), Computer Model Utilization, Social Cognitive Theory (SCT) and Innovation Diffusion Theory (IDT))[31]. UTAUT encompasses four main predictors of the behavioural intention to use: performance expectancy (comparable to perceived usefulness in TAM), effort expectancy (comparable to perceived ease of use in TAM), social influence (comparable to subjective norm in TAM) and facilitating conditions (similar to perceived behavioural control in TPB). They considered age, gender, experience, and voluntariness of use as moderators.

Table 10 below presents an overview of the different theoretical frameworks that were developed to explain user acceptance of information communication technologies and adapted to explain user acceptance of automated vehicles.

[31] The Combined TAM and TPB model (C-TAM-TPB) consists of combining the constructs of the Theory of Planned Behaviour (TPB) and perceived usefulness from TAM to create a more hybrid model to predict the BIU. Motivational Model (MM) is a widely used theoretical framework in psychology to support motivational theory. This conceptual model assumes that intrinsic and extrinsic motivation are the prior antecedents of the BIU. The Model of PC utilization (MPCU) and the Social Cognitive Theory (Social Cognitive Theory) are among the popular conceptual models in human behaviour theory. However, these two conceptual models aim to predict usage behaviour rather than the intention to use.

Model	Dependent variable	Determinants or independent variables.	Strengths	Weaknesses
The theory of reasoned action (TRA)	Behavioural intention to use and usage behaviour.	Attitude toward technology Subjective norm	• Pioneer theoretical framework that explains intention to use.	• Psychological theory. • Assume that only attitudes and the influence of important others explain the intention to use.
The theory of planned behaviour (TPB)		Attitude toward technology Subjective norm Perceived behaviour control	• Extension of the theory of reasoned action. • Add perceived behavioural control as a construct that explain behavioural intention to use. • Consider external factors (organisational support) to explain the behavioural intention to use.	• Explain the user acceptance of information and communication technologies.
The technology acceptance model (TAM)		Perceived usefulness Perceived ease of use Subjective norm (only in TAM2)	• Constructs that explain the utilitarian motivation to use the technology.	• Theory developed to explain user acceptance in an organisation / professional context. • Decision-making process based on rational evaluation regarding performance expectations and effort. • Theory based on the utilitarian motivation.
Unified Theory of Acceptance and Use Technology (UTAUT)		Performance Expectancy Effort Expectancy Social influence Facilitating conditions	• Summarise eight predominant user acceptance models. • UTAUT2 is developed to explain to explain consumer acceptance.	• UTAUT is developed to explain user acceptance in an organisational/professional context. • Exclusion of technology / service-related constructs.

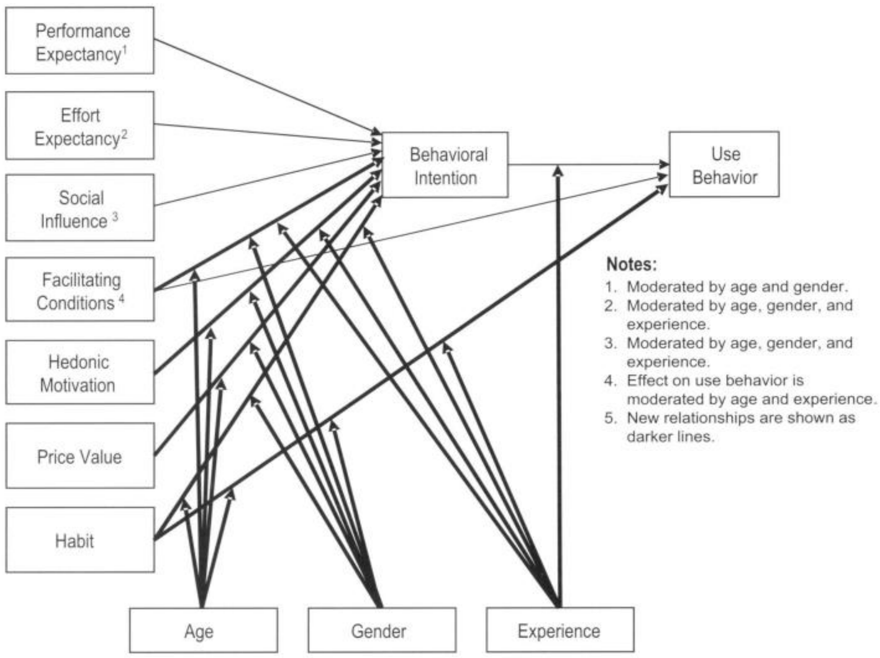
		Hedonic motivation (only in UTAUT2) Price value (only in UTAUT2) Habit (only in UTAUT2).	• UTAUT2 included relevant constructs (such as hedonic motivation and price value) that influence consumer behaviour. • More holistic compared to the other theoretical framework. • Have the highest explanatory power in explaining the variance of behavioural intention to use.	
Innovation Diffusion Theory (IDT)	Intention to use.	Relative advantage Ease of use Image Visibility Compatibility Results demonstrability Voluntariness of use	• Applied to study the acceptance of different innovations. • Help to identify early adopters, and late adopters.	• Developed to explain acceptance in a professional context. • Ignores complex factors such as culture, economics, etc.
Model of PC utilisation (MPCU)	Usage behaviour.	Job-fit Complexity Long-term consequences Affect toward use Social factors Facilitating conditions	• Predict individual acceptance and use of a range of information technologies. • Competing with the theory of reasoned action (TRA) and the theory of planned behaviour.	• Explain usage behaviour instead of behavioural intention to use. • Limited applicability to certain contexts
Car Technology Acceptance Model (CTAM)	Intention to use and usage behaviour.	Performance expectancy Effort expectancy	• Include basic psychological needs that could influence the	• Developed to explain user acceptance of advanced driving systems.

		Social influence Facilitating conditions Safety Anxiety	behavioural intention to use, such as safety.	• Lack of holistic approach to explain user acceptance.
Autonomous Vehicle Acceptance Model (AVAM)	Intention to use and usage behaviour.	Performance Expectancy Effort Expectancy Attitude Social Influence Self-efficacy Anxiety Self-efficacy		• Same theoretical framework as CTAM.
Multi-level model on automated vehicle acceptance (MAVA)		Performance Expectancy Effort Expectancy Facilitating conditions Safety Social Influence Hedonic Motivation Perceived benefits Perceived risks	• Two levels: micro and meso level. • Divided the process of decision making in four steps.	• Lack of high contextual factors. • Less parsimonious model. • Explain acceptance of level 5 AVs.

Table 10: Overview of the theoretical framework that explain user acceptance

UTAUT has been applied to evaluate the acceptance of various technologies and different user groups over the years (Venkatesh et al.,(2012); Venkatesh, Thong and Xu, (2016)). With the burgeoning development of automated vehicles, the theoretical framework of UTAUT (mainly focused on ICTs) and its extensions were adapted to explain the adoption of automated vehicles. Venkatesh et al. (2012) published the first extension of the original UTAUT, called UTAUT2. The development of this model was mainly addressed to consumers of eMobile services. They expanded the original UTAUT by adding hedonic motivation, price value and habit as new constructs that proved relevant in the context of consumer behaviour (See Figure 28 below).

Figure 28: UTAUT2 model



(Source : Venkatesh et al., 2012).

The extended UTAUT2 was developed to explain consumer acceptance of mobile services and considered relevant constructs to explain user acceptance in the context of consumer behaviour. The conceptual models (CTAM (Osswald et al., 2012), AVAM (Hewitt et al., 2019), and MAVA (Nordhoff et al., 2019) that were developed to explain user acceptance of automated vehicles mainly extended the UTAUT framework by adding additional constructs. For the social acceptance assessment of the AV in MaaS, we will develop an extended version of the UTAUT2 (Venkatesh et al., (2012)).

Indeed, our "AV in MaaS" object and its scope of analysis are perfectly suited to a UTAUT2 model for several reasons:

- UTAUT2 was developed to explain user acceptance of e-mobile services for consumers rather than the acceptance of information and communication technologies in an organisational context. We can consider AV in MaaS as an e-mobile service and apply the UTAUT2 model. Following (Ventakesh et al., 2012), UTAUT2 should explain 74% of the behavioural intention to use e-mobile services, which could be a good starting point for our analysis.

- Needs and attitudes are considered essential determinants in UTAUT2. This is also our hypothesis
- We have retained the possibility for users and non-users to position themselves in relation to the behavioural acceptance of AV in MaaS. The “performance/use expectancy” determinants of the UTAUT2 model allow us to take this phenomenon into account.
- Travel pattern data is considered in UTAUT 2. However, in our problem of priority to intramodality choice, this is important data to keep.
- The UTAUT2 model allows multi-scale analysis. However, the macro scales of the transport system, meso (territorial governance), and micro (socio-economic, cultural, environmental characteristics) interact in the logic of acceptance.

Finally, the UTAUT2 model ensures a feedback loop between behavioural intention and use behaviour. We plan to interview users over the long term and in accordance with the SUMP benchmark to measure acceptance in the different phases of implementation of the AV in the MaaS experiment (strategy development, measure planning, implementation and monitoring). (See SUMP, 2021, social impact assessment: tools, methods and approaches).
In addition, automated vehicle acceptance models integrate new constructs compared to ICT acceptance models, such as safety, perceived risks, service characteristics, anxiety, and well-being. Thus, it is necessary to develop a more holistic model that encompasses service characteristics, psychological, socio-economic, socio-demographic factors, perceptions, values, and attitudes to explain the adoption of automated vehicles integrated in Mobility as a Service (MaaS). The design process for the conceptual model is presented in Section 3.4 (Conceptual model to predict AV adoption integrated in MaaS).
In the following subsection, we will present the learnings and contributions of other EU CCAM projects.

4.2.2 Insights from other EU CCAM projects

In this subsection, we will review and analyse some of the EU CCAM projects and the studies conducted within each project. We will explain existing knowledge gaps. Then, we will compare our approach with those applied in different EU CCAM projects and present the potential contribution of our methodology.

Table 11: Summary of some EU CCAM projects.

Project	Theoretical framework	Constructs	Moderating variables	Key findings
AVENUE (Korbee et al., 2019 ; Naderer et al., 2021 ; Korbee et al., 2022 ; Dubeilzig et al., 2018 ; Dubeilzig et al., 2020 ; Dubeilzig et al., 2021).	Not specified	Surveys to identify and measure perceptions and attitudes	Not specified	• 7 categories of user needs were identified: ○ the need for efficiency. ○ the need for reliability. ○ the need for cognitive relief. ○ the need for physical relief. ○ the need for emotional relief ○ the need for environmental relief. ○ the need for financial relief. • The authors evaluated the perceptions, expectations, and attitudes toward automated mobility. • The authors found: ○ on average, 23% of people living around the four deployment sites (Luxembourg, Copenhagen, Geneva and Lyon) are willing to use automated minibuses (AM). ○ men are more willing to use AM compared to women. ○ five (5) target groups of potential users: enthusiastic, uncritical goodwill, sceptical goodwill, indifferent, and refusers. ○ more than 50% of respondents are unwilling to pay more for automated minibuses compared to current public transportation.

				○ people who at least took a ride in the AM perceive less concerns compared to non-users.
ULTIMO (Matthewson, 2023)	Not specified	Not specified	Not specified	The authors found several users' needs like: • the need for temporal flexibility or high frequency of the service. • the need for local flexibility (for all user groups and mainly for people with reduced mobility). • The need to overcome the difficulties of using the MaaS app or phone (mainly elderly people). • the need for safety and security. • the need for assistance to help (elderly people and people with special needs). • the need for affordable service. • the need for easy accessibility (to get in/out of the vehicle for elderly people and people with reduced mobility). • the need for comfortable and clean vehicles and space for wheelchairs.
SHOW (Coueugnet et al., 2020).	Not specified	Not specified	Not specified	The essential user needs identified among the four scenarios[32] developed within the SHOW project were: • the need for safety. • the need for security. • the need for fast transport. • the need for affordable tickets. • the need for accessibility for all users. • The need for easy-to-use systems and apps. While secondary and additional needs are: • the need for clean transport.

[32] They developed four scenarios for automation: 1) automation of private vehicles, 2) automation of PT, 3) automation and MaaS, and 4) automation and DRT.

				• the need for comfortable transport. • the need for a safety driver on board.
	For a priori acceptance: Unified Theory of Use and Acceptance of Technology (UTAUT)	• Performance Expectancy. • Effort Expectancy. • Facilitating conditions. • Social Influence.	Not specified.	In this deliverable, the authors explained the applied theoretical framework.
	For observed acceptance: Nielsen Model on System Acceptability	• The utility of the mobility services and/or vehicles. • The usability of the mobility services, including satisfaction. • The compatibility of the mobility services. • The reliability perceived by users.	Not specified.	In this deliverable, the authors explained the applied theoretical framework.
SINFONICA (Anke and Ringhand, 2023).	Not Specified.	Not specified.	Not specified.	The authors four (4) needs: • the need for availability. • the need for accessibility. • the need for affordability. • the need for acceptability.

	Extended Theory of Planned Behaviour (TPB).	• Attitudes and behavioural beliefs. • Subjective norm. • Perceived Behavioural Control.	Not specified.	The authors developed a framework comprising three levels: • the first consists of users' mobility needs. • the second level encompasses the user requirements for CCAM solution design. • the third level describes the process to form an intention to use, and usage behaviour of the proposed service by CCAM.

SUaaVE (Post et al., 2019 ; Post et al., 2020).	Not specified	Not specified	Not specified	The authors reviewed:
				• the evolution of technology acceptance models from the Theory of Reasoned Action (TRA) to the latest extension of the Technology Acceptance Model (TAM3).
				• the psychological factors that could influence the acceptability of CAV (Connected Automated Vehicles) such:
				  ○ the perceived characteristics:
				    ▪ Perceived Control.
				    ▪ Perceived Safety.
				    ▪ Perceived Trust.
				    ▪ Perceived Convenience.
				    ▪ Perceived Pleasure.
				The authors also explained the moderating effects of:
				• individuals' characteristics:
				  ○ socio-demographic characteristics.
				  ○ personal values.
				  ○ driving style.
				  ○ type of road user (cyclists or pedestrians).
				  ○ vulnerabilities in the relationship between exogenous variables and the intention to use (usage behaviour).

	Extended Theory of Planned Behaviour	• Perceived Control.	Values (Hedonistic, egoistic, altruistic and biospheric).	The results revealed that: • perceived safety had an important effect on the acceptability of CAV technology, followed

	(developed a conceptual model to predict the acceptability of CAV).	• Perceived Safety. • Perceived Convenience. • Trust in CAV technology. • Perceived Pleasure. • Perceived Behavioural Control. • Perceived adoption norm. • Perceived Environmental Sustainability. • Perceived Status Enhancement.	Types of road users (cyclists, pedestrians). Need for control.	by perceived convenience and perceived environmental sustainability. • perceived pleasure had a medium size effect on the acceptability of CAV.
MOVE2CCAM (Quijano et al., 2023)	Not specified	Not specified	Not specified	The authors found that the main perceived benefits among all user groups are: • convenience. • safety (in terms of reduction in the number of accidents). • enhancement in social status (in case of owning an AV). • a way to social interact, pleasure, and comfort. Regarding concerns related to CCAM solutions, the review shows that users were concerned about the following: • system failure (due to distrust in the technology). • legal liability in case of accidents.

				• privacy concerns related to data transmission and misuse. • security. • cost of owning and using AV. • job losses for bus drivers. • interaction between AV and other road users (like pedestrians and cyclists). Older adults perceive that AV will enhance their independent mobility and were concerned about physical accessibility (issues related to getting in/out of the vehicle.

4.2.3 Discussion of findings from EU CCAM projects and knowledge gaps

Within the scope of this task, we reviewed some EU projects that investigated the social acceptance of automated vehicles. We organised this review following our three research questions.

Regarding the identification of mobility needs (QU1), we have selected some studies that analyse the conditions of social acceptance of automated vehicles (Dubielzig et al., (2018); Mathé et al., (2020); Coeugnet and Métayer (2020); Dubielzig et al., (2021); Korbee et al. (2019); Naderer et al. (2021); Korbee et al., (2022); Matthewson (2023); Anke and Ringhand (2023), Quijano et al. (2023)). The ULTIMO project partners (in particular Siemens and Open Geneva from WP2 also collected and identified user mobility needs and requirements (see Annex). We summarise the mobility needs in seven (7) categories: (i.) service improvement needs, (ii.) psychological needs, (iii) economic needs,(iv) reliability, (v) physical, (vi) facilitating, and (vii) environmental needs (see Table 12 below). Service improvement, psychological, financial, and economic needs are essential. Improving the service needs is crucial because those aspects are the most important when the passengers choose their preferred means of transport. Psychological needs are essential because they are the basic human needs identified in the Self-Determination theory, and people also want to be safe and secure from intentional and non-intentional action (Sheldon et al. (2001)) The physical, facilitating, and environmental needs appear less critical (secondary needs).

In the SINFONICA project (Anke and Ringhand (2023)), the authors identified four main categories of mobility needs: availability, accessibility, affordability, and acceptability. The authors also developed a three-level framework that shows how mobility needs could be translated in user requirements, and in case the user requirements are satisfied during the design process, they could influence the perceptions of users and increase acceptability. The authors applied an extended version of the Theory of Planned Behaviour to explain the intention to use the proposed services by CCAM (Connected, Cooperative and Automated Mobility). The developed framework within the SINFONICA project seems promising. However, they did not explain how mobility needs could be translated into constructs that influence social acceptance. In this task, we will build upon the insights on mobility needs, and a shortlist of the collected needs will be selected and used as input to develop a decision-making process for the intention to use AV.

Table 12 below shows the identified users' mobility needs found in the literature and EU CCAM projects. Different terms are used to describe mobility needs. Anke and Madlen (2023) found that mobility needs were referred to in two different ways. The first considered "mobility needs" as the need to change the location, and the second referred to "mobility needs" as user requirements toward the transport ecosystem. In the ULTIMO project, we will use the second approach to describe user requirements toward the transport system, describing the user needs that should be fulfilled to use the service. Anke and Madlen (2023) defined mobility needs as "all physical and psychological user-related requirements towards mobility solutions, like CCAM, that arise from users' individual psychological motives, characteristics, and situational factors and determine the (intention) to use.

Table 12: Identified mobility needs.

Category of needs	Identified needs	Reference
Service improvement needs	Temporal flexibility	Korbee et al., (2019); Naderer and Korbee (2021).
	Time Independence	Anke and Madlen (2023).
	Less Waiting Time	Dubelzeig et al., (2018).
	High frequency of the service/ frequent service in the village.	Coeugnet and Métayer (2020); Matthewson (2023).
	Spatial flexibility	Korbee et al., (2019); Naderer and Korbee (2021); Matthewson (2023).
	Closer bus station to work or home	Dubielzig et al. (2018) ; Mathé et al. (2020) ; Dubeilzig et al. (2021) ; Matthewson (2023).
	Reachability	Anke and Madlen (2023).
	The need for fast transport	Matthewson (2023); Coeugnet and Métayer (2020).
	Accessibility/free barrier access	Anke and Madlen (2023); Dubielzig et al. (2018); Mathé et al., (2020); Dubielzig et al. (2021); Coeugnet and Métayer (2020); Matthewson (2023).
Psychological needs	Safety	Korbee et al., (2019); Naderer and Korbee (2021); Coeugnet and Métayer (2020); Anke and Madlen (2023), Matthewson (2023).
	Security	Korbee et al., (2019); Naderer and Korbee (2021); Anke and Madlen (2023); Matthewson (2023).
	Privacy (social, psychological needs).	Anke and Madlen (2023).
Financial/economic needs	Affordability/minimal + capped pricing/simple + consistent pricing/ease of price comparison	Anke and Madlen (2023); Coeugnet and Métayer (2020).
	Cost of mobility	Matthewson (2023).
	Minimal (technological) equipment requirement	Anke and Madlen (2023).
Reliability needs	Punctuality / on time	Korbee et al., (2019); Naderer and Korbee (2021).
	Reliable information/information access	Korbee et al., (2019); Naderer and Korbee (2021).; Anke and Madlen (2023).
	Reliability	Anke and Madlen (2023).
	Trust	Anke and Madlen (2023).
Physical needs	Comfort	Korbee et al., (2019); Naderer and Korbee (2021); Coeugnet and Métayer (2020); Anke and Madlen (2023); Matthewson (2023).

	Children friendliness/travel companion/storage space/baggage friendliness/ wheelchair space	Anke and Madlen (2023); Matthewson (2023).
	Cleanliness/ensuring hygiene/clean Interior	Anke and Madlen (2023); Matthewson (2023); Coeugnet Métayer (2020).
	Enjoyment/option to interact/feel welcome, attractiveness/pleasure	Korbee et al., (2019); Naderer and Korbee (2021); Anke and Madlen (2023); Matthewson (2023).
Facilitating needs	Assistance availability/assistance or help	Korbee et al., (2019); Naderer and Korbee (2021); Anke and Madlen (2023
	Difficulties to use ICT / comprehensibility/simplicity/ ease of use/user-friendly app and system	Matthewson (2023); Anke and Madlen (2023); Korbee et al. (2019); Naderer and Korbee (2021); Coeugnet and Métayer (2020).
	Convenience/equality with other modes	Korbee et al., (2019); Naderer and Korbee (2021); Anke and Madlen (2023).
Environmental needs	Impacts on the environment/sustainability	Korbee et al., (2019); Naderer and Korbee (2021).

For our second research question (QU2), focused on determinants of behavioural acceptance, we checked different European projects.
In the AVENUE project (Korbee et al., 2019; Naderer and Korbee, 2021), the authors measured the social acceptance of automated vehicles by evaluating the perceptions, attitudes, and expectations toward automated vehicles. Building upon these insights, we will develop a framework that describes the decision-making process of the intention to use automated vehicles integrated in a MaaS.

In the ongoing EU SHOW project, Cougnet and Métayer (2020) provide us with insights on the mobility needs for different scenarios: automated private vehicles, automated public transport (PT), automated DRT (Demand Responsive Transport), automated vehicles and MaaS. For the user acceptance assessment, they evaluated the a priori acceptance and the observed acceptance (acceptance in use). To evaluate the behavioural intention to use (a priori acceptance), the authors applied the Unified Theory of Acceptance and Use of the Technology (UTAUT, Venkatesh et al., (2003)). On the other hand, they used Nielsen's system acceptability model to evaluate the observed acceptance on site. The model developed by Nielsen encompasses the social and the practical acceptability components. The latter includes the assessment of the utility and usability of the service and user satisfaction, as well as the compatibility of the service and the reliability perceived by users. The approach applied by the SHOW project seems promising because they measured the expected usage (by evaluating the behavioural intention to use) and the real usage behaviour (by assessing the acceptance – use on site). Nonetheless, to the best of our knowledge, they did not empirically validate their assumptions. Thus, there is a need to design a survey and empirically test the hypothesised relationships between exogenous variables and acceptance (behavioural intention to use or use).

In the EU SUaaVe project, Post et al. (2019) reviewed the social-psychological factors that could influence the acceptability of CAV (Connected Automated Vehicles). However, in our framework, we assume that the social acceptance of automated vehicles is explained by psychological, and economic, environmental, and behavioural travel factors. Additionally, we aim to deploy Level 4 AVs and not Level 3 as tested in SUaaVe. The authors reviewed the theoretical underpinnings of the Technology Acceptance Model (TAM). They also reported that perceived control, perceived safety, perceived trust, perceived convenience, and perceived pleasure will influence the acceptability of CAV. In the MOVE2CCAM project (Quijano et al., 2023), the authors reviewed the general perceptions regarding CCAM solutions and perceptions of specific user groups (such as elderly people, people with special needs and children). Within the scope of MOVE2CCAM, they evaluate the attitudinal acceptance. The insights from this deliverable will be used as input to identify the opportunities and barriers behind the adoption of AV.

Finally, for the third research question (QU3), we investigate different European projects to identify how we can change user mobility behaviour. Different models were tested. For example, Post et al., (2019) represent the moderating effects of socio-demographic characteristics (such as age and gender), personal values, type of road user (pedestrians and cyclists), and driving style on the relationships between the exogenous variables and the intention to use. In the second deliverable (Post et al., 2020), they developed a conceptual model that predicts CAV's acceptability. The proposed model was built based on the results of the literature review and several focus groups. In the focus group, the authors found two additional constructs: perceived environmental sustainability and perceived status enhancement. They developed an extended version of the Theory of Planned Behaviour (TPB) that claims that the acceptability of CAV is explained by perceived control, perceived safety, perceived convenience, trust in CAV technology, perceived pleasure, perceived adoption norm, perceived behavioural control, perceived environmental sustainability, and perceived status enhancement. The results revealed that perceived safety had higher effects on the acceptability of CAV, followed by perceived convenience and perceived environmental sustainability. Perceived pleasure had a medium-sized effect on the acceptability of connected automated vehicles.

Individual user characteristics and their interactions impact the needs of the individuals being tested. We defined user characteristics as follows:

- Socioeconomic and sociodemographic factors, including age, gender, family and social support, education level, occupation, and income level. These criteria are essential because they influence mobility behaviour, in particular modal choice and travel behaviour.
- Psychological characteristics describe a person’s needs, beliefs, and personality traits. In the context of AV in MaaS, trust, well-being, and affinity for technology are relevant. The SINFONICA project highlighted that a more pleasant, pro-environmental personality is positively linked to the use of public transport. Trust as a factor in the context of technology acceptance was tested in the project to assess the influence of personality traits on travel behaviour.
- Cognitive abilities describe a person’s skills (language, attention, memory), experiences (with public transport or digital applications), and knowledge (e.g., regarding the technical background of autonomous mobility, auditory processing, processing speed). European standards aimed at making information easy to read and understand involve integrating users with specific needs: elderly, ethnic minorities, digital illiteracy, and people living in rural areas.

- Physical characteristics are features of a person's body. The overall health constitution can vary broadly for different user groups. Following SUMP characteristics, we consider people with disabilities in the research program (see WP2).

In addition to user characteristics, situational factors define the scope of our analysis. We consider in the research all travel motives, such as going to work, shopping, accompanying other people (e.g. children, elderly people), and recreational travel.

4.3 Our model proposition to predict AV adoption integrated in MaaS

The main objective of the social acceptance assessment is to develop a citizen-centric approach to satisfy mobility needs, increase the social acceptance of automated services, and improve citizens' quality of life. By applying a holistic approach within the social acceptance assessment, we will develop a conceptual framework that predicts the adoption of automated vehicles integrated in MaaS. The development process includes several steps, from identifying factors that could influence behavioural intention to use to the empirical validation of the assumed relationships between the determinants and the expected observed behaviour. Figure 29 below shows the process of defining our conceptual model, the empirical validation of this theoretical framework, and the underlying assumptions.

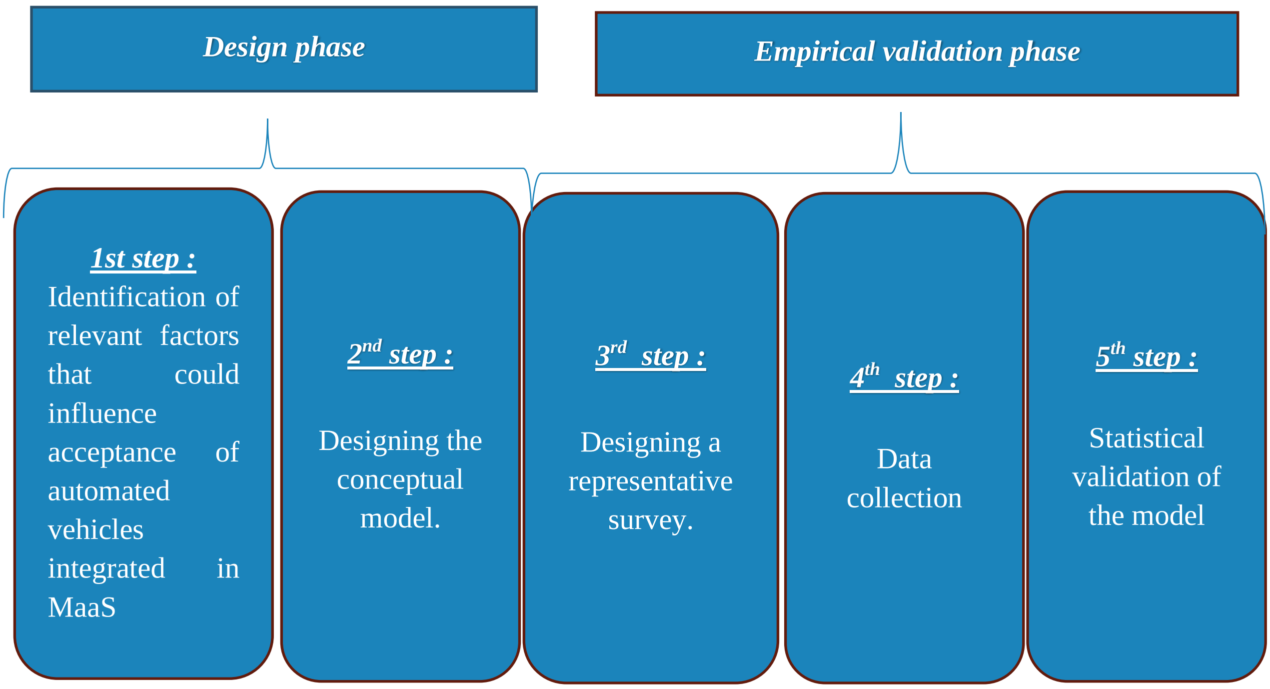


Figure 29: Overview of the conceptual framework

The first step is a literature review to identify the factors influencing the acceptance of automated vehicles integrated in MaaS. Furthermore, we will conduct interviews with experts of WP2 (definition of users' needs and use cases) and WP5 (demonstration sites) to select the relevant mobility needs in each pilot site. The interviews will also help to investigate if any other potential factors not found in the literature review could influence the acceptance of AV integrated in MaaS. After the identification step, we will develop our conceptual framework that will be used to predict the adoption of AV in the MaaS ecosystem. Then, we will proceed toward the empirical validation phase. The empirical validation phase consists of designing the survey, data collection and data analysis. The survey design consists of the definition of questions and items that will be used to measure the constructs and will be used to collect the data. The planning of the steps will be presented in section 7.

We build upon the theoretical framework of UTAUT2 (Unified Theory of Acceptance and Use of Technology 2); we will develop an extended version of UTAUT2 that includes socio-economic, socio-demographic, psychological, service characteristics, symbolic-affective, normative motives[33] to predict user acceptance of automated vehicles integrated in MaaS. Thus, the relevant mobility needs of people who live around the pilot sites of the ULTIMO project (Grorudalen (Norway), Champagne (Switzerland), and Herford (Germany)) will be integrated into the model as predictors of the behavioural intention to use. The work-in-progress conceptual framework is presented in Figure 30 below.

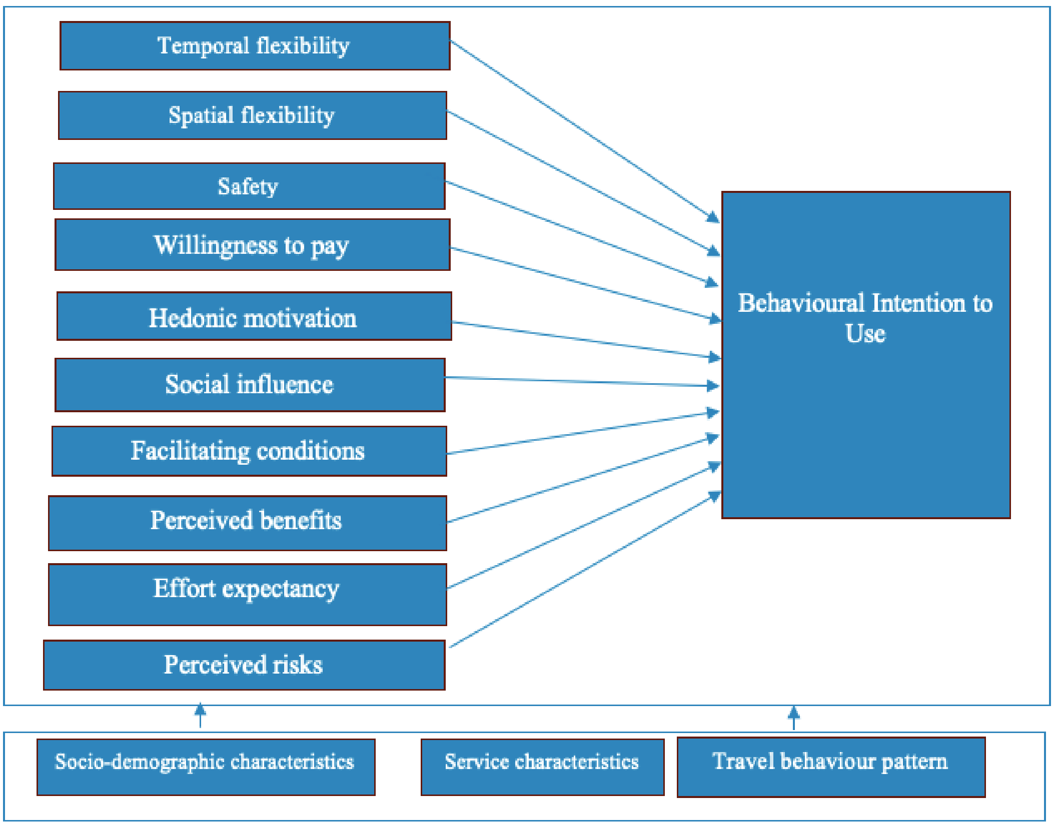


Figure 30: Conceptual model that predicts the adoption of automated vehicles integrated in MaaS.

Similar to Nordhoff et al. (2019), we will develop a multi-level conceptual model to predict the acceptance of automated vehicles integrated in MaaS. The micro level refers to individual characteristics such as socio-demographic and economic characteristics (gender, age, income and level of education), service characteristics (travel time), and travel behaviour pattern (trip purpose, commuting mode). The meso level consists of beliefs, perceptions, and fulfilled

[33] Motives are the contrast of needs; motives provide reasons for specific actions and are directed towards a desired goal. We have different types of motives, the instrumental motives, symbolic, normative, and affective motives. Affective are emotions evoked when using the service (Anke and Madlen, 2023).

mobility needs. We assume that behavioural intention to use is explained by instrumental motives such as temporal flexibility, spatial flexibility, perceived benefits, and effort expectancy; symbolic-affective motives: hedonic motivation and social influence; psychological motives like safety and economic motives: the willingness to pay or the cost of the service. Also, we will conduct further research on privacy under psychological needs (see Table 12). For example, some users may be unwilling to share AV or switch to AV for personal privacy reasons. As the conceptual model is still a work in progress, we will present the complete model, the definition of the construct, and the scale items that will be used to measure the constructs in the second deliverable due in September 2026. We also suppose that socio-demographic characteristics like age, gender, income, level of education and service characteristics like travel time and travel behaviour patterns such as trip purpose, commuting mode, and possession of public transport subscription will moderate the effect of the constructs on behavioural intention to use.

In the next section, we will present our methodology to test and validate the hypothesised relationship between the antecedents of BIU and BIU.

4.4 Methodology

In this deliverable on social acceptance assessment, we will analyse the conditions that could influence behavioural intention to use AV integrated in MaaS in Norway (Grorudalen), Switzerland (Champagne), and Germany (Herford) (the three deployment sites of ULTIMO).
First, we will define our quantitative survey to collect the data. The expected representative potential users' survey will be conducted online. The expected dataset will incorporate measured (observed) and unmeasured (latent) variables. An important number of variables in our survey will be measured based on multiple items with a 7-point Likert scale that ranges from totally disagree to totally agree. The questionnaire will contain questions about socio-demographics, socioeconomic characteristics, perceptions toward AV, beliefs, service characteristics, and travel behaviour patterns.

Second, we will apply second-generation data analysis techniques, also called Structural Equation Modeling (SEM), to test the relationships between the independent variables and the behavioural intention to use, using Rstudio[34]. Structural equation modelling is a statistical approach to test hypotheses about relationships between observed and latent variables. Furthermore, it could test the direct and indirect relationships among a set of measured and unobserved variables (Suhr, 2006). We found that different SEM approaches are widely used in the literature: covariance-based SEM (CB -SEM), partial least squares SEM (PLS-SEM, also called PLS path modelling) and confirmatory factor analysis. CB-SEM is used to confirm or reject theories and their underlying assumptions. However, PLS-SEM has been introduced as a "causal-predictive" approach to SEM, which focuses on explaining the variance in the model's dependent variables (Hair et al. 2021). Confirmatory factor analysis was mainly used to test the reliability and validity of the constructs. This approach will help us identify the relevant behavioural determinants that could significantly influence the behavioural intention to use AV integrated in MaaS.

The SEM methods have several advantages over traditional statistical techniques: (1) incorporate in the model estimation observed and unobserved (latent) variables, (2) explicit

[34] Rstudio is a computer programming language.

assessment of the measurement error, (3) resolve multicollinearity problems, (4) model testing where a structure can be imposed and assessed as to fit the data. Applying SEM techniques requires a sample of at least 200 observations to test basic models. Like traditional techniques, the SEM methods evaluate the fit of the models. Different statistics are used to assess the quality and the fit of the models. The individual paths are evaluated among criteria to satisfy, and the acceptable threshold is 0.5 or higher. Furthermore, different measures are considered to evaluate the fit of the model: (1) Comparative Fit Index and (2) Normed Fit Index (NFI) are used as incremental indices, with values higher than 0.9; (3) the Chi-Square statistic, (4) Goodness Fit Index (GFI) and the (5) Root Mean Square Residual (RMSR) are used as absolute indices with values less than 3, higher than 0.9 and less than 0.5 respectively. Finally, the Root Mean Square Error Approximation (RMSEA) is used to evaluate the fit error with an acceptable indicative lesser than 0.08.

Several studies on the acceptance of automated vehicles applied the Partial Least Squares (Nastjuk et al. (2020); Etminani-Ghasrodashti et al. (2023); Venkatesh et al., (2012); Chen and Yan (2019); Schikofsky et al. (2020)) and few of them applied the CB – SEM (Nordhoff et al. (2021)). These studies provide insights into the drivers of behavioural intention to use AV in the transport ecosystem and give an overview of the main factors that influence the behavioural intention to use (Novikova et al., 2013).

4.5 Proposed Work Plan

For the remaining period of the ULTIMO project (March 2024 – September 2026), we will proceed in a sequential phase to accomplish our goals. We will complete the literature review to identify the potential factors that could explain the intention to use AV integrated in MaaS. Then, we will conduct interviews with experts (WP2 and WP5) to determine the relevant user needs for each pilot site and for people with special needs. This step will help us to ensure if there is any relevant factor that could affect social acceptance that is not considered in the literature. Building upon the results from the literature review and the interviews with experts, we will build a user-centric and holistic model that explains the decision-making process to use automated vehicles integrated in MaaS.

After validating and constructing the conceptual model, we will design a questionnaire to measure the constructs and collect data. We plan to conduct a potential users representative survey at the city level (Oslo, Geneva and Herford). The data collected will be used to empirically validate the relationships between the exogenous variables and the behavioural intention to use. We will collaborate with the public transport operators (PTOs) and authority (PTA) to design user surveys and collect data. Then, we will launch a user survey at the pilot site level in collaboration with the partners (PTO/PTA) to evaluate user satisfaction and test if the service will satisfy the needs of the residents in the pilot sites.

Studies to conduct	Target groups	Purpose	Methodology	Sample size	Expected period
Literature review	Studies on the acceptance of automated services	Identify behavioural determinants that influence acceptance.	Qualitative	-	March 2024 – July 2024
Interviews	Experts (WP2 and WP5).	Identify relevant user needs.	Interviews (Qualitative)	To be defined	August 2024 – September 2024
Define the final framework of the conceptual model.	-	Understand the process of decision-making to adopt AV.	-	-	September 2024 – October 2024.
Define the questionnaire (representative survey of potential users at the city level)	Potential users	Collect data to empirically validate the assumptions.	Quantitative online survey.	-	November 2024 – December 2024
Data collection (representative survey of potential users at the city level)	Potential users	To create our dataset and test the hypothesised relationships between exogenous variables and BIU.	Quantitative online survey.	To be defined	January 2025 – April 2025
Data analysis	Potential users	Validate the assumed relationship between the exogenous variables and behavioural intention to use.	Descriptive statistics and econometrics tools (like SEM).	-	May 2025 – December 2025.
User survey at the pilot site level	Users	Identify the antecedents of mobility behaviour change.	Quantitative survey on site	To be defined	To define the expected period with PTO/PTA.
Data analysis				To be defined	Q1 – Q3 2026.
Second deliverable report					

Table 13: Overview of studies to be conducted in the remaining period of the ULTIMO project within the social acceptance assessment.

4.6 Expected results/outcomes.

The second deliverable of the social acceptance assessment will provide insights on:

- Translating potential AV users into regular, intensive users of AV integrated in a MaaS innovation.
- The determinants that could encourage potential AV users to use the service and facilitate acceptance of AV integrated in MaaS.
- The conditions to increase the usability of the proposed service and satisfy the users' need to shift from private cars to automated public transport services with a push and not a coercive pull strategy to change user behaviour through better service.
- The willingness to pay of citizens/potential users of AV for the offered services by AV to help PTO/PTA determine the best pricing strategies.
- The appropriate public policy and effective economic tools/incentives to facilitate citizen acceptance of AV in MaaS.

4.7 Conclusion

The current transport system faces different challenges, like an increase in congestion, air pollution, noise, and road accidents. AV is a mobility technological innovation expected to increase safety, reduce congestion and CO_2 emissions, and increase the mobility of people with mobility challenges. This deliverable will contribute to the social acceptance assessment of AV integrated in MaaS in the three deployment sites of ULTIMO (Grorudalen (Norway), Champagne (Switzerland), and Herford (Germany). We will focus on evaluating the behavioural intention to use; this evaluation will help us understand in which condition potential AV users will become regular AV users. First, we reviewed the theoretical framework that was used to explain user acceptance of information communication technologies, followed by the learnings from other EU CCAM projects, namely AVENUE, ULTIMO, SHOW, SINFONICA, SUaaVE and MOVE2CCAM. We found that there is (a) a lack of a holistic and citizen-centric approach (model) that predicts the adoption of automated vehicles integrated in MaaS, (b) a lack of empirical evidence on the relationship between the antecedents of behavioural intention to use and behavioural intention to use. Therefore, we propose to bridge this knowledge gap within the social acceptance assessment. We will design a representative survey of potential users at the city level and test the hypothesised relationships between the antecedents of BIU and the behavioural intention to use.

Third, we discussed developing our work-in-progress conceptual model to predict the adoption of AV integrated in MaaS. By applying a holistic approach, the conceptual model will incorporate sociodemographic, socioeconomic characteristics, service characteristics, travel behaviour patterns, beliefs, attitudes, and perceptions about AV integrated in MaaS. Fourth, we discussed our proposed methodology for the second deliverable (due for submission in September 2026). We will define and design a quantitative questionnaire incorporating observed and unobserved (latent) variables. We will analyse the relationship between the antecedents of behavioural intention to use and behavioural intention to use. This analysis will provide insights into the significant and relevant behavioural determinants that could influence the behavioural intention to use.

Finally, we offer to propose key results to support public transport operators (PTO) or authority to design the service proposed by AV integrated in MaaS : (1) recommendations for PTO/PTA on conditions that could create a positive public perception and lead potential users to become regular users, (2) recommendations for policymakers on economic and non-economic incentives that could lead to higher acceptance of automated vehicles integrated in MaaS.

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5 Environmental Impact Assessment

The environmental impact assessment investigates the external costs connected to automated vehicles (AVs) in Mobility as a Service (MaaS) and Intelligent Transport Systems (ITS), which constitute part of the mobility ecosystem in the three case studies of the ULTIMO project. This task will also consider the potential rebound effects of AV implementation. This evaluation intends to examine not only environmental costs such as greenhouse gas emissions, particulate matter, and noise, but also social and economic factors that impact various stakeholders, including accidents, discrimination and congestion costs. To achieve this, a Life Cycle Sustainability Assessment (LCSA) approach is adopted that considers the three dimensions of sustainability: environmental, social, and economic (UNEP/SETAC, 2011). This study assesses external economic costs to understand the hidden costs of mobility for society. By employing a life cycle thinking approach that considers the entire system, this research evaluates the potential externalities associated with deploying AVs at various locations and the overall integrated system, including transporting goods using automated minibuses.

The following subsection 5.1 gives an overview of other EU CCAM projects. We present key takeaways and knowledge gaps we intend to address in ULTIMO. Section 5.2 provides insights into the first estimates of external costs from climate change, air pollution and accidents for different deployment scenarios of AVs in Grorud Valley, Oslo (Norway), one of the pilot sites. Afterwards, building upon the first estimates, we explain the research questions, the methodology, the expected results, and the work plan in Section 5.3. Section 5.4 is the conclusion.

5.1 Key takeaways from other EU CCAM projects

Some EU CCAM projects have worked on ‘environmental assessment related topics. We review these projects to build upon their research findings. In particular, AVENUE (the predecessor project of ULTIMO), INTERREG, FAME, SECAP and MOVE2CCAM. Table 14 illustrates the key findings from these projects. Through reviewing the literature on these projects, valuable insights have been gained into the environmental consequences, economic implications, and societal aspects of AV deployment and MaaS integration. Incorporating these insights, this assessment intends to further the understanding of the consequences of AV deployment and MaaS integration. Leveraging insights from previous CCAM projects and adopting a comprehensive assessment approach, this study seeks to contribute valuable insights into the sustainable deployment of AVs and the integration of MaaS within the transportation ecosystem. Incorporating data from new test sites and integrating usage scenarios into the LCA, we aim to enhance the understanding of the environmental impacts associated with AV deployment. Furthermore, by monetarising the impacts of the LCAs, this study seeks to provide a comprehensive assessment of the economic implications of AV deployment and MaaS integration.

Table 14: Key takeaways on environmental assessment of AVs from other EU CCAM projects

Project	Key takeaways	Deliverable / Source
AVENUE	• Automated Minibuses (AM) uses less than 5% of the total energy throughout the entire life cycle. • In a near future scenario, the use phase accounted for 59% of the total AM climate impact, while component production accounted for 39%. The impacts of the use phase mainly resulted from burning fossil fuels to generate electricity for driving the AM. • AM pilot site deployment did not show significant environmental benefits; future use cases were expected to improve substantially. The environmental friendliness of AM depends on factors such as occupancy, vehicle speed, mileage, and lifetime. • AMs were viewed as a complementary service in public transport, delivering benefits by reinforcing shared, multi-, and intermodal mobility when combined with door-to-door, on-demand, and driverless services.	D8.1 (Huber 2019) D8.2 (Viere et al. 2021) D8.5 (Viere 2022) Huber et al. (2022)
AVENUE	• Replacing all cars with AVs resulted in the most significant reduction in external costs, including air pollution, climate change, noise pollution, habitat damage, accidents, and congestion. • AV in MaaS is a favourable approach because of its user-centric and less restrictive nature. • AV as robotaxis increased external costs. • Rebound effects were discussed briefly and qualitatively, with the recommendation to investigate them in more detail in future studies.	D8.3 (Antonialli et al. 2019) D8.4 (Antonialli et al. 2021) D8.6 (Antonialli et al. 2022)
INTERREG	• Developed a CO_2 impact Estimation Methodology that can be applied when planning autonomous vehicles. • A flowchart emission reduction estimator points out important aspects that need to be considered and provides calculations for CO_2 impact Estimation. • Provides a simplified overview and guidance for CO_2 emissions.	D3.3 (Bilstrup and Jonsson 2023)
FAME	• The creation of a standardised Common Evaluation Methodology for CCAM should offer directives on establishing and executing evaluations or assessments focused on both direct and broader socio-economic impacts, targeting various user demographics. • The following domains could be of interest to ULTIMO: Quality of life, energy and environment,	No deliverable is available yet on this topic; information from the website (Connected Automated Driving 2023)

	land use, liveability, equity, growth and employment, socio-economics, and sustainability.	
SECAP	• Proposed an emissions inventory to assess the volume of CO_2 or GHG emissions, expressed in CO_2 equivalents, within a designated local region for a given year. They are calculated for a baseline year, which serves as the benchmark against which emission reduction goals are measured. • Mentioned two allowed approaches for the emissions inventory calculation, one of which is an LCA. • Shipping is excluded in SECAP.	Guidebook Part 1 (Rivas et al. 2018) Guidebook Part 2 (Bertoldi et al. 2018) Guidebook Part 3 (Kona et al. 2018)
MOVE2 CCAM	• Designed nine passenger transport scenarios (including AV in MaaS) and seven freight transport scenarios. • Literature review of indicators found in other CCAM projects showed an abundance of different indicators and impact assessments. • A categorisation of indicators into focus areas and impact dimensions suggests potential areas of evaluation and indicators. • Acknowledged the importance of considering the complete life cycle and the three sustainability dimensions: environmental, social, and economic. • Plan to build a system dynamics model to provide a comprehensive understanding of the potential impacts of CCAM solutions based on the three sustainability dimensions. • Plan to conduct a social and environmental life cycle analysis. • Literature review on indicators of LCA and S-LCA compares evaluation frameworks of different databases and publications and provides an overview of the LCA and S-LCA.	D1.1 (Quijano et al. 2023)

As FAME and MOVE2CCAM projects have just started, we will keep monitoring their progress and deliverables to integrate their findings, especially the forthcoming social and environmental life cycle analysis and the evaluation framework of MOVE2CCAM and the Common Evaluation Methodology of FAME. Concerning SECAP, this environmental impact assessment can be seen as a part of the baseline inventory analysis of the transportation sector and verification of whether the future transportation plans align with the European reduction goals for the coming years (such as climate neutrality until 2050). It also provides value by including logistics, as shipping is excluded in SECAP (Bertoldi et al. 2018). INTERREG offers a simplified CO_2 emissions impact calculation to compare the emissions of a fossil-based AV with those of a non-fossil-based AV. The authors exclude changing bus routes or operations, combining services of different transport operators, and possible modal shifts. This environmental impact assessment in ULTIMO intends to bridge these knowledge gaps by including the MaaS ecosystem in the analysis, therefore including many different mobility services and incorporating possible modal shifts and the closely related rebound effects.

This task in ULTIMO also intends to build upon the knowledge base of AVENUE while bridging the knowledge gaps. The environmental impact assessment will build upon the LCA conducted in AVENUE. Since COVID-19 disrupted AVENUE and was therefore not able to generate much data on the test sites, this environmental impact assessment intends to incorporate more usage data from the new test sites and integrate the usage scenario into the LCA to enhance it, that is, conducting an LCA for AV in MaaS, including the MaaS system and other transportation modes, and the entire transportation system. Also, the AVENUE LCA and external cost analysis, which were rather standalone assessments (except for the air pollution and climate change categories), will be connected by monetarising the impacts of the LCA. This will ensure a holistic life cycle thinking approach and, at the same time, a simplified result that can be easily understood by stakeholders who are interested in ULTIMO without the need for prior knowledge in LCA. To provide a more holistic approach and illustrate the effects on and benefits for society, a social perspective will be integrated for a complete overview of the three sustainability dimensions. The external costs calculated in AVENUE are based on precalculated cost factors from van Essen et al. (2019). We will develop a framework for monetarising the indicators to provide an enhanced analysis. The added value of this analysis with regards to the already existing projects and analysis and especially AVENUE are:

- A holistic approach, considering all three dimensions of sustainability
- An assessment of the entire transportation system with different transportation modes integrated in a MaaS system, not only single transportation modes separately
- A comparison of the status quo and the new proposed AV in MaaS solution, including the MaaS system in the analysis and not only the different transportation modes
- A translation of the environmental and social impacts into monetary values for better communications and comparison.

We will, therefore, use Ultimo to develop new AV in MaaS scenarios and complete existing models (inspired by Avenue's work) with more data. We will add other impacts that are delayed over time (for example, with the rebound effect) or of a different nature (socio-economic impacts). Finally, we propose a monetary translation of the identified and measured impacts.

5.2 Methodology

The research is based on the hypothesis derived from the AVENUE project that integrating AV in MaaS can reduce externalities and consequently decrease the external costs of future mobility systems. This hypothesis is explored and assessed in this study.
We attempt to answer the following research questions in ULTIMO's environmental impact assessment:

- How can we analyse the impact of potential positive and negative externalities of the deployment of AV in MaaS/LaaS embedded in the transportation system in monetary terms (external costs) based on a life cycle approach at the pilot sites?

A second research question is:

- How can we analyse the rebound effects of AV in a MaaS in a suburban and rural transport system?

The environmental impact assessment would show how AV in MaaS contribute to sustainable mobility and, therefore, include at least some of the indicators developed within the SUMI framework. Indicators that will be included are GHG emissions, air pollutant emissions and modal split as a baseline for the calculations. Indicators that will be included are road deaths, noise hindrance, access to mobility services, congestion and delays, energy efficiency, and maybe opportunity for active mobility (Rupprecht Consult 2019).

Figure 31 shows an overview of the methodology that will be applied to answer the research questions:

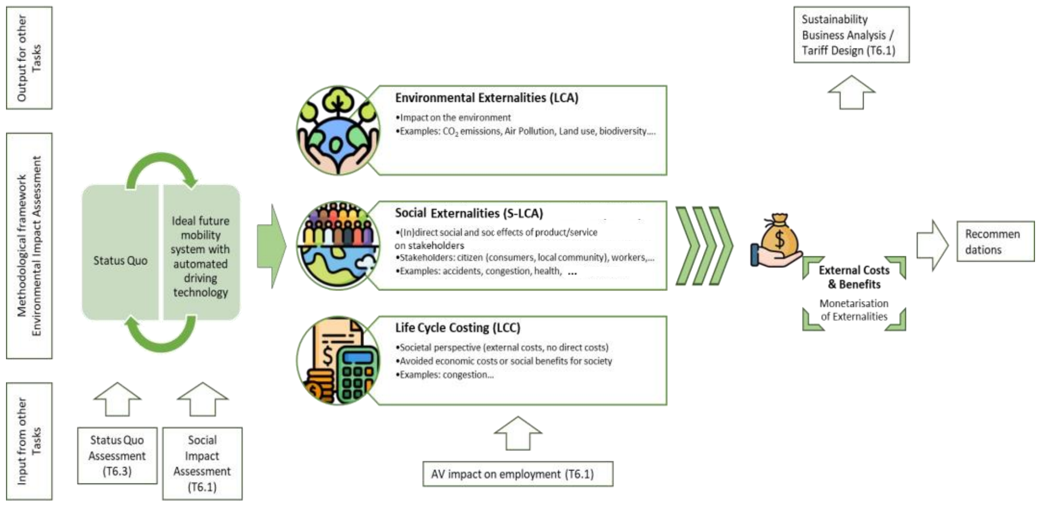

Figure 31: Methodology Environmental Impact Assessment

First, the Status Quo is being assessed to design the ideal future mobility system that includes AVs. This stage involves an examination of the potential rebound effects that may arise from implementing an efficient public transportation system through the utilisation of AVs in MaaS, such as the increase of pkm and vkm or the reduction of the modal share of active mobility (cycling and walking).

In the next step, these two mobility/transportation ecosystems will be analysed regarding their life cycle impact on the environment, showcasing their environmental externalities. Impact categories considered in this analysis include but are not limited to CO_2 emissions, air pollutants (PM, NO_x, NMVOC…), land use, and biodiversity. Additionally, the social and socio-economic life cycle impacts – social externalities, will be assessed. These externalities will mainly be calculated based on the new S-LCA standard (ISO/DIS 14075 - Draft)[35] that is currently in development and on the recommendations of UNEP (UNEP 2020; UNEP 2021). There are impacts on stakeholders such as citizens (the local community and especially users) and workers. Other impact categories include but are not limited to safety (for example, accidents), congestion, health, privacy, end-of-life responsibility and discrimination (UNEP 2020).

[35] This standard is not officially published yet, it´s a draft version. Interested parties are able to review and send their comments to the committee that is working on the standard. It will be published in 2024.

A Life Cycle Cost Analysis (LCC) will be conducted to complete the three dimensions of sustainability. LCC is a robust financial analysis method that can be applied to transportation projects, offering a comprehensive approach to evaluating costs over the entire lifespan of assets or systems. The methodology usually involves systematic considerations of planning, design, construction, operation, maintenance, and disposal phases. For LCC, three dimensions exist with different perspectives to calculate the related costs: conventional LCC, LCC and societal LCC (Ciroth et al., 2011). In this task, a societal perspective is taken, and external costs or benefits are assessed because the total costs of mobility are already part of the sustainable business analysis in this work package. External costs that will be assessed include but are not limited to congestion costs.

The obligatory property of the functional unit for the LCSA is one passenger kilometre (pkm), following other passenger transport-related LCA studies (Huber et al. 2022; Klopfer et al. 2023). There will be obligatory and positioning properties of the functional unit that are still to be defined in detail (European Commission JRC, 2010). The approach selected for the LCSA is a cradle-to-grave approach, as shown in Figure 32. To gather all the data for the Life Cycle Inventory (LCI), primary data from the test sites and the OEM will be used together with data from LCA databases such as ecoinvent and the literature.

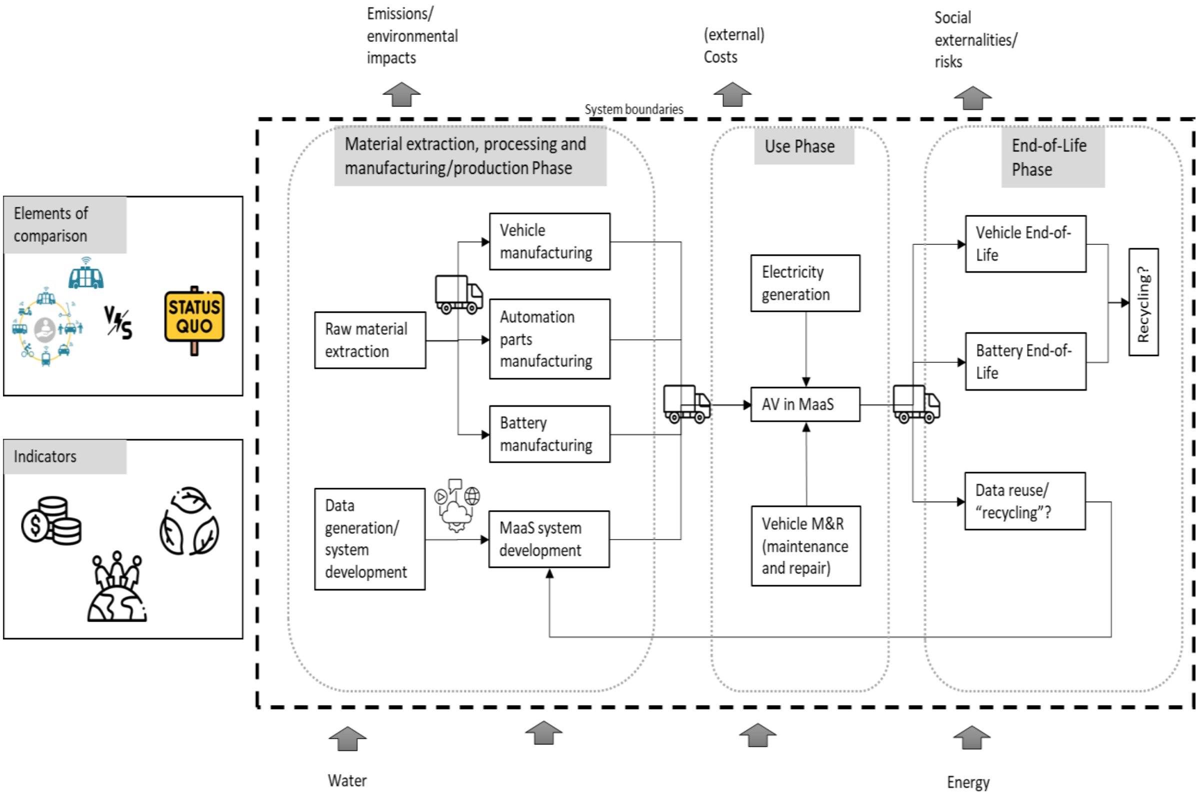

Figure 32: Preliminary system boundaries for LCSA

Afterwards, the results of all assessments will be monetarised into external costs while carefully avoiding double counting of any cost category. It is important to note the difference between monetisation and monetarisation in this context, although these terms are often used interchangeably in the LCA literature. While monetisation refers to "the act of making money from something" (Cambridge Dictionary 2024), monetarisation means "to assign monetary status to" something (WordSense Dictionary 2024). This study will employ monetarisation, assigning a monetary value to the environmental and social impacts assessed. The monetary evaluation intends to guarantee that the complete cost of environmental commodities and services, including raw materials, uncontaminated air, and unpolluted water, is fully understood and taken into consideration in economic calculations, although putting a price on nature and social impacts is a challenging task that has to be evaluated carefully. The underlying rationale is incorporating expenses presently excluded from economic evaluations (Antheaume 2004). Bünger and Matthey (2018), van Essen et al. (2019), and Matthey and Bünger (2020) describe some of the various methods that can be used to monetarise environmental and social impacts and calculate cost factors for them in their extensive reports. Arendt et al. (2020) compare different methods to monetarise the environmental effects of LCAs qualitatively and quantitatively. They include LIME3, Ecotax 2006, EVR (Environmental-Cost/Value-Ratio), EPS (Environmental Priority Strategies), Environmental Prices, MMG-Method and Trucost. These methods provide monetary factors for different impact categories of LCAs, although their approach to discounting and the variety of assessed impact categories differ. The monetarisation process is a crucial aspect of the Sustainability Business Analysis. It is essential to compare the external costs with the Total Costs of Mobility calculated through the Sustainability Business Analysis to determine the worthiness of the investment in AVs. As a final step, a sensitivity analysis will be conducted to determine the responsiveness of the output to changes in selected variables.

This study aims to investigate the environmental consequences of AV in MaaS and LaaS and to evaluate how it compares to the current transportation system without this solution. The objective is to present a comprehensive assessment that is not limited to environmental considerations alone but encompasses environmental, social, and economic impacts to promote a holistic sustainability-based approach. We intend to incorporate the total life cycle emissions and impacts and assign monetary values to them to present a simplified conclusion that can be easily understood without prior knowledge of Life Cycle Assessment (LCA), which can serve as a basis for political decisions. If our hypothesis proves true, public transportation agencies and local governments can use the findings to justify the implementation of AV in MaaS/LaaS and demonstrate the resulting impacts and benefits to the local communities.
The environmental impact assessment proposed in the ULTIMO project aims to examine the external costs associated with integrating AVs into MaaS and ITS across the three separate pilot sites.

Next, we present some results of a first test on evaluating three external factors (climate, pollution, and accidents). We discuss our analysis of a simplified estimation of three external cost categories for four different deployment scenarios, including AV in MaaS scenario, to understand how this scenario could lower the external costs compared to other deployment scenarios.

5.3 Preliminary estimates of external cost of AV deployment scenarios in Grorud Valley

Since AVENUE was more focused on metropolitan areas and city centres with test sites in different European countries. AVENUE´s externalities analysis tested the metropolitan areas of Luxembourg (Luxembourg), Geneva (Switzerland) and Copenhagen (Denmark). As ULTIMO's test sites are distinct and its focus leans more towards suburban and rural areas, we opted to initiate preliminary estimates for the Grorud Valley test site to verify that the outstanding results demonstrated by AVENUE for the AV in MaaS solution would also prove applicable to this new test site. This would enable a more comprehensive analysis of the specific AV in MaaS solution that could be implemented.

The following subsections describe and evaluate potential scenarios for deploying electric automated vehicles in suburban settings, utilising the pilot site Grorud Valley, Oslo Norway as a case study. The objective is to identify how the AV in the MaaS deployment scenario compares to the existing situation and to other scenarios. We evaluate four distinct scenarios regarding global warming potential, air pollution emissions, and accidents. Each parameter was assigned a weight through an external cost factor, enabling the calculation of aggregated total external costs for each scenario. The findings indicate that integrating electric automated vehicles with ridesharing in MaaS produced the most favourable outcomes. Using a 100% market penetration[36] assumption, external costs could be reduced by 66%, and with a 30% market penetration, a 20% reduction was observed. Climate change costs emerged as the primary contributors, constituting over half of the total costs across all scenarios. While incorporating AVs alongside public transport and ridesharing within a MaaS framework contributes to reducing external costs, most benefits stem from electrifying the vehicle fleet rather than introducing the new mobility concept.

5.3.1 Testing scenarios of AV for the external cost calculation

The chosen deployment scenarios for further examination (see Table) have been derived from prior investigations in Lisbon and Oslo (OECD/ITF 2015; OECD/ITF 2016; OECD/ITF 2017; Ruter 2019) and the research conducted by Miskolczi et al. (2021). These scenarios were specifically selected based on their interaction with existing public transport (PT) systems, whereby AVs were considered as substitutes for current PT options, enhancements to existing PT, or alternatives in competition with it. A collaborative effort involving PTAs, researchers, and project partners assessed these scenarios for their applicability and relevance. In the case of vehicle sharing, AVs were modelled as SUVs without onboard security drivers. For ridesharing, Automated Minibuses (AMs) were utilised to augment capacity, with an assumed average occupancy factor of 5 (Huber et al. 2022). Both AVs and private cars were presumed to have identical average occupancy rates. To simplify the modal shift expectations, the behaviours of train users, metro users, cyclists, and pedestrians are assumed to remain unchanged, while bus and car users adapted their behaviours.

Table 15: Testing scenarios of AVs

	Scenario 1 (S1)	Scenario 2 (S2)	Scenario 3 (S3)	Scenario 4 (S4)
Description	AV shuttle as Bus Line	AV in MaaS	AV as robotaxi in MaaS	AV as robotaxi in competition with PT
PT interaction	Substitute	Enhance	Enhance	Compete

[36] 100% market penetration means that all cars have been replaced by AVs in the market

Service offering	AMs[37] replace buses while maintaining the same stops and timetable	AMs[2] offer ride-sharing and on-demand, door-to-door services	AVs[2] offer vehicle-sharing and on-demand, door-to-door services	AVs[2] offer taxi services with only vehicle sharing
Market Penetration Rates	100%	30% and 100%	30% and 100%	30% and 100%
Changes in vkm	+/-0	-15% (OECD/ITF 2015; OECD/ITF 2016; Ruter 2019)	+5%[38]	+25% (OECD/ITF 2015; OECD/ITF 2016; Ruter 2019)

S1: *AV Shuttle as Bus Line*, a transition from traditional combustion engine buses to AMs is proposed. Under this scenario, the existing bus schedules and stops remain unchanged, ensuring continuity for commuters. A significant shift in commuting behaviour is assumed, with all previous bus users opting for the newly introduced AMs.
S2: *AV in MaaS*, AVs are integrated into the broader Mobility-as-a-Service framework. Here, AVs are envisioned as a complementary solution to existing Public Transport services, particularly for ridesharing purposes. This integration seeks to provide on-demand, door-to-door transportation services. The scenario also introduces two distinct market penetration rates: either a 30% adoption rate (most likely to happen in the near future, according to Dubey et al. (2022)) or a comprehensive 100% shift, showcasing the potential transformative change in transportation patterns.
S3: *AV as Robotaxi in MaaS* builds upon the foundations of S2 but introduces a distinct layer of privacy. In this setup, AVs operate as Robotaxis within the MaaS ecosystem, eliminating ridesharing functionalities to cater to customers seeking enhanced privacy during their commutes. Similar to S2, this scenario also presents two market penetration alternatives.
S4: *AV as Robotaxi in competition with PT*, presents a more competitive landscape for public transportation. AVs are envisaged as Robotaxis, operating independently of existing PT infrastructures. While still offering on-demand, door-to-door services, this scenario introduces

[37] AMs were used in S2 because they offer a more spacious environment for shared journeys, while smaller, passenger car sized AVs may inadvertently compel passengers into more confined and less comfortable seating arrangements in the backseat. S3 focuses on an individual solution and privacy and therefore reduces the size of the vehicle to a passenger car sizes AV.
[38] The existing demand for pkm has remained constant across the various scenarios, featuring a redistribution of vkm among different transport modes and assumptions on changes. Rebound effects were not factored into the analysis. For instance, in Scenario 1, the entirety of the pkm previously covered by buses was reallocated to AMs. In Scenario 2, either 30% or 100%, of all pkm originally undertaken by private cars was redirected towards AMs. Additionally, based on insights from the Oslo and Lisbon studies, Scenario 2 experienced a supplementary 15% reduction in vkm due to ridesharing and integration into PT. In contrast, Scenario 4 resulted in a 25% increase in vkm, primarily attributed to deadheading resulting from individual trips. Scenario 3, which was not subject to scrutiny in the aforementioned studies, was approached by considering the general trend wherein individual trips contribute to an increase in vkm, while PT integration typically results in a decrease. Consequently, a 5% rise in vkm was projected for this scenario, positioning it between Scenarios 2 and 4.

a nuanced challenge: the potential increase in deadhead miles, which could have implications for overall transportation efficiency.

In exploring these scenarios, it becomes evident that the transition to automated mobility solutions can potentially reshape traditional commuting patterns. As we delve into the transformative possibilities outlined in scenarios S1 to S4, it is crucial to contextualise these changes within the broader landscape of the transportation sector. Therefore, the following subsection explains the methodology for the calculation of the external costs to compare the different scenarios with one other.

5.3.2 Calculation method of external costs

The transportation sector, contribute to 30% of greenhouse gas (GHG) emissions in developed nations and 23% globally (UNECE, 2023), assumes a pivotal role in shaping climate change and stands as a major contributor to urban Air Pollution (AP) (NEMO, 2023). Furthermore, accidents significantly impact external transportation costs and serve as a crucial metric for mobility in Oslo. These considerations underscore the significance of the mentioned externalities within the scope of this study. Subsequently, these impacts were combined into external costs to derive a consolidated value.

The calculation of Global Warming Potential (GWP) takes into account the complete life cycle (LC) emissions per scenario due to variations in emission generation among internal combustion engine vehicles (ICEV), battery electric vehicles (BEV), and plug-in hybrid electric vehicles (PHEV) regarding their life cycle phases. Emissions from ICEVs primarily arise during the use phase, while BEV emissions are tied to energy generation or production, depending on the energy source used to generate the electricity needed in the use phase (Buberger et al., 2022). To derive the comprehensive GWP value for each scenario, the GWP in CO_2eq from Table 16 was multiplied by the vehicle performance data per scenario in vkm and subsequently summed. For electric vehicles, these factors were adjusted to align with the Norwegian electricity mix. Cyclists and pedestrians were assigned zero value due to their negligible impact. For external climate change costs (CCC), a damage cost factor of €215/tCO_2eq for 2030 and a 1% time preference, as recommended by Matthey and Bünger (2023), were utilised.

Table 16: CO_2 Emissions per vehicle category

	Life Cycle (gCO_2eq/ vkm)
ICEV-$G_{asoline}$ (Hill et al. 2020)	269
ICEV-D_{iesel} (Hill et al. 2020)	229
BEV (Hill et al. 2020)	59
PHEV (Hill et al. 2020)	180
Bus-D_{iesel} (Hill et al. 2020)	1396
Bus-$E_{lectric}$ (Hill et al. 2020)	228
Cyclist	0
Pedestrian	0
AM (Huber et al. 2022)	170
AV (Kemp et al. 2020)	45

Air Pollution emissions encompass NO_x, NMVOC, and both exhaust and non-exhaust PM_{10} emissions, the latter of which involves emissions from road vehicle tyres, brake wear, and road-surface wear. Initially, the emission factors from (EMEP/EEA 2019) shown in Table 17, were applied by multiplying them with the vehicle performance data and aggregating the results to determine the overall Air Pollution emissions for each scenario. Once again, pedestrians and cyclists were excluded from the study. For AMs, the PM_{10} non-exhaust parameter of light-duty trucks was utilised since specific data for PM_{10} emissions from minibuses is not currently available. Subsequent to this, the emissions were further multiplied by the cost factors adapted for Norway to derive the total external costs. This cost estimation follows a damage cost approach that considers health effects, crop loss, material and building damage, and biodiversity loss.

Table 17: AP emissions in g/vkm per vehicle category (EMEP/EEA 2019)

	NO_x	NMVOC	PM_{10} exhaust	PM_{10} non-exhaust
ICEV-G	0.6594	0.40353	0.00068	0.026
ICEV-D	0.3318	0.01392	0.01187	0.026
BEV	0	0	0	0.026
PHEV	0.0133	0.00074	0.00061	0.026
Bus-D	5.7855	0.20286	0.20143	0.097
Bus-E	0	0	0	0.097
AM	0	0	0	0.035
AV	0	0	0	0.026

The cost factors were taken from van Essen et al. (2019), as shown in

Table 18. They are adapted for Norway using the damage costs approach, including health effects, crop loss, material and building damage, and biodiversity loss caused by the abovementioned pollutants.

Table 18: AP cost factors (van Essen et al. 2019)

€/ton NO_X (Rural)	€/ton NMVOC (All areas)	€/ton PM exhaust (Rural)	€/ton PM non-exhaust (Average)
17,250	1,643	95,833	30,530

The calculation of accidents was derived from the actual number of casualties, adjusting for under-reporting and the severity of incidents. This correction, with assigned factors of fatalities =1, severe injuries = 1.25, and slight injuries = 2, aims to account for accidents that go unreported and thus are not reflected in standard statistics. Notably, research indicates that 93.5% of all accidents result from human error, with the remaining 6.5% attributed to weather-related incidents or technical problems (Winkle 2016). Given that AVs and AMs are expected to operate without drivers, their anticipated contribution is limited to reducing the number of under-reported accidents specific to the mode of transportation they are replacing. Estimating the exact number of accidents is challenging, as it involves various factors. On the one hand, AVs may further decrease accidents by influencing other vehicle categories, as pedestrians are currently involved in 6% of car accidents and 22% of bus accidents in Oslo (SSB 2023). This number may even be higher for cyclists, particularly in areas where they share roads with motorised vehicles. On the other hand, the complexity of AV technology may lead to more accidents resulting from technical failures. Therefore, predicting a precise decrease of 93.5% is difficult, but it allows for estimating potential outcomes.

The number of underreported corrected accidents is then multiplied by the external cost factors of van Essen et al. (2019) in Table 19, which include human costs, production loss, medical costs, and administrative costs not covered by insurance.

Table 19: External cost factors (van Essen et al. 2019)

	Cost factor (cent/vkm)
Car	2.358
Bus	14.004
AM	0.910
AV	0.153

Without data specific to Grorud Valley, data on accidents in Norway was used and adjusted to reflect the population distribution in Grorud Valley. Motorcycles and mopeds were excluded from the analysis as they were assumed to have a low impact on the overall results.

The methodology used to calculate external costs was then applied to the various testing scenarios outlined in subsection 5.2.1. The current status quo, described in the following chapter, was assessed to provide a basis for comparison with future scenarios.

5.3.3 Status Quo Situation

We refer to the Status Quo (SQ) as a point of comparison to assess the impact of different scenarios. Figure 33 illustrates the distribution of passenger transport in Grorud Valley, except for long-distance train trips outside the valley. The total distance travelled was 1,450,311 pkm and 929,037 vkm.

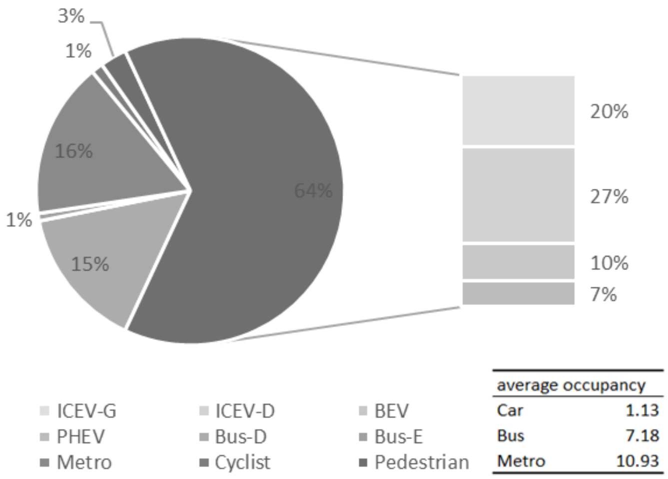

Figure 33: Modal split in pkm of SQ (Ruter 2023)

We conduct our calculations using data provided by the project partner - Ruter (2023), and SSB (2023), van Essen et al. (2019), Matthey and Bünger (2023), Hill et al. (2020), Kemp et al. (2020), Huber et al. (2022), and EMEP/EEA (2019).

5.3.4 Externalities and external cost of scenarios

Figure 34 indicates that all scenarios lead to a decrease in CO_2eq emissions when compared to the SQ. The most significant reduction was observed in the 100% market penetration scenarios because of the electrification of private cars and the utilisation of Norway's renewable hydro energy used to power the electric vehicles.

Scenario recapitulation:

SQ:	**Status Quo** – current situation
S1:	**AV Shuttle as Bus Line**
S2 (30%):	**AV in MaaS** with 30% market penetration
S2 (100%):	**AV in MaaS** with 100% market penetration
S3 (30%):	**AV Robotaxi in MaaS** with 30% market penetration
S3 (100%):	**AV Robotaxi in MaaS** with 100% market penetration
S4 (30%):	**AV as Robotaxi in competition with public transport** with 30% market penetration
S4 (100%):	**AV as Robotaxi in competition with public transport** with 100% market penetration

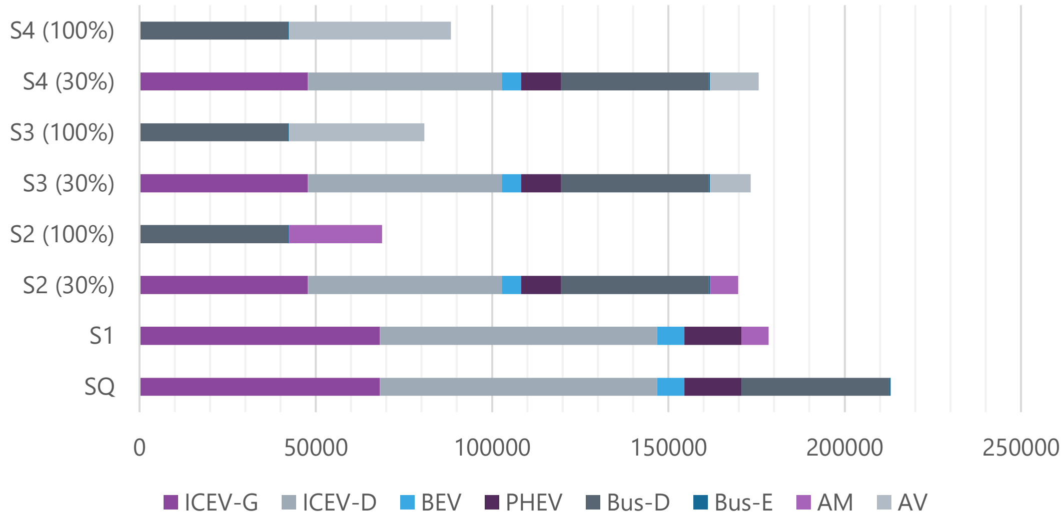

Figure 34: LC GWP in kg CO2eq

The full electrification of vehicles led to the disappearance of NO_x, NMVOC, and exhaust PM_{10} emissions, making the 100% market penetration scenarios the most attractive option, but it is even more interesting to compare non-exhaust PM_{10} emissions. Figure 35 demonstrates that even though S2 (100%) was by far the scenario allowing the largest reduction, more than half of all scenarios resulted in increases in non-exhaust PM_{10} emissions compared to the SQ. However, when combined with exhaust PM_{10} emissions, the results changed. S2 (100%) was still the best option, but the exhaust emissions from ICEV increased the total PM_{10} emissions of the SQ so much that only S4 (30% and 100%) performed worse than the baseline. Non-exhaust PM_{10} emissions depend significantly on the vkm, and with S2 likely to decrease vkm by ridesharing and the capacity of Ams to transport more people at the same time than the smaller AVs that are likely to increase vkm because of empty miles, the results can be explained.

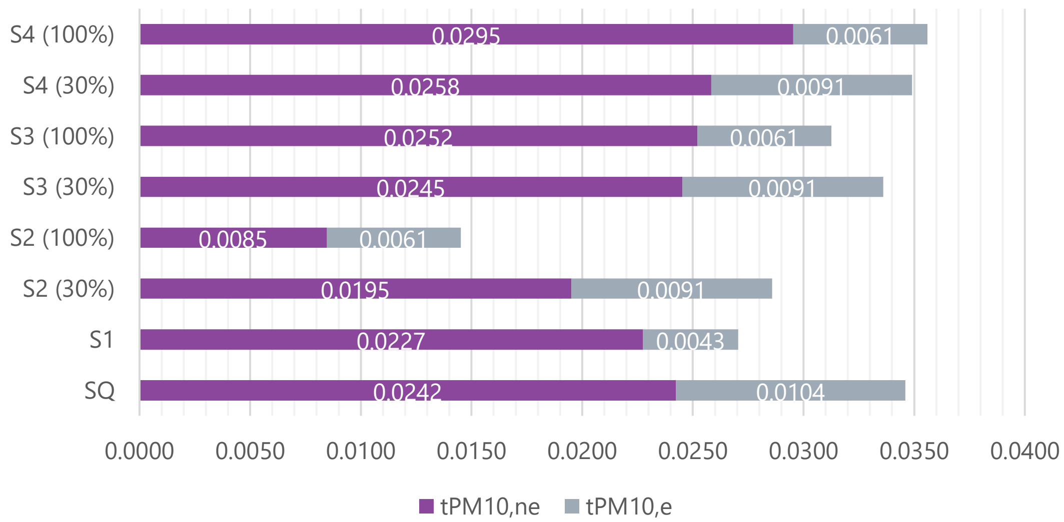

Figure 35: PM10 emissions in tons (ne = non-exhaust ; e = exhaust)

As discussed, the new technology of AVs is assumed to prevent accidents caused by human error. The result is foreseeable because human error is the main reason for road traffic accidents: the more AVs/AMs on the road, the fewer accidents as Figure 36. In particular, private cars cause many accidents, so S1 did not significantly improve. Because the risk of accidents also increases with vkm, S3 and S4 generally generated slightly worse results than S2.

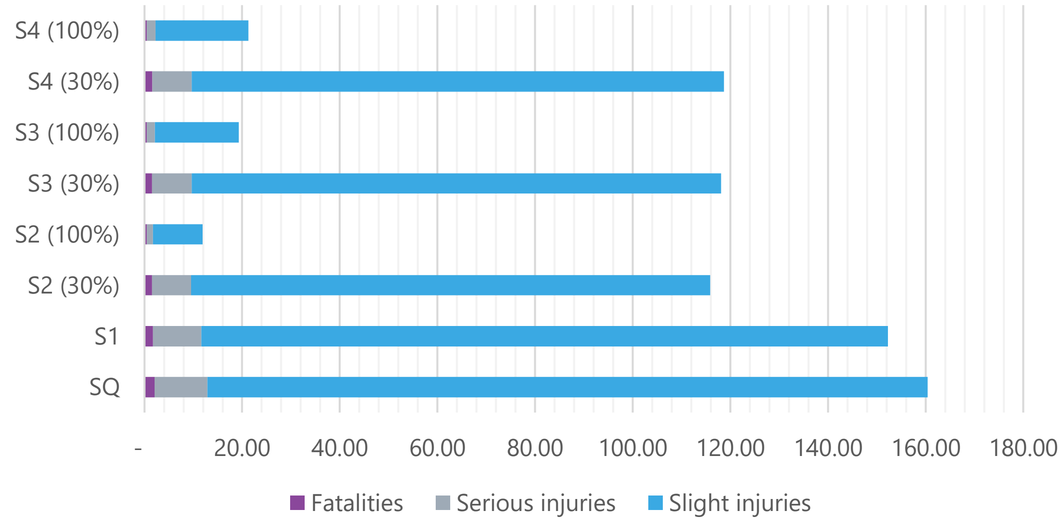

Figure 36: Accidents

Scenario recapitulation:

SQ:	**Status Quo** – current situation
S1:	**AV Shuttle as Bus Line**
S2 (30%):	**AV in MaaS** with 30% market penetration
S2 (100%):	**AV in MaaS** with 100% market penetration
S3 (30%):	**AV Robotaxi in MaaS** with 30% market penetration
S3 (100%):	**AV Robotaxi in MaaS** with 100% market penetration
S4 (30%):	**AV as Robotaxi in competition with public transport** with 30% market penetration
S4 (100%):	**AV as Robotaxi in competition with public transport** with 100% market penetration

The total external costs for each vehicle category and scenario are depicted in Figure 37. Private cars were the predominant contributors to the total costs, comprising more than half of the total costs in each scenario where they were included. If private cars were replaced with 100% AMs, the external costs could be reduced by up to ten times when only considering the change from private cars to AMs. In scenario S4 (100%), AVs resulted in higher costs than diesel buses due to increased vkm. S2 (100%) emerged as the most cost-effective option. Upon examining the external costs by category (Figure 38), it was observed that CCC costs accounted for 51-63% of the total costs, while AP costs constituted only 10-17%. Scenario 2 recorded a 68% reduction in CCC costs compared to SQ. Scenarios S3 and S4 experienced 62% and 59% reductions, respectively, while the other scenarios only witnessed a 16-20% reduction. Scenario S2 (100%) demonstrated a 61% decrease in AP costs, and scenario S4 (30%) recorded a 16% reduction. Scenario S2 (100%) experienced an 80% decrease in accident costs, and scenario S1 recorded a minimum 18% reduction.

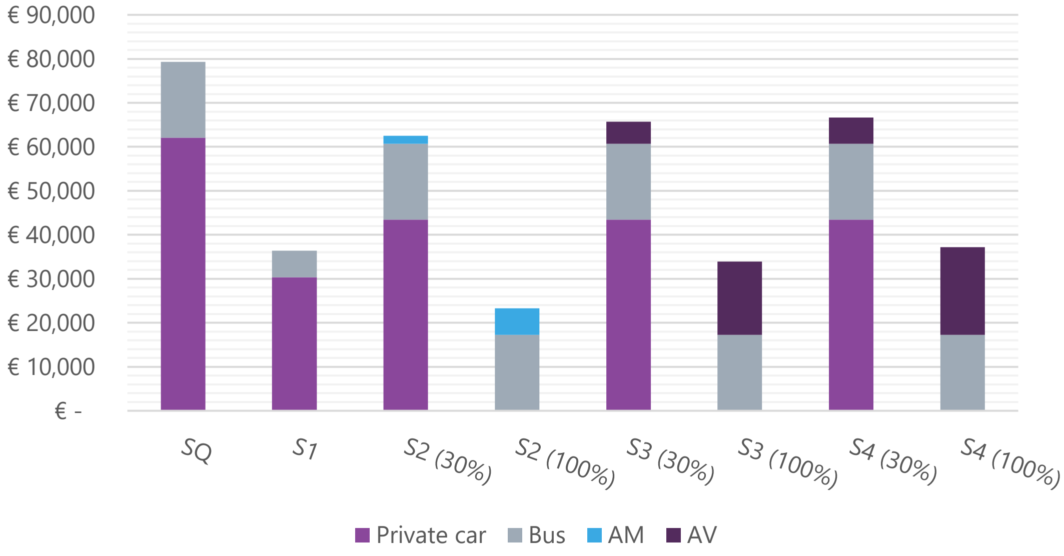

Figure 37: External costs per vehicle category

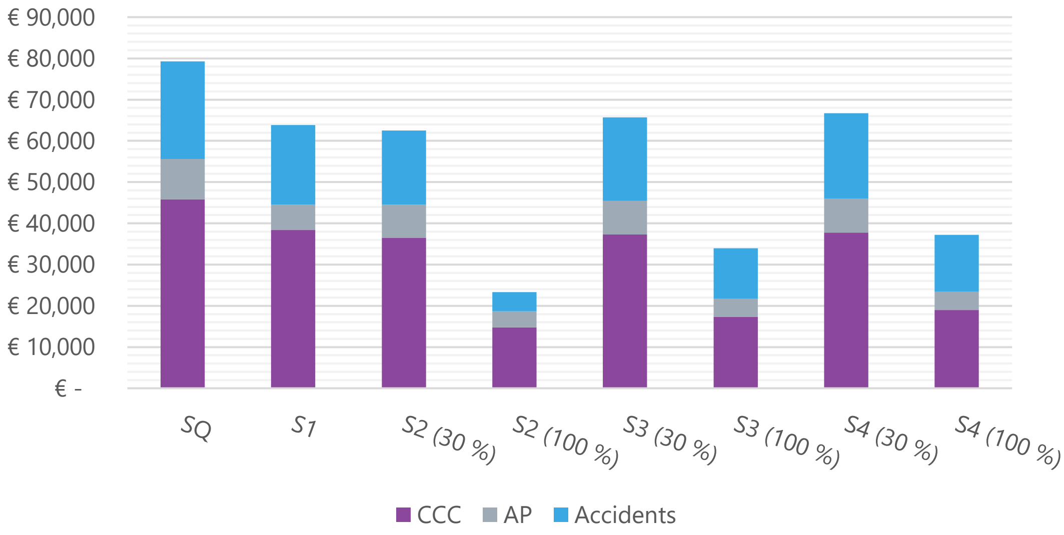

Figure 38. External costs per impact category

Table 20 presents the costs per vkm and per pkm and the changes in total external cost. Remarkably, AMs demonstrated the lowest costs per pkm, gasoline cars exhibited the highest costs per pkm. Across all scenarios, external costs were reduced compared to the current status quo, ranging from 16% (S4, 30%) to 71% (S2, 100%). The specific reductions are detailed in the table below.

Table 20. External costs per vkm/pkm and changes in total external costs compared to SQ

	cent/vkm	cent/pkm
ICEV-G	9.43	8.32
ICEV-D	8.05	7.10
BEV	3.71	3.27
PHEV	6.34	5.59

	Change
SQ (Baseline)	79,305 €
S1	-15,448 €
S2 (30%)	-16,798 €
S2 (100%)	-55,997 €

Bus-D	56.26	7.83
Bus-E	19.20	2.67
AM	3.90	0.78
AV	1.96	1.80

S3 (30%)	-13,609 €
S3 (100%)	-45,362 €
S4 (30%)	-12,627 €
S4 (100%)	-42,091 €

Table 21 shows that S2 (100%) demonstrated the most favourable performance across all impact categories. On the other hand, S1 exhibited the poorest results regarding GWP, NMVOC, and accident externalities. NOx pollution demonstrated poor outcomes in all 30% market penetration scenarios, while all 100% market penetration scenarios showed a positive result. S4 (100%) demonstrated the worst PM_{10} pollution due to increased vkm despite substituting ICEVs with electric AVs. Ultimately, S2 (100%) exhibited the most favourable results for accidents externalities through a combination of AVs and reduced vkm.

Table 21. ´Winner´ and ´Loser´ Scenarios

	LC GWP	AP			Accidents	External costs
		NO_X	NMVOC	$PM_{10,all}$		
SQ (Baseline)						
S1	L		L		L	
S2 (30%)		L				
S2 (100%)	W	W	W	W	W	W
S3 (30%)		L				
S3 (100%)		W	W			
S4 (30%)		L				L
S4 (100%)		W	W	L		

It is worth noting that, although S4 (30%) ranked low in the impact indicators once, it provided the least cost reduction in the external costs comparison and was therefore chosen as the ´loser´ scenario.

Our preliminary calculations were instrumental in refining our approach and strategy for conducting an environmental impact assessment. Our findings emphasised the need to incorporate MaaS, as it provided the highest benefits through decreasing vkm. Moreover, we identified the need for additional indicators and a more clearly defined methodology. This methodology is described in the next subsection.

5.4 Next steps

Establishing a structured approach for our research and implementation strategy is critical to effectively conduct the aforementioned assessment. Besides, creating a solid framework for collaboration and dialogue with PTOs and PTAs is essential, ensuring that assessments are grounded in real data and considering the practical implications for existing public transport networks. Additionally, this cooperation facilitates the identification of potential synergies, challenges, and mitigation strategies, thereby enhancing the comprehensiveness and accuracy of impact assessments. The following are the key next steps:

Continuation of Status Quo Analysis

Based on our initial assessments and conversations with stakeholders, it is essential to maintain the current trajectory of the Status Quo Analysis. This involves continuous evaluation of the public transportation infrastructure and operational systems. Our analysis will employ qualitative and quantitative approaches to evaluate the current status, pinpoint strengths and shortcomings, and uncover patterns. This will enable us to establish benchmarks, formulate strategies, and enhance our integration efforts, ensuring their relevance to stakeholder expectations and urban growth objectives.

Identification of important Indicators

Our primary objective is to identify the important environmental and social indicators for stakeholders, focusing on PTOs and PTAs. To accomplish this, we will conduct a series of consultative meetings, workshops, and surveys designed to gather insights from these key stakeholders. By engaging in these activities, we aim to understand the metrics, benchmarks, and criteria essential in assessing the success and impact of integrated transportation initiatives.

Data Assessment and Feasibility Analysis

Our next step involves evaluating the availability and suitability of data sources related to these indicators. A thorough review of existing data repositories, data collection methodologies, and data-sharing agreements will be conducted. Simultaneously, a feasibility analysis will be carried out to determine whether the available data can support the calculation and interpretation of the identified indicators. This phase will involve data validation exercises to guarantee the accuracy, reliability, and pertinence of the chosen metrics.

Conceptual Integration of LaaS and AVs

Thus far, our primary focus has been on AVs in the context of MaaS. In order to extend our examination to include LaaS, we will conduct a comprehensive analysis of the interplay between LaaS and AVs, focusing on identifying the mutual benefits, barriers, and transformative potential resulting from their integration. This analysis will involve a review of the literature, as well as consultations with stakeholders and interdisciplinary dialogues. By synthesising these insights, we aim to construct a robust theoretical foundation that explains the complex dynamics of this integrated ecosystem. Once we have identified a suitable framework for the implementation of AV and LaaS, it will be necessary to evaluate this scenario's environmental and socio-economic impacts throughout its entire life cycle. Furthermore, we intend to incorporate this scenario into the current AV in MaaS future scenario assessment.

By following this methodical, stakeholder-focused strategy, we will ensure that interventions in public transport integration are well-informed, data-driven, and context-sensitive. This approach will allow us to effectively address the complexities of urban transport systems and move towards a future characterised by seamless, inclusive, and environmentally responsible mobility solutions. Furthermore, the detailed work plan outlined in Table 22 provides a roadmap for the various concrete steps of this environmental impact assessment, ensuring that we meet our objectives within the designated timeframe to complete the project.

Table 22: Work Plan – Environmental Impact Assessment

	2024				2025				2026		
Planning & Literature Review	Q1	Q2									
LCA			Q3	Q4	Q1	Q2					
S-LCA			Q3	Q4	Q1	Q2					
LCC			Q3	Q4	Q1	Q2					
Monetarisation							Q3	Q4			
Generalisation									Q1	Q2	
Final Report											Q3

This task will contribute to a holistic impact assessment of AV in MaaS in urban transport systems (Task 6.1). This task will provide insight into Task 6.2 on the business strategies, models, and cases for future intelligent citizen-centric transport and sustainable business model design for AV integrated in MaaS. It will contribute to designing a mobility business ecosystem and support the strategy design or transformation concept towards a future intelligent citizen-centric transport ITS/CCAM ecosystem for persons and goods. It will also provide insight into developing and validating innovative cross-sectoral business models (Task 6.2) for private and public stakeholders (ULTIMO's key objective 6) and to achieving realistic, long-term transition planning and design for integrating AVs in MaaS (Task 6.3).

In conclusion, the ULTIMO project aims to examine the external costs associated with integrating AVs into MaaS and ITS across the three distinct pilot sites. By employing a LCSA methodology, the assessment goes beyond environmental factors and strives to delve into the three pillars of sustainability - environmental, social, and economic - in order to reveal the unseen costs of mobility for society. We will integrate a social perspective to ensure a comprehensive assessment, providing insights into the societal implications of AV deployment and MaaS integration. By considering the complete life cycle and conducting our calculations for external cost factors, we aim to provide a robust assessment of the environmental, social, and economic impacts of AV deployment and MaaS integration. The work plan outlined for this assessment emphasises collaboration with public transport operators and authorities, ensuring that assessments are grounded in actual data and aligned with stakeholder expectations. Through structured approaches such as continuation of status quo analysis, identification of important indicators, data assessment, and conceptual integration of LaaS and AVs, we aim to provide actionable insights that drive towards a future of seamless, inclusive, and environmentally responsible mobility solutions.

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6. Technical Impact Assessment

6.1 Introduction

The World Health Organization estimates 1.35 million road accident deaths and 50 million injuries annually, with human error responsible for around 95 percent of cases (KPMG, 2020). More importantly, crash incidences and their severity are rising and causing significant economic losses (Mehdizadeh et al., 2020). Thus, road transport safety is a crucial issue that requires urgent attention. Safety is the absence of unreasonable risk of a mishap resulting in a loss event (Koopman and Wagner, 2018). Automated Vehicle (AV) represents a potentially disruptive yet beneficial change to the transport system with the potential to improve safety (Fagnant and Kockelman, 2015). AV is primed as a potential solution to reduce road accident deaths and injuries. However, AV is a complex interconnected system consisting of sensors, processors, and external units to ensure automated driving (Benyahya et al., 2023). Level 4 (driverless) AV could process sensors' inputs and exchange data with other vehicles and intelligent transport systems to achieve real-time assimilation of their surroundings (Benyahya et al., 2022). Algorithms form the basis of decision-making in AVs, allowing them to perform driving tasks in an automated manner. Nonetheless, technical issues in the AVs' perception, decision-making and control algorithms can undermine the performance of an AV system and create safety hazards. Level 4 AV loss events can include fatalities potentially attributable to design defects or operational faults (Koopman and Wagner, 2018). Therefore, technical safety is also one of the foremost concerns in adopting automated systems (Sohrabi et al., 2021; Tan et al., 2023) and a critical precondition for public trust (Mattas et al., 2022).

Crucial to ensuring AV safety is the proper functioning of the complex array of sensors, which are essential for interpreting the surrounding environment and facilitating decision-making processes. A compromised sensor system could result in a distorted understanding of the environment, elevating the risk of accidents and safety hazards (Giannaros et al., 2023; Mulder and Vellinga, 2021). Thus, the reliability of the sensor system is one of the most important criteria for decision-making on AV safety (Pickner et al., 2022). Safety risks can arise from control algorithms' potential inaccuracies in modelling the AV's motion in unexpected road conditions. Safety risks can also arise when errors in AV perception propagate to other software components, leading to potential failure to correctly interpret the meaning of certain decision-making rules during complex driving scenarios. Interpretational failures could make AV to display behaviours that contradict its programmed principles and potentially create safety risks for all road users (Lim and Taeihagh, 2019). Therefore, decision-making algorithms could be constrained by computational complexities that can undermine AV's safety in dynamic environments.

Safety is also a key concern of fully automated driving systems due to the need to consider/understand several complex factors, such as the environment, traffic, hardware and software systems' reliability, information availability, and cyber security (Pickner et al., 2022). Vulnerable road users (VRUs) such as pedestrians, cyclists, and users of new micro-mobility transport modes such as e-scooters have a high risk of injury and fatality when involved in vehicular accidents. Automated driving systems must also perceive static objects and obstacles across the road, like bushes, trees, safety fences, pedestrian barriers, and street nameplates. Thus, before AVs can be widely accepted in urban environments, convincing demonstrations should prove that AV technology can detect and safely respond to VRUs and static objects (Tengilimoglu et al., 2023a).

To address the safety concerns of AV users and VRUs, there is a need to correctly predict potential failures and quality defects in normal AV operations and emergency events that could lead to human injuries or death (Zoghlami et al., 2022; Cortez et al., 2018). In this context, there are recent advancements to help improve the safety of AV users and VRUs. For example, vehicular communication systems have emerged as a transformative force for improving road safety and traffic efficiency. Vehicle-to-Everything (V2X) communication is one of the safety features that can establish communication among various entities on the road for cooperative safety. V2X involves communication between Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I) and Vehicle-to-Pedestrian (V2P) (Sewalkar and Seitz, 2019). For example, AVs could leverage V2V communication to share pivotal data points, such as positional coordinates and speed metrics, and V2I communication to interface with the embedded electronic devices in transportation infrastructure (Giannaros et al., 2023).

Another way to address safety issues involves the implementation of collision prediction algorithms using V2X communication technologies. Predictive models are helpful to understand and quantify crash risk based on different driving conditions (Mehdizadeh et al., 2020). Upon predicting a possible collision, the system could alert both the pedestrian and the automated vehicle, enabling them to take necessary action(s) to prevent accidents and enhance the safety of all road users. Moreover, predictive maintenance of AV systems could be valuable in improving the safety of AV operations. For example, using machine learning and datasets of sensor measurements, the probability of failure of AV systems can be estimated. The estimates can then be further utilised in optimisation models to propose optimal maintenance actions and minimise crash risk.
Also, it is worth noting that collaboration among stakeholders and technical standards are necessary to ensure that AVs and their operational environments are safe (Tengilimoglu et al., 2023b). In sum, addressing the safety issues of Level 4 AV is paramount to facilitating public acceptance and trust in AV systems.

In the following section, we will discuss the key insights from technical assessment-related deliverables from other EU CCAM projects to complement the scientific literature. We have structured the technical evaluation problems around three issues:

a) AV safety: It involves analysing and measuring reliability conditions to ensure confidence in software and hardware. Operations and maintenance processes must be continuously evaluated to improve decision-making and control to limit safety risks.
b) Driving system: It involves cybersecurity in the GDPR context and the evaluation of V2X reliability. In the Ultimo project, we also analyse the specificity of vulnerable users and evaluate how interaction with them can be continuously improved. Finally, the interaction between LaaS and MaaS has to be questioned considering the optimal use of AVs.
c) Safety of AV users: All technical questions about predictive maintenance, emergency events management and European standardisation are considered.

Then, we will discuss the knowledge gaps and the potential contribution of this task to the ULTIMO project.

6.2 Learnings from EU CCAM projects and Ultimo's technical assessment context

Table 23 summarises the key findings (what barriers were identified and what evaluation method was used) from EU CCAM projects' technical assessment/safety-related deliverables, and we checked how the Ultimo project positions itself in relation to the work already carried out, and what is its contribution to the theme of technological evaluation (with the three issues selected above).

Table 23: Key findings from CCAM projects' technical assessment/safety-related deliverables.

EU CCAM projects	**Key findings**	**Ultimo's issues**
AVENUE (Beye, 2021), (Fournier et al., 2023)	Assessed AV technical barriers with the following taxonomy: • Automated shuttle technical capabilities (general aspects, hardware-related and software-related limitations). • Automated shuttle environment (general aspects, weather-related, city and digital infrastructure limitations. • Human involvement (the need for an onboard supervisor). • Other technical barriers (processing power, speed, cyber security, 5G networks, number of AVs on the same route, safety demonstration to show that AV can be operated without driver intervention, and access for disabled people. Conducted expert interviews with PTOs on the level of relevance of the technical barriers to identify important ones: • Safety demonstrations to show that AV can be operated without driver intervention, the need for an onboard supervisor, cybersecurity, and access for disabled people are the most relevant technical barriers. Other significant findings from the expert interviews are: • AV deployment in urban and rural settings requires AV to handle all safety-related scenarios and fully integrate into the digital traffic infrastructure. • Integration of API and passenger apps with the route planning of automated minibuses is problematic.	(a) (b)
AI4CCAM (Quintero et al., 2023)	Proposed an assessment methodology for building trust in CCAM based on seven key requirements of trustworthiness (human agency and oversight, technical robustness, safety, privacy and data governance, transparency, diversity non-discrimination and fairness, societal and environmental well-being, and accountability): • Problem specification (what use case, what question to solve and by what means).	(b) (a)

	• Data Engineering (data processing before model design). • Model Design (training of the model and refinement). • Evaluation and verification (testing the model, deployment) Proposed to apply the trustworthiness assessment methodology to three use cases: Case 1: validating AI-enhanced automated driving assistance system Case 2: Validating explainable predictive AI models in environment perception systems. Case 3: Validating user acceptance of AVs with AI-driven VRU prediction systems.	
AWARE2ALL (Jimeno et al., 2023)	Discussed road safety and changes in the interaction of different road users caused by highly automated vehicles (HAV). Discussed three critical accidents that can occur when HAVs are introduced on the roads. • Critical accidents caused by human errors. • Critical accidents caused by HAVs interaction with humans • Critical infrastructure errors. Proposed safety parameters and safety metrics for occupants and VRUs.	(a) (b)
HIDRIVE (Vater et al., 2023)	Discussed methods and evaluation plans for safety impact assessment to evaluate the effects of automated driving on preventing accidents and injuries. Discussed the effects of automated driving function under test in the defined driving scenarios regarding crash avoidance and crash mitigation. Proposed a nine-safety mechanism approach for direct and indirect safety impact assessment of automated driving function. Discussed direct safety impact assessment investigating the safety performance scenarios in six steps (preparing the assessment, scenario description, execution and simulation, evaluation of simulation results, and plausibility check). Discussed indirect impact assessment with the ‘nine-safety mechanism approach’ plus qualitative assessment.	(c)

From the AVENUE project, the key findings point to safety as one of the most critical technical barriers to AV adoption: (i.) Safety demonstrations to show that AV can be operated without driver intervention and (ii.) AV’s ability to handle all safety-related scenarios and fully integrate into the digital traffic infrastructure points to safety as a crucial issue. The AI4CCAM project focuses on trustworthiness, with safety as one of the key requirements of trustworthiness. However, the AI4CCAM project use cases differ from the ULTIMO’s use cases (see page 12). Nonetheless, there are valuable insights from the AI4CCAM project that ULTIMO would build upon. Furthermore, ULTIMO would build upon the insights from the proposed safety parameters and safety metrics for occupants and VRUs from the AWARE2ALL project.

Moreover, the HiDrive project seems to offer a robust methodology for safety impact assessment. Therefore, this task will build upon the key findings from AVENUE and the insights from the ongoing AI4CCAM, AWARE2ALL and HiDrive projects and the scientific literature in the ULTIMO project. To the best of our knowledge, no past or ongoing EU CCAM project has studied AV safety with a focus on AV integrated in MaaS innovation (our focus in ULTIMO) and the ULTIMO use cases (see page 12). This will be the unique contribution of this task to the EU CCAM knowledge base.

With the advances in information technology, we would collect data from the ULTIMO project partners to support data-driven analytics approaches to AV safety (Mehdizadeh et al., 2020). We will offer solutions to safety-related scenarios with real data from naturalistic driving studies from the ULTIMO pilot sites. We will adopt a user-centric approach to analyse AV road test data from the AV services from WP4 and PTA/PTOs partners while ensuring data privacy in compliance with the GDPR (European Commission, 2016). Table 24 shows the AV services and data to be collected. Based on the AV services at the ULTIMO test sites, we will evaluate safety to improve reliability, preventive maintenance, and system integration with innovative mobility platforms and infrastructure.

Table 24: AV services and data requirements (See WP4 to coordination)

AV Services	**Data**
Facilitation of augmented security for public transport	Passenger Data, Real-time Abnormal Events Detection data, Real-time Petty Crimes Detection, Route and Scheduling, System Configuration, geolocation, Security Logs, Emergency Data, Notifications, System Performance Metrics, Accessibility Data, and Security Logs.
Access for the elderly without human intervention	Passenger Data, System Performance Metrics, Notifications, Security Logs, system configuration data, and emergency data.
V2X with connected VRUs, V2X with unconnected VRUs	VRUs data, Vehicle Information, Real-time Vehicle Occupancy, System Configuration, System Performance Metrics, Notifications, Emergency data, Security Logs, and Geolocation.
Predictive Maintenance	Sensor Data, Historical Maintenance Data, Failure and Anomaly Data, Operational Data, Sensor Calibration Data, Environmental Data, Maintenance Task Data, Diagnostic Data, Sensor Health Data, Maintenance Actions Data, Security Logs.
Manage incident resolution	Telecommunications inter-connectivity data, Passenger Information, Vehicle information, Route and Scheduling, Accessibility Data, System Performance Metrics, Notifications, Security Logs, Geolocation.
Anticipate and mitigate security incidents.	Data stored regarding any operation of the Transportation system, System Performance Metrics, Accessibility Data, Notifications, and security Logs.

Source: Author’s compilation based on insights from Nikoletos and Lalas (2023).

The following sections will discuss our methodology, the link between this task and others in the ULTIMO project, the proposed work plan, and the expected results.

6.3 Methodology

This task will contribute to evaluating safety in real-world deployments (Azad, 2019), using qualitative approach and data analysis.

- Qualitative data analysis

Our qualitative data analysis will be conducted using semi-structured expert interviews to investigate the safety issues of Level 4 AV integrated in MaaS. The semi-structured expert interviews will allow us to better identify underlying issues from the stakeholders' perspective (Schepis et al., 2023). Qualitative research through interviews is suitable for uncovering and understanding the diversity of opinions (Suck et al., 2023). We provide below some (tentative) interview questions:

- What are the main safety issues to address to support public acceptance of Level 4 AV integrated in MaaS?
- How do we ensure safety in the current deployment of Level 4 AV integrated in MaaS?
- What are the potential expectations regarding future technological advancement in the safety of Level 4 AV?
- What are the technical obstacles to articulate LaaS and MaaS performance?
- How can collaborations and standardisations among stakeholders be facilitated to ensure the safety of L4 AV integrated in MaaS?

Using data collected from AVs at the ULTIMO pilot sites could confirm our understanding of the technical obstacles.

6.4 Link between the technical assessment and the other tasks in the ULTIMO project.

This task will contribute to providing safe and quality automated passenger service (Último's key objective 5). This task is linked to WP 2 (passenger use cases for CCAM, in particular Task 2.1 on the passengers and PTO needs and use cases), WP4 (AI leverage services for MaaS, LaaS, vehicle and infrastructure and ITS management), and WP 5 (site deployment and data collection from AVs in Oslo, Geneva, and Herford). Moreover, this task will contribute to a holistic impact assessment of AV integrated in MaaS in urban transport systems (Task 6.1). It will also provide insight into the impact of AV safety on the AV in MaaS business case and model design to contribute to developing and validating innovative cross-sectoral business models (Task 6.2) for private and public stakeholders (Ultimo's key objective 6). It will also provide insights into achieving realistic, long-term transition planning and design for integrating AVs in MaaS and support the strategy design or transformation concept towards a future intelligent citizen-centric transport ITS/CCAM ecosystem for persons and goods (Task 6.3) in the public transport system to serve the general interest (Ultimo's key objective 8).

The following section discusses our proposed work plan for the second deliverable due for submission in September 2026.

6.5 Proposed Work Plan

Following the submission of this deliverable in March 2024, we will proceed to deepen the literature review on safety of AV and vulnerable road users for seamless citizen-centric Level 4 AV services. We will complement the literature review with semi-structured expert interviews of stakeholders on safety issues of Level 4 AV integrated in MaaS.

Based on the available data from the pilot sites, we will then conceptualise and build safetystrategy. A final report with our findings will be submitted to the European Commission in September 2026. See the Gantt chart in Figure 39.

Activities	Start date	End date	Q2 2024	Q3 2024	Q4 2024	Q1 2025	Q2 2025	Q3 2025	Q4 2025	Q1 2026	Q2 2026	Q3 2026
Literature review (safety issues of seamless citizen-centric Level 4 AV services)	01/04/2024	30/06/2024										
Semi-structured expert interviews	01/07/2024	31/03/2026										
Final Report with policy recommendations	01/04/2026	30/09/2026										

Figure 39: Proposed work plan for technical assessment deliverable.

6.6 Expected results.

The final report of this deliverable in September 2026 will offer the following insights to stakeholders:

- Guidelines to improve safety, reliability, inclusiveness to achieve a cost-optimised integration of AV in MaaS in a public transport system.
- Guidelines to integrate LaaS management in MaaS system.
- Recommendation to support the PTA/PTOs in planning and designing sustainable business models.

6.7 Conclusion

Proponents of AV inclusion in the future of transportation have emphasised the possibility of reducing accidents with AV deployment, arguing that human errors are responsible for most accidents. While Level 4 AV may live up to expectations after successful road pilot demonstrations such as in the ongoing ULTIMO project, there is no gainsaying that challenging tasks lie ahead to ensure Level 4 AV safety since it is a foremost concern in adopting automated systems. This task will offer insights into enhancing the safety of Level 4 AV occupants and vulnerable road users (VRUs) in European cities (Oslo, Norway; Geneva, Switzerland; and Hertford, Germany). First, we explain the technical complexities of the level 4 AV system because of the interconnected system of sensors, processors, and external units. We explain that technical issues in AVs' perception, decision-making and control algorithms can undermine the performance of an AV system and create safety hazards. Therefore, there is a need for the proper functioning of the complex array of sensors, which are essential for interpreting the surrounding environment and facilitating decision-making processes. Then, we explain that to enhance the safety of AV users and VRUs, there is a need to correctly predict potential failures and quality defects to protect users and VRUs in normal AV operations and emergency events.

Second, we discuss the key insights from other technical assessment-related deliverables from other EU CCAM projects that have worked or are working on AV safety issues. The AVENUE project deliverable argues that (i.) safety demonstrations are among the most relevant technical obstacles and (ii.) the deployment of automated driving in urban and rural settings requires AV to handle all safety-related scenarios and be integrated into the digital traffic infrastructure. The Hidrive project proposed an insightful methodology for safety impact assessment, and AWARE2ALL proposed safety parameters and safety metrics for occupants and VRUs. The AI4CCAM project provides some insights on assessing safety in their use cases. We explain that ULTIMO will build upon the insights from these projects while uniquely focusing on AV integrated in MaaS innovation and the ULTIMO use cases.

Then, we discuss V2X technologies to establish communication among various entities on the road for cooperative safety, collision prediction algorithms using V2X communication technologies. We explain that predictive maintenance of AV systems can be valuable in enhancing the safety of AV operations. Therefore, addressing safety issues of Level 4 AV is the sine qua non to facilitating public acceptance and trust in AV systems.

Finally, we discuss the key insights we will provide stakeholders in the next deliverable due for submission in September 2026: (i.) Guidelines to improve safety, reliability and inclusiveness to achieve a cost-optimised integration of AV in MaaS in a public transport system. (ii.) Guidelines to integrate LaaS in MaaS system. (iii.) Recommendation to support the PTA/PTOs in planning and designing sustainable business models.

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7. General Conclusion

This report is the multivariate (governance, economic, social, environmental, and technical) impact assessment of the ULTIMO CCAM ecosystem as a contribution to some key objectives of the ULTIMO project: (i.) To develop and validate cross-sectoral business models (Key objective 6) (ii.) To develop a realistic, long-term transition planning design for deploying AV in MaaS and LaaS (Key objective 8). (iii.) Provide automated passenger services for safety and service quality (Key objective 5).

We summarise the key insights from each of the assessment as follows:

Governance Impact Assessment

- ### Data Governance

We discuss that AV requires a workable data governance framework, considering the vast amount of data it produces. Then, we discuss that in-vehicle AV data can be analysed to generate economically valuable insights for stakeholders. Nonetheless, in-vehicle AV data has to be accessible to maximise its benefits, and the decision on its access depends on the specific economic and technological context. From an economic viewpoint, we discuss the debate on AV in-vehicle data access, which hinges on market failure issues and how to address them. The market failure issues are competition problems, lock-in problems and quasi-monopolistic markets, information asymmetry, behavioural issues, externalities, low levels of interoperability and standardisation, and innovation problems.
From the technical viewpoint, we discuss that the fundamental debate hinges on whether AV in-vehicle data should be 'closed' or 'open' and to what extent. We discuss three technical solutions for in-vehicle data access in a closed system: (i.) On-board application platform, (ii.) an internal or external applications programming interface (API) to access in-vehicle data, and (iii.) an external data server to manage third-party applications and data access, which offers possibilities with (i.) extended vehicle concept, (ii.) shared/neutral server and (iii.) B2B marketplace. Besides, we discuss the open AV data ecosystem that involves co-creation and collaboration to harness innovation potential from data and manage costs. Thus, we argue that a standardised and harmonised open data and open API could be promising when AV is integrated in MaaS.

Building upon theoretical insights, we argue that a scenario where public and private transportation entities would make their data available on an open data and open API platform and serve as integrators could address AV integrated in MaaS data governance issues. The open data platform would be set up by a public authority or a neutral party with rules that apply to both parties. The open data platform would be a back end for private and public MaaS providers to build their systems and source data. We argue that this scenario could facilitate AV integrated in MaaS innovation and enable the sharing of mobility data, avoid competition between private and public transport, and facilitate MaaS that includes integrating societal goals. We explain that the ULTIMO project will work on this scenario to contribute to the EU's harmonised and standardised open data and open API objectives.

Next steps (data governance)

We propose to use the CCAM data sharing and access framework for analysis and conduct semi-structured interviews and co-creation workshops with stakeholders to address the techno-economic data governance issues in the ULTIMO project. We will report our findings in the second deliverable, due for submission in September 2026. The second deliverable could offer the following insights: (i.) Guidelines for decision-makers on designing robust data governance framework for AV and AV integrated in MaaS while preserving the general interests. (ii.) Context-specific roadmaps and guidelines to overcome techno-economic data governance challenges for AV and AV integrated in MaaS innovations to achieve sustainable business models. (iii.) Insights on the governance framework to balance privacy and the Intellectual Property Rights (IPR) of ULTIMO partners (iv.) Insights on how to avoid a closed data ecosystem and prevent a dominant market position of some stakeholders or mitigate a winner-takes-all situation.

- **Regulatory Analysis**

This task contributes to the AV integrated in MaaS governance debate from the regulatory viewpoint, focusing on how AV and MaaS regulations (at the EU, national and local levels) can support market development and serve the general interest. We discuss regulatory issues such as the tendency for technological advancement to eclipse regulatory oversight, regulation lagging behind technological innovation, regulation lagging behind marketplace changes, the winner-takes-all market problem, decision-making challenge on whether to use ex-ante or ex-post regulation, regulations favouring particular interest group(s), regulatory silos at the national and local levels, and the intriguing challenge of balancing stakeholders' diverse interests. We review the literature and find that (i.) there is a lack of harmonised regulations for testing and deploying AVs. (ii.) there is a challenge to harmonise regulations because of the different and specific national and local contexts among the EU countries (iii.) there are diverse regulatory barriers for AV among EU countries, and (iv.) national frameworks are structured differently among EU countries.

We hypothesise to adapt the collaborative governance model to address context-specific regulatory barriers at the national and local levels for AV integrated in MaaS innovation in Switzerland, Norway, and Germany. That is, for public institutions (focusing on PTOs and PTAs) to play a central role in fostering AV integrated in MaaS innovation from a regulatory viewpoint. We hypothesise that insights from the collaborative governance model could be helpful to bridge some knowledge gaps and overcome context-specific regulatory barriers at the national and local levels for AV integrated in MaaS innovation.

Next steps (regulatory analysis)

We propose to combine three data collection and analysis methods: machine learning (text mining/analytics and clustering), semi-structured interviews, and co-creation workshops (to test our collaborative governance hypotheses) in a complementary manner to offer insights to address AV integrated in MaaS regulatory issues. We will report our findings in the second deliverable, due for submission in September 2026. The second deliverable could offer the following insights: (i.) context-specific guidelines and roadmaps to adopt collaborative regulation for AV integrated in MaaS innovation at the national and local levels, (ii.) recommendations for designing new regulatory frameworks to support AV integrated in MaaS innovation. (iii.) recommendations for PTA/PTOs on collaborative regulation, (iv.) guidelines for collaborative governance among regulatory institutions at the national and local levels, and (iv.) insights on how to align regulations with industry requirements while preserving the general interests.

Economic Impact Assessment

• Economic cost-benefit analysis

This task contributes to the AV integrated in MaaS debate from the economic viewpoint. We conduct a literature review and find a need for a detailed understanding of the economic impact of AV services, particularly within the MaaS and LaaS ecosystems. To bridge the knowledge gap, we conduct a preliminary analysis for two ULTIMO project scenarios: ‘AV as a bus line’ and ‘AV in MaaS’ using the Oslo site. We find that (i.) labour costs (including the salaries of on-board supervisors) contribute significantly to the total operations costs in both scenarios. (ii.) energy and maintenance cost savings led to a slight decrease in the total cost per kilometre under the scenarios. (iii.) The ‘AV as a bus line’ scenario had a lower cost per kilometre compared to ‘AV in MaaS’, although the latter offered greater flexibility in service provision. (iv.) Using offboard supervisors led to potential cost reductions, for ‘AV as a bus line’, where the cost per kilometre decreased by over 50% in the most extreme case.

Next steps (economic cost-benefit analysis)

We propose to use the Total Cost of Mobility (TCM) framework to provide a quantitative economic impact assessment in line with the larger goal of developing sustainable business models. We anticipate that the economic insights from TCM calculations could become integral to a holistic approach that considers social and environmental dimensions, favouring balanced and sustainable business models. We will report our findings in the second deliverable, due for submission in September 2026. The second deliverable could offer the following insights: (i.) Enhance understanding of the economic implications of AV services by delving deeper into the factors influencing cost structures and exploring scenarios for optimising operational efficiency and cost-effectiveness of AV in MaaS and LaaS. (ii.) Propose a comprehensive cost-benefit assessment framework tailored to the objectives of the ULTIMO project to provide further perspectives and practical implications for assessing the economic feasibility of AV services. The cost-benefit analysis extended to consider the MaaS eco-system's stakeholders (as a value chain) will be treated in the form of a sustainable business model, which will be part of the answers provided in T.6.2.

• Dynamic Price Modelling of AV integrated in MaaS.

We analyse dynamic pricing strategies for the integration of AV in MaaS. We conduct a comparative analysis of dynamic pricing and static pricing for AV. The insights from the review of existing literature suggest that (i.) dynamic pricing offers a strategic advantage for private transport operators integrating AVs into MaaS. (ii.) adopting dynamic pricing to assess the economic viability of AV integrated in MaaS could offer a step towards realising an adaptable transport model aligned with the evolving transport needs of urban societies.

We review different methodologies for dynamic price modelling to understand what methodology could be more suitable for developing an efficient dynamic pricing algorithm for AV in MaaS. We find that: (i.) The adoption of machine learning (in particular, reinforcement learning) technique for dynamic price modelling appears more promising than the other methodologies, given its efficacy in refining pricing strategies to align with fluctuating market demands and operational challenges. (ii.) Reinforcement learning seems promising in contributing to the economic viability and sustainability of AV integrated in MaaS innovation.

(iii.) Reinforcement learning could offer a robust framework for understanding decision-making in complex environments while highlighting the intricate balance between operational efficiency, revenue maximisation, and customer satisfaction. Nonetheless, reinforcement learning could be computationally challenging. Therefore, its successful application in dynamic price modelling requires quality data to model market dynamics and customer behaviour complexities.

Next steps (dynamic price modelling)

Depending on data availability, we propose to use reinforcement learning with actual or simulated data for dynamic price modelling of AV integrated in MaaS innovation. We will report our findings in the second deliverable, due for submission in September 2026. The second deliverable could offer the following insights: (i.) Optimal pricing strategies specific to the three different use cases for public transport operators and authorities (PTAs and PTOs). (ii.) Commercially viable and sustainable solution when AVs are integrated in MaaS. (iii.) Understanding of the relationship between user demand and price changes (elasticity). (iv.) Policy recommendations to support AV integrated in MaaS in urban transport systems.

- ### Social Acceptance

We conduct a literature review on user acceptance of AV. We find a lack of a holistic and citizen-centric approach that could predict the adoption of AV integrated in MaaS innovation. There is also a need to create a positive public perception and to make potential AV users become regular AV users. Therefore, we propose to bridge this knowledge gap within the social acceptance assessment in the ULTIMO project.

Next steps (social acceptance)

We propose to design a representative survey of potential users at the city level and test the hypothesised relationships between the antecedents of the behavioural intention to use AV and the behavioural intention to use. Our conceptual model will incorporate sociodemographic, socioeconomic, service characteristics, travel behaviour patterns, beliefs, attitudes, and perceptions about automated vehicles integrated in MaaS in a holistic approach. We will report our findings in the second deliverable, due for submission in September 2026. The second deliverable could offer insights on: (i.) The significant and relevant behavioural determinants that could influence the behavioural intention to use AV integrated in MaaS. (ii.) Constructs to predict the adoption of AV integrated in MaaS. (iii.) The behavioural determinants that could encourage potential AV users to use the service and facilitate acceptance of AV integrated in MaaS. (iv.) The conditions to improve to increase the usability of the proposed AV service and satisfy the users' need to facilitate a shift from private cars to AV services. (iv) The willingness to pay of potential users of AV for the offered services by AV to support PTO/PTA pricing strategies. (vi.) Appropriate public policies to facilitate acceptance of AV in MaaS. (vi) Recommendations for policymakers on the economic and non-economic incentives that could lead to higher acceptance of AV integrated in MaaS.

- ### Environmental Assessment

We conduct a preliminary analysis of the environmental impact of mobility innovations. We find that AV in MaaS could be a promising innovation with low environmental impact. Then, we argue that using a Life Cycle Sustainability Assessment (LCSA) methodology will provide insights beyond environmental factors to include social and economic factors in order to understand the hidden costs of mobility for society. LCSA will provide a holistic approach, considering all three dimensions of sustainability with an assessment of the entire transportation system with different transportation modes integrated in a MaaS system. Also, LCSA will translate the environmental and social impacts into monetary values for better comparison.

Next steps (environmental impact assessment)

We propose to apply the LCSA methodology for AV in MaaS innovation in the ULTIMO project. We will report our findings in the second deliverable, due for submission in September 2026. The second deliverable could offer the following insights: (i.) A comprehensive assessment encompassing environmental, social, and economic impacts to promote a holistic sustainability-based life cycle approach (ii.) Guidelines to support an inclusive, and environmentally responsible mobility solutions. (iii.) Total life cycle emissions and external costs (environmental and social) with monetary values with insights to support policymakers.

- ## Technical Assessment

We conduct a literature review on the technical assessment of Level 4 AV. We find that safety is a key concern in adopting AVs. We explain that this task will offer insights into enhancing the safety of Level 4 AV occupants and vulnerable road users (VRUs) at the ULTIMO pilot sites. We argue that to enhance the safety of AV users and VRUs, there is a need to correctly predict potential failures and quality defects to protect users and VRUs in normal AV operations and emergency events. We argue that addressing safety issues of Level 4 AV is the sine qua non to facilitate public acceptance and trust in AV systems. Stakeholder interviews, V2X technologies analysis could be insightful to increase the safety of Level 4 AV.

Next steps (technical impact assessment)

We propose to apply a qualitative approach and using data collected from AVs at the ULTIMO pilot sites to provide insightful contributions on Level 4 AV safety issues. We will report our findings in the second deliverable, due for submission in September 2026. The second deliverable could offer the following insights: (i.) Guidelines to improve safety, reliability, inclusiveness to achieve a cost-optimised integration of AV in MaaS in a public transport system. (ii.) Guidelines to integrate LaaS performance in MaaS governance. (iii.) Recommendation to support the PTA/PTOs in planning and designing sustainable business models.

Annexe

This annexe is from Partners in WP2 and used by all ULTIMO project partners to deliberate on the user mobility needs and requirements. It is linked to the identification of mobility needs in the social acceptance assessment.

User Mobility Needs and Requirements
The user shall have access to complete information on the service and the vehicle.
The PTO/PTA shall provide complete and accessible information about the service e.g., that it exists, where and when it is offered, what price to expect, what can be brought, how to book it, etc.
The PTO/PTA shall provide accessible information about the vehicle e.g., what it looks like (outside and inside), how it can be identified, implemented safety measures, etc.
The system shall provide FAQs (Website and in-app), plus a form to send in other questions.
The user shall be able to book a ride, pay for a ride, take a ride without a (working) smartphone.
The passenger shall be able to use different public transport services seamlessly (including first mile/last mile to and from the mobility hub)
The user shall be able to book a trip with a fixed ETA (e.g. to a doctor's appointment or a connecting means of transport)
The passenger shall be able to book a trip for the current moment.
The passenger shall be able to schedule a trip in advance.
The user shall be able to book for other passengers, for example for children that do not use smartphones, grandmother. etc.
The user shall be able to book a solo ride, e.g., at night, for a young child, etc.
The user shall be able to book a ride with a safety operator on board.
The user with special needs shall be able to book a ride specifying the needs, e.g. with/without a ramp, space for luggage, space for a guide dog, low-floor vehicle, group of people, and dog-free vehicle.
The system shall confirm that all special needs are considered, e.g. that the vehicle with the ramp is booked, and that space in the vehicle is reserved, and if necessary, provide details, e.g., how much weight the ramp can support.
The passenger with special needs shall be able to book their ride spontaneously like any other passenger.
A user with a mild cognitive impairment shall be able to book a ride independently, with the booking process designed in plain language and featuring intuitive operation.
The user shall be able to book recurring trips.
The user shall be able to book a shuttle for additional persons (=me plus others)
The user shall be able to make changes or cancel a trip at short notice.
The user shall be informed about the (time) consequences and/or price benefits of ride-sharing
The user shall be informed about the location of the PUDOs and be able to view the chosen PUDOs on a map with the walking distance between their current location/destination and the designated PUDOs
When booking for a group, the user shall have the option to add multiple destinations, accommodating the needs of the person(s) accompanying them.
When booking for a group, the user shall have the option to add multiple pick-up points, accommodating the needs of the person(s) accompanying them.
The passenger shall be able to select pick up and drop off points with criteria important to them (e.g. shortest walk vs. no road to cross)
The passenger without a (working) smartphone shall be able to get a confirmation of the booking for the trip.

The confirmation of the booking shall contain all essential information, including the location of PUDOS, estimated time of arrival (ETA) at start and destination, properties of vehicle (when indicated), price, wait time of the vehicle and (if applicable) connections at a connecting station.
The user shall have the option to confirm the trip details, including the assigned vehicle.
Classic PT tickets shall be valid for this service as well.
The user shall be informed about potential video surveillance.
The specified price shall be reliable.
The user shall be able to register a payment card or use vipps or the like
The user shall be able to pay automatically for the trip.
The user shall be clearly informed of the time period available for boarding the vehicle.
The user shall be able to input their start and stop points.
The system shall provide suggestions for trips with the estimated journey time and specified price.
The system shall onboard the user easily, requiring only essential information such as name, relevant details, and payment method.
The user shall be provided with information regarding the presence/absence of a safety operator in the AV.
The user shall be promptly notified during the early stages of the booking process if no transportation options are available.
The user shall be informed if the service cancels or changes their trip.
The user shall receive updates on any changes to their itinerary (new prices, route changes, new ETAs)
The user shall be able to save favourites (trips, PUDOs) without booking them.
The user shall be able to request longer boarding and disembarking time during the booking process.
The user shall be informed of the consequences of changes to a booking before they confirm the changes or cancellations.
The system shall provide suitable PUDOs when the user asks for specific criteria (e.g. no road to cross to destination, suited for wheelchair ramp --> gradient)
If a booked route is available with conventional service, the system shall inform the user of this fixed line service providing the same route and encourage the user to book fixed line.
The Service shall be accessible by all passengers (visually impaired, blind, deaf, motorically impaired, cognitive impairment, etc.)
When of another nationality (language!), the passenger shall be able to book and use the service.
The user shall be able to save and edit a user profile, including preferences and special needs.
The system shall provide the properties of the booked vehicle (if special requirements are part of the booking)
The user shall be able to compare the costs - travel time - CO2 footprint of different PT options.
The system shall inform the user about the expected demand (how crowded the vehicle might be)
The system shall provide the essential boarding information: the estimated arrival time of the AV at the PUDOS and the AV's identifier, such as its name or license plate number.
The user shall be provided with an accurate and accessible description of how to find their pick-up point.
The user shall be provided with a real-time time estimate indicating the distance between their current location and the PUDO/the vehicle.
The user shall receive a confirmation when they have arrived at the correct PUDO.
The user shall get updated on how long the AV will wait for them at the PUDO.
The system shall provide a map with PUDOS and the user position marked
The user shall be able to cancel the trip if they cannot make it to the pick-up point in time.

If the system predicts that the user will be late and the vehicle can wait, the system shall ask the user if the waiting period shall be extended (and inform about the consequences)
If the system predicts that the user will be late and the vehicle cannot wait, the system shall ask the user if a new trip in the next vehicle shall be booked (and inform about the consequences)
PUDO shall be marked in such a way that it can be easily recognised
The user shall be able to report an issue with a PUDO.
The user shall be informed about the time when the vehicle will arrive at the pickup point.
The user with special needs shall not experience any additional waiting time for the vehicle to pick them up compared to any other passenger.
The user shall be able to mark the ride as a no-show and contact customer support if the vehicle fails to arrive.
The vehicle shall let the user know when it approaches the pickup point.
The system shall provide a time estimate of how far away the vehicle is
The user shall be able to get a confirmation that this is the correct location.
The user shall be able to track the vehicle (its position and time to arrive at PUDO)
The vehicle shall have AVAS or similar (so that users can hear the vehicle coming)
The system shall be able to cancel the ride if no passenger shows up.
The user (incl. visually impaired) shall be able to clearly identify their assigned vehicle as "my vehicle" (e.g. clear correspondence between the vehicle's name or number displayed in the app and the physical vehicle itself)
The vehicle shall make itself easy to locate (e.g., blink or make a noise)
The vehicle shall be able to 'recognise' the user.
The vehicle shall be clearly marked as a service from the PTO/PTA.
The vehicle shall provide door localisation.
The user shall be able to authorise themselves easily to unlock doors.
The vehicle shall inform the PTO if pax do not board as supposed to
The system shall associate items with passengers.
The vehicle shall welcome (regular) passengers by name.
When using a wheelchair, the user shall be able to access the vehicle, i.e., the vehicle has a ramp, the ramp has an appropriate gradient, and the ramp supports the weight of the wheelchair.
The user shall be able to get heavy luggage into the vehicle.
When using a wheelchair, the user shall be able to securely fix the wheelchair in the vehicle.
The wheelchair ramp shall indicate how much weight it supports.
When using a walker or stroller, the user shall be able to securely fix the walker or stroller in the vehicle.
The visually impaired passenger shall be able to locate the door.
The visually impaired passenger shall be able to board and disembark safely, e.g., the ramp does not move towards the waiting passenger, the ramp not in the way of the passenger, etc.
The user shall be able to board safely using the time they need
The vehicle shall wait until the door, seat sensors, and seatbelt sensors say 'OK' before it starts moving.
The passenger shall be ensured that the vehicle is not driving off before being seated.
The user shall be able to signal if they are not ready to start the trip.
When having booked for another person, the user shall be sure the passenger boards the correct vehicle.
The user shall be able to unlock the door as soon as the vehicle arrives.
The user shall be clearly informed of the time period available for boarding the vehicle.
The user shall easily identify available seating options without any confusion or ambiguity.
If a passenger exceeds the boarding time limit, the customer support team shall be alerted to address the situation to facilitate the movement of the vehicle.
The user shall be able to hold on to handles, etc., to safely get to the seat/door.

The user shall be able to request that the vehicle drives on a few meters if the PUDO is unsafe to embark on (e.g. if there is a big puddle, a pile of snow, etc.)
The vehicle shall provide an alert signal when the ramp is moving.
The doors shall indicate before they close (alert signal)
The vehicle shall provide boarding confirmation (Pax-AV match)
The vehicle shall provide boarding confirmation (Pax-AV match)
The system shall detect if the passenger violates the booking agreement (e.g. no. of persons, luggage, ...)
Rules in the vehicle shall be obvious (e.g., seat belt or sitting down required).
The user shall be able to board the vehicle without a (working) smart phone.
The system shall communicate all information following the dual-channel principle.
The disabled user (deaf, hearing impaired, blind, visually impared, ...) shall get the same amount of information everyone else gets (preferably by following the dual-channel principle)
The user shall be able to feel and be safe and secure inside the AV.
The user shall be informed about the time when the vehicle will arrive at the drop-off point.
The system shall provide information on how the passengers will get from the drop-off point to the destination.
The user shall be informed about the connections at the connecting station.
The user shall be able to access all relevant information via the app and via PIS onboard.
The passenger shall have the means to securely stow luggage, a stroller or a walker.
The passenger shall have space under their seat for a guide dog/service dog.
The (blind) passenger shall be informed about unforeseen stops during the ride (construction site, traffic jam, rail crossing, etc.)
The (disabled) user shall be able to get help / have a contact person in case of unforeseen situations (e.g. technical issues, lack of information, accident, etc.)
When having booked for another person, the user shall be sure that the passenger arrives safely.
The passenger shall be able to report littering/damages, etc.
The passenger shall have alternative travel options suggested in the event of a disruption.
The passenger shall have a comfortable distance from other passengers.
The passenger shall have enough space for their belongings/luggage.
The passenger shall be guaranteed a seat during the ride.
The passenger shall be able to return to their starting point without finishing the booked ride.
The passenger shall be able to initiate a halt request to immediately leave the vehicle at the next possible stop.
The passenger shall be able to change their trip destination (during the trip)
The user shall be informed how long the AV will wait at the PUDOS (when the vehicle is waiting on route for other pax)
The vehicle shall arrive at the user's destination by the "promised" ETA, regardless of ride-sharing
The user shall be able to open and use the trunk.
The service shall implement measures to identify and address any instances of "ghost riders" before driving.
The fellow passengers shall behave in a respectful and appropriate manner / The service provider shall promote and encourage good behaviour among passengers.
The system shall inform users about rules regarding the use of the AV (e.g. "This is a shared service. Remember to respect other passengers")
If all sensors indicate that the vehicle is in an operational state, both the Voice Over system and the in-car screen shall display a message instructing the user to "Press GO to start the ride."
The in-vehicle screen shall display the route information and the pickup and drop-off points (PUDOs)
The user shall be informed if new passengers will board their bus.
The user shall be informed of changes to their itinerary due to new passengers.

The user shall be informed about the (time) consequences and/or price benefits of ride-sharing
The system shall inform the passengers about the interim stop and the vehicle's arrival/departure time there.
The user shall receive the reasons for slowing down or stops (AV 'stream of conciousness'?)
The AV shall indicate the name of the PUDO as the vehicle arrives at each location (acoustic, visual, in-app)
The vehicle shall monitor, e.g., seatbelt and seat sensors, decibel levels, help request of pax, etc.
The user shall be able to contact customer service via a button in the AV, app functionality, shouting for help, etc.
The vehicle shall inform passengers about any unforeseen events or changes to the route and their cause (dual-channel principle!)
Customer service shall be able to provide assistance on how to disembark using the onboard camera to see what is happening.
When the user discontinues/cancels a trip, the user shall be offered a list of close PUDOs to choose from (closest PUDO = default)
Users shall be informed of being dropped off before they confirm the cancellation.
The customer service (CS) shall be notified if the system detects that passengers experience problems.
The vehicle shall signal (a beep or the like) if the doors are not properly locked.
The system shall activate a notification (Voice Over script or the like) to notify the user if the user fails to properly close the door or clear the door area.
The user shall not be required to confirm their intention to leave the vehicle.
As a user, I need to be reminded if I have to confirm that my trip is concluded, but I would rather not have to
The user shall be able to interact with the control centre in the way that suits them.
The in-vehicle screen shall not display the user's private or personal information.
The in-vehicle screen shall provide a map display with the position of the vehicle and the PUDOS and POIs
The in-vehicle screen shall provide emergency information and the option to request help.
The in-vehicle screen shall provide information about the ride like upcoming PUDOS, ETA at the PUDOS, delays, interchange information (MaaS)
The in-vehicle screen shall provide information about the vehicle, such as battery status, sensor info, speed, etc.
The user shall be able to see an in-vehicle screen from every seat.
The vehicle shall inform passengers about the upcoming stop.
The vehicle shall alert passengers about arriving at their destination at an appropriate time before reaching it.
The user shall arrive in time to reach the connection.
If the vehicle fails to reach the connection, it shall inform the user and offer an alternative.
If the vehicle fails to reach the connection, the system shall inform the driver of the connecting vehicle and ask to wait.
User shall be informed of the consequences (e.g. repayment) of a change in the booking before they confirm the changes or cancellation.
The user shall be able to see the person from CS when talking.
The user shall be able to talk directly to customer service in case of an incident or any concerns.
The user shall be able to stop the vehicle and open the doors so they can exit the vehicle in case of an incident.
Customer service shall be able to activate and watch video feed in case of unexpected events.
The system shall inform the passengers about any unforeseen events and ask if they want to resume the ride.

The doors shall unlock automatically if the emergency stop button is pressed.
Emergency personnel shall be notified automatically when required.
The user shall get a full refund if the reason for discontinuing is the service provider's fault.
The user shall be able to report an incident
The system shall provide instructions to the pax in the event of an incident (using the dual channel principle)
The system shall send another vehicle if there is a problem with the vehicle and inform the passengers.
The vehicle shall drop (visually impaired) passengers off only at safe locations (no traffic, no puddles, no pile of snow, no sprouted bush)
The visually impaired passenger shall be informed about any obstacles between the drop-off point and their destination.
The (visually impaired) passenger shall be guided from the drop-off point to their destination.
For disembarking, the vehicle shall stop, automatically unlock the doors, and inform pax about destination PUDO (e.g. voice-over announcement or display or app)
The system (e.g., app, in-vehicle screen) shall inform the passenger that the vehicle has now reached the passenger's destination.
The vehicle shall indicate the remaining time available for disembarking (e.g. timer on the big screen, with an option to request more time)
The user shall get a reminder to ensure they remember their belongings.
The door of the full automated vehicle shall be automatically unlocked when the user is disembarking.
The doors shall indicate before they close (alert signal)
The user shall be able to request that the vehicle drives on a few meters if the PUDO is not safe to disembark (e.g. if there is a big puddle, a pile of snow, etc.)
The user shall be able to exit the vehicle without a (working) smart phone.
The vehicle shall check if it is safe before it opens the doors for passengers to disembark.
The system shall provide info about the changeover time for connecting means of transport.
The vehicle shall inform the PTO if pax do not disembark as supposed to
The user shall have the option to request additional time for disembarking.
The vehicle shall provide an alert signal when the ramp is moving.
The customer service (CS) shall be notified after a certain time if pax exceed the boarding time limit to address the situation to facilitate the movement of the vehicle.
PUDO must provide space to move on safely and be free of obstacles
When having booked for another person, the user shall be sure the passenger disembarks at the correct location.
The vehicle shall inform Customer Service if a passenger falls while disembarking.
The user shall be able to rate the experience.
The user shall be able to share the experience.
The user shall be able to report forgotten items in the vehicle.
The user shall be able to provide feedback on the service.
The user shall be able to receive a receipt of the trip.
The service shall provide a process for retrieving/returning lost items (e.g., a vehicle could bring the item back to PUDO, etc.)
The user shall be able to save a trip as a favourite.
The user shall be able to report an issue with a PUDO.
The vehicle shall provide means to store goods/packages safely so that they cannot fall or break.
The vehicle shall provide means to store goods/packages securely so they cannot be stolen.
The customer shall only have access to the correct package (to avoid they take the wrong one)
The customer shall be able to pick up a package while the vehicle does not move/drive off.
The customer shall be able to monitor their package in transit until delivery.
The vehicle shall inform the LaaS service provider if the package is not picked up.

The vehicle shall provide means to store goods/packages at the right temperature so that they will not spoil.
The customer shall be able to choose an exact time for the delivery of the parcel.
The app shall support standard accessibility features like text size and voiceover mode to guarantee access to all.
The PTO shall know the location of all vehicles.
The PTO shall be informed about events impacting passengers in real-time.
The user shall have their data protected.
The PTO shall see in real-time the status of the service.
The PTO shall have statistics on the services.
The PTO shall be able to respond to any events impacting the services.
The PTO shall be able to monitor vehicles, passengers and activities.
The system shall provide an integrated control centre in another branch. The PTO shall be able to test reliability at another location.
The PTO shall be able to communicate to passengers inside a specific vehicle.
The PTO shall be able to communicate to passengers inside all vehicles in an area.
The PTO shall be able at all times to remotely stop the vehicle and open the doors.
The PTO shall be able to remotely manoeuvre the vehicle to a safe location at low speeds.
The PTO shall be able to remotely manoeuvre the vehicle at low speeds to overcome an obstacle.
The PTO must be the only one to remotely manoeuvre vehicles.
The PTO shall be able to remove operators from vehicles to make certain services financially viable.
The PTO shall be able to easily integrate new vehicles procured from different manufacturers.
The services shall be able to reroute to pick up other demands (pax?)
The services shall be able to dispatch vehicles adapted to passengers with special needs when required.
The services shall be able to make predictions to have the right equipped vehicle already in the area when a booking is made with special needs.
The services shall be integrated into the existing transport services.
The PTO shall communicate connecting options between conventional PT and OnDemand Services.
The PUDOs shall be maintained for safe boarding/disembarking (e.g. clear of ice and snow, treated with salt to prevent slippery conditions, etc.)
The PTO shall be alerted if there are any problems with any of the vehicles.
The PTO shall be alerted if there are any problems with the fleet management software.
The PTO shall be alerted if there are any traffic problems on the route.
The PTO shall see the status of the fleet.
The PTO shall see the status of each vehicle (in-vehicle camera, sensors, outside camera for 360 views, etc.): overview plus the option to have a closer look.
The PTO shall be able to see the interior of the vehicle.
The PTO shall be alerted if the system detects any anomalies with passengers or objects in the vehicle.
The system shall highlight relevant pax/objects in the camera feed if an anomaly is detected.
The PTO shall be able to quickly contact an ambulance if required.
The PTO shall be able to request a maintenance team, if required, with all relevant monitoring data included in the request.
The PTO shall be able to identify passengers.
All audio and video recordings shall be encrypted, securely stored, and accessible only by authorised personnel.
The system shall add "smart" annotations to the audio and video recordings.
The PTO shall be able to monitor seatbelt and seat sensors.
The system shall alert CS if it detects littering.

The system shall alert CS if it detects low air quality.
The system shall alert CS if it detects temperature outside the specified range.
CS staff shall be trained for disability awareness and accessible communication.
The PTO shall provide means of communication for all, e.g., mute, deaf, or visually impaired passengers.
The system shall dispatch vehicles with special features only when needed by users with special needs or when all other vehicles are in use in order for them to be as highly available as possible.
The PTO shall be able to monitor the battery status of all fleet vehicles.
The system shall send vehicles with low battery to the depot for charging.
The system shall make sure the vehicles are operational with charged batteries during peak hours.
The system shall alert if the battery status of a vehicle is below a certain threshold.
The vehicle shall be able to detect if the number of occupied seats deviates from the number of registered passengers in the vehicle ("ghostriders")
The vehicle shall be able to interact with elements of infrastructure.
The vehicle shall be able to interact with the depot it is entering/leaving.
The vehicle shall be able to interact with barriers and gates.
The vehicle shall be able to interact with traffic lights equipped with V2X.
The vehicle shall be able to interact safely with other road users.
The vehicle shall provide handles for passengers to hold on to when getting to the seat/door.
The vehicle shall be clean.
The vehicle shall provide clean air throughout the journey.
The vehicle shall provide a pleasant temperature throughout the journey.
The in-vehicle screen shall be designed with a size that allows for easy readability of information.
The seating arrangement in the vehicle shall provide some separation between passengers (e.g., include separators between side-by-side seats)
The vehicle shall provide emergency equipment like a window breaker, and fire extinguisher (the vehicle shall meet all regional safety standards)
The vehicle shall be equipped with onboard cameras, microphones and speakers.
The vehicle shall be able to detect forgotten items (and inform the owner if ownership is known?)
The vehicle shall have a wheelchair ramp with the appropriate gradient so that a wheelchair user can board and disembark without assistance.
The vehicle shall have an identifier (unique, easy to identify, accessible)
The vehicle shall be able to interact with the passenger app.
The in-vehicle screen shall provide sufficient contrast.
The vehicle shall get the user to their destination significantly faster than walking.
All systems shall be secured against cyber attacks.
The vehicle shall have space for passengers using wheelchairs, mobility aids, strollers, etc.
The vehicle shall have means to secure wheelchairs, mobility aids or, strollers, etc.
The vehicle shall provide data like battery status, etc., to other systems.
The passenger shall be able to comfortably transport their shopping.
The doors shall indicate when they open (alert signal). The signal shall... • be clearly audible to persons inside the train and outside the train • be clearly visible to persons inside and outside the train • last for a minimum of 3 s from the moment that the door starts to open
Doors or the outline of doors operated by passengers shall be detectable by the visually impaired on the outside of the vehicle.
Doors shall recognise objects of 1.5 cm diameter over the entire height (white cane or dog leash).

Automatic and semi-automatic doors shall incorporate devices that detect if they close on a passenger. Where a passenger is detected, the doors shall automatically stop and remain free for a limited period of time.
If the passenger enters or leaves the vehicle while the door is closing, the closing process shall be interrupted automatically and the door shall return to the open position.
Door controls, whether manual, pushbuttons or other devices, shall contrast with the surface on which they are mounted.
A door control device shall have a visual indication on or around it when enabled and shall be operable by the palm of the hand exerting a force not greater than 15 N. It shall be identifiable by touch (for example, tactile markings); this identification shall indicate the functionality.
Displays shall be sized to show individual station names or words of messages. Each station name or words of messages shall be displayed for a minimum of 2 seconds.
If a scrolling display is used (either horizontal or vertical), each complete word shall be displayed for a minimum of 2 seconds, and the horizontal scrolling speed shall not exceed 6 characters per second
Displays shall be designed and assessed for an area of use defined by the maximum viewing distance according to the following formula: Reading distance in mm divided by 250 = font size (for example: 10 000 mm/250 = 40 mm).
Volume of acoustical announcements shall adjust automatically depending on the noise level in the vehicle.
The spoken information shall have a minimum STI-PA level of 0,45, in accordance with the specification referenced in Appendix A, index 5 (TSI/PRM 4.1.2.11).
The spoken information shall have a minimum RASTI level of 0,5, in accordance with IEC 60268-16 part 16, in all areas.
Where provided, spoken information shall be consistent with essential visual information that is being displayed.
Where spoken information is not provided automatically, an audible communication system shall be provided to allow users to get information upon request.
Acoustic passenger information must be easily understandable for the hearing impaired, and in particular, appropriate acoustic announcements in passenger compartments must be provided. If necessary, they must be repeated or be repeatable on demand.
The vehicle shall clearly indicate its status while waiting or boarding (e.g., hazard lights or blinker)
The vehicle shall inform the PTO about forgotten items and provide any available information about them (e.g. video sequences, data of owner)
The vehicle shall have smooth braking behaviour.
The system shall detect incidents in the vehicle (unconscious pax, fighting, fire, vandalism, attacks, etc.)
The system shall inform the PTO about any detected incidents.
The vehicle shall be able to detect if sensors are damaged or dirty (and inform the PTO)
The vehicle shall be able to go above 70 km/h while still being safe for passengers and its environment.
The vehicle shall be able to accommodate at least # passengers (number of pax to be defined per site)
The vehicle shall be able to monitor its own health, e.g., tyre pressure, (and inform the PTO)
The vehicle shall be able to operate without human intervention under most or all driving conditions.
The vehicle shall have advanced sensor systems, including cameras, lidar, radar, and other relevant sensors, to accurately detect and monitor its surroundings in real time.
These sensors should provide comprehensive coverage and be capable of recognising various objects, such as pedestrians, cyclists, and other vehicles, within the detected environment.

The vehicle should employ sophisticated algorithms and artificial intelligence (AI) techniques to process sensor data and plan safe and efficient routes, considering dynamic traffic situations, obstacles, and unforeseen events.
The vehicle should make real-time decisions based on the processed data, ensuring it responds appropriately to the ever-changing conditions of the road.
The vehicle shall have redundant systems, both hardware and software, to ensure fault tolerance and reliability. Redundancy may include duplicate sensors, redundant computing systems, and backup power supply to prevent critical failures and enable safe operation in the event of component malfunctions.
The vehicle shall have robust cybersecurity measures to protect against potential hacking or unauthorised access --> secure communication protocols, encryption techniques, intrusion detection systems, and regular security updates.
The vehicle must adhere to applicable regulatory standards and requirements specific to autonomous driving. This may involve obtaining necessary certifications, passing safety assessments, and meeting specific guidelines established by transportation authorities.
The vehicle shall have undergone rigorous testing.
The vehicle shall have robust safety protocols in place, including collision avoidance systems, emergency braking mechanisms, and fail-safe mechanisms to mitigate risks and protect passengers, pedestrians, and other road users in critical situations.
The vehicle shall be able to operate in difficult weather conditions: Extremes Temperature, Rain and Wet Conditions, Snow and Ice, Strong Winds, Fog and Reduced Visibility, Off-Road Capability, Salt and Corrosion Resistance
The vehicle shall be able to operate in difficult traffic situations: Heavy Traffic Congestion, Urban Street Gridlock, Highways and Interchanges, Roundabouts and Traffic Circles, Busiest Intersections, Emergency Vehicle Response
The vehicle shall use standardised HD maps.
The blind passenger, accompanied by his dogs, has a special place to seat his dog comfortably.
Passengers can suggest temporary decorations/designs for the shuttle.
Passengers would like to have access to entertainment activities to make better use of their travel time (e.g. eating an ice cream in summer, drinking a hot beverage in winter, etc.).
The vehicle must be able to transport goods from the store to the customer (vegetable baskets from farmers, etc.).
Each vehicle should have a specific interior design (colour, world) to differentiate them and encourage passengers to discover the different shuttles.
Passengers can book a shuttle at any time of the day or night.
The vehicle can be used occasionally as an escape game to raise awareness among young people of the mobility issues of the future.
Passengers would like to participate in discovery days for automated vehicles, to be reassured about safety.
Passengers can indicate preferences for sharing the shuttle (women only, etc.) to ensure the safety of certain categories of the population and sexual minorities.
For special events (Pink October, Gay Pride, Marathon, etc.), the vehicle could be decorated (colour, world) to attract the interest of passers-by.
The vehicle easily connects the most frequented areas of the villages, i.e. homes or schools, with shops and tram/bus stations.
The vehicle must be able to carry medicines to deliver to pharmacies.
Passengers can add interests to their profile to connect with other passengers (I like chatting, I like silence, I like listening to my music, etc.)
Passengers can see in advance with whom they will be sharing the vehicle to see if they have common interests.
Passengers can indicate their particular needs (luggage, shopping, dog, stroller, surfboard, bike) on their profiles to reserve additional space in the vehicle.
Vehicles could be equipped with comfortable seats.
Passengers want to be able to recharge their electronic devices during their trip.

The vehicle shall be able to detect abnormal events occurring inside the shuttle.
The operator or the security supervisor shall be notified upon detection of an abnormal event.
The commuter shall receive appropriate notifications and/or instructions to implement actions accordingly, in case of an abnormal event.
The vehicle shall be able to track luggage for the entirety of the route.
The vehicle shall be able to identify luggage that have been unmoved from their designated position for a prolonged period of time, and the security operator shall receive a notification to intervene accordingly.
In case of a bag snatch detection scenario, the operator shall decide to stop the vehicle or notify the commuters via the radio system.
The vehicle shall be able to identify a commuter that is committing vandalism inside the shuttle and notify the operator accordingly.
In case of a vandalism detection scenario, the operator shall warn the commuter responsible through the radio system or shall request the security personnel to intervene by stopping the vehicle.
The vehicle shall be able to identify if any commuter is fighting inside the shuttle and notify the operator accordingly.
In case of a fighting scenario, the operator shall decide to provide a verbal warning to the commuter(s) via the radio system or stop the vehicle.
The vehicle shall be able to receive colour depth images of the commuters and feed the given colour depth images of the commuters to the system's video analytics algorithms in order to identify the commuters.
The caretakers/family members of the commuter shall be able to monitor if they are inside the vehicle via a designated dashboard or a mobile app and receive notifications.
The caretakers/family members shall be able to know the designated route of the trip in which their patient/family member travels by knowing the ID of the vehicle.
Each caretaker/family member shall be able to add people to the commuter's guarded list.
The vehicle should collect data from in-vehicle sensors to assess air quality, temperature, humidity, and smoke levels and transmit the data to the dedicated ULTIMO platform.
The system should analyse the data and detect deviations from acceptable environmental conditions.
The system should trigger notifications to passengers and operators if unacceptable environmental conditions are detected.
The PTO should know the number of passengers at any given time.
The vehicle should collect passenger presence data.
The vehicle should transmit passenger occupancy data to the ULTIMO Data Management Platform.
The vehicle should detect the passenger presence and allocation using in-vehicle sensors.
The commuter should be able to know a vehicle's capacity and occupancy in advance.
The PTO shall know the number of onboarding and offboarding passengers at every stop.
The PTO shall communicate with the ULTIMO Data Management Platform for efficient booking and scheduling.
The PTO shall be able to schedule routes efficiently, depending on the commuters' demands.
The system should be adaptable to different autonomous vehicle models and manufacturers.
The system should maintain a historical log of deviations over time, allowing for trend analysis.
The system should be able to perform automatic HVAC interventions based on the environmental parameters.
The system should be able to measure occupants' body temperature using thermal cameras.
The system should inform passengers that may be unwell in a discrete way.
Passengers should receive real-time notifications if their body temperature increases.
The system should be able to keep track of passengers through their electronic tickets.

The system should be able to count occupants using either electronic tickets or image recognition algorithms.
Passengers and environmental data should be securely transmitted and stored to prevent unauthorised access.
The commuter shall receive notifications considering the vehicle capacity and availability.
The operator could change the commuter allocation in the seats.
The operator should provide a system that recognises “thumbs up” and “thumbs down” as positive and negative feedback, respectively.
The operator should provide a user manual/training for commuters on how to use the feedback system.
The operator should ensure that the “Smart Feedback” service can be integrated into all the autonomous shuttles in their fleet.
The service shall provide a visual indicator (e.g. green LED) confirming that the feedback was submitted successfully.
The service provider shall ensure that this service does not disrupt the commuter safety and does not interfere with the journey completion.
The service provider shall embed the feedback outcome to an app or website to track service improvements.
The service could allow commuters to provide detailed comments and share their experience via voice feedback, along with the hand gestures.
The service could expand the feedback system to include a wider range of gestures.
The service could integrate facial recognition and / or sentiment analysis algorithms for more accurate feedback.
The service could utilise machine learning algorithms to identify recurring issues and proactively suggest improvements.
The service could allow commuters to provide feedback on specific parts of the journey.
The service could allow operators to respond directly to passenger feedback.
The service could offer multi-language support for diverse demographics and better inclusion.
The abnormal events should be verified and recorded.
The intervention team should be able to provide appropriate services to the passengers, the vehicles, the personnel as well as the infrastructure.
The intervention team should be able to provide suggestions and guide passengers to safety away from unexpected situations.
The prediction software will notify for the anticipation of an unexpected event in the near future.
The software will suggest the appropriate team to be dispatched.
The management centre will verify the suitability of the team and will invite the team to intervene.
The abnormal events should be verified and recorded for future use from the software.
The AV should transmit location, speed, traffic and VRUs data to the ULTIMO Data Management Platform.
The RSU should transmit connected VRUs, traffic, road conditions and AVs relevant data to the ULTIMO Data Management Platform.
The RSU should transmit warning messages.
The AV shall detect the line of sight connected VRUs using OBUs signal detection and processing.
The AV shall detect other vehicles using sensors.
The VRU shall detect connected AVs using V2X-compatible hardware devices.
The RSU could estimate the number of nearby pedestrians and vehicles.
The vehicle should collect non-connected VRUs and traffic-relevant data.
The RSU should detect vehicles and pedestrians through cameras and active sensors.
Telecommunications professionals should be able to estimate the map of the active jammer positions at the given time.

Telecommunications professionals should be able to take advantage of the equilibrium state of the antenna network in order to route the transmitted telecommunications messages along low interference paths.
The management should be aware of any jamming attack over a given threshold of interference.
The vehicle shall monitor the distance covered.
The operator shall have secure access to generated maintenance insights, enabling them to make informed decisions about fleet maintenance.
The vehicle should utilise predictive models to forecast when specific components or systems may require maintenance.
The vehicle should employ advanced data analysis techniques and algorithms to process and interpret the collected data, identifying patterns and anomalies.
The vehicle must gather real-time data from various vehicle sensors and systems, including engine performance, tyre pressure, brake health, battery health and more.
The vehicle shall react on a collision risk detected by the infrastructure.
The RSU should transmit non-connected VRUs, traffic and AVs relevant data to the ULTIMO Data Management Platform.
The cybersecurity system shall integrate an Intrusion Detection System (IDS) to monitor network traffic for suspicious activity.
The cybersecurity IDS shall generate real-time alerts for any detected threats or anomalies.
The system shall allow Vehicle Owners and Operators to view IDS alerts and notifications through onboard interfaces or mobile applications.
The system shall ensure that the IDS operates effectively under various network conditions and loads.
The operator shall be able to input historical passenger demand data into the system for analysis.
The system shall allow the operator to customise time parameters, specifying the time range for demand predictions (next hour, next day, next week).
The system shall integrate real-time weather data to enhance the accuracy of passenger demand forecasts.
The system shall calculate and display accuracy metrics, including confidence levels and error rates, to assist operators in evaluating the reliability of predictions.
The system shall integrate with existing planning tools and systems used by operators for seamless data flow and enhanced transportation management efficiency.
The operator shall receive real-time updates on demand forecasts, allowing them to adapt transportation services to sudden changes or events.
The operator shall have the ability to select and apply different machine learning algorithms for demand forecasting based on their preferences and system requirements.
The system shall be able to detect and identify individuals within public transportation facilities or vehicles who are not wearing masks.
The service shall provide real-time notifications to intervention teams when public health measures, such as mask-wearing, are violated.
The system shall monitor and assess the distance proximity between individuals within public transportation settings to ensure compliance with recommended social distancing guidelines.
The operator shall facilitate communication and coordination among intervention teams, providing them with relevant information and instructions for responding to health violations.
The operator shall monitor and enforce in-vehicle hygiene standards, including cleanliness and sanitation measures, to ensure a safe and healthy environment for passengers.
The operator shall alert intervention teams and transportation authorities when in-vehicle hygiene standards are unmet, triggering appropriate corrective actions.
The intervention team shall implement a public communication interface to inform passengers about the importance of adhering to public health measures and hygiene standards.

Include a reporting mechanism for passengers to notify authorities of observed health violations or concerns within public transportation facilities.
The service provider shall design the system to be scalable, accommodating the diverse needs of different types and scales of public transportation systems.
The operator shall ensure the system can adapt to evolving health guidelines and recommendations, allowing for updates and modifications as public health knowledge advances.
The system shall be capable of detecting and identifying in-vehicle accidents, capturing relevant details such as location, severity, and involved vehicles.
The service provider shall design the system to be scalable, accommodating the diverse needs of different types and scales of public transportation systems.
The operator shall ensure the system can adapt to evolving health guidelines and recommendations, allowing for updates and modifications as public health knowledge advances.
The system shall be capable of detecting and identifying in-vehicle accidents, capturing relevant details such as location, severity, and involved vehicles.
The passenger shall be able to report out-of-vehicle accidents, providing information such as location, description, and any injuries or hazards present.
The operator shall monitor for accidents occurring on the road, utilising sensors, surveillance, or user reports to identify incidents.
The operator shall promptly notify the corresponding intervention teams (emergency services, law enforcement, etc.) about the occurrence of accidents, providing detailed information.
The system shall continuously track and update the location of accidents, allowing intervention teams to reach the scene quickly.
The system should establish communication channels with emergency services to facilitate coordinated responses and provide real-time information on accident situations.
The operator could enable users and intervention teams to upload photos or videos of the accident scene to aid assessments and documentation.
The operator shall send alerts to relevant authorities and navigation services to inform about road closures resulting from accidents.
The system could with traffic management systems to dynamically adjust traffic signals and control systems based on accident information.
The users could have the option to provide emergency contact information, facilitating communication with family members or designated contacts in the event of an accident.
The service shall implement privacy controls to protect sensitive information related to accidents and ensure compliance with data protection regulations.