Autonomous Vehicles to Evolve to a New Urban Experience

DELIVERABLE

D8.12 Sustainability assessment

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Acronyms

ADS	Automated Driving Systems
AM	Automated minibus
API	Application Programming Interfaces
AV	Automated Vehicle
BEV	Battery electric vehicle
CAPEX	Capital expenditure
CH4	Methane
CO	Carbon Monoxide
CO2	Carbon dioxide
EU	European Union
EV	Electric vehicle
GHG	Greenhouse gases
GNSS	Global Navigation Satellite System
H2020	Horizon 2020
ICEV	Internal combustion engine vehicle
ITS	Intelligent Transportation System (ITS)
LCA	Life Cycle Assessment
LiDAR	Light Detection And Ranging
MaaS	Mobility-as-a-Service
N20	Nitrous Oxide
NMVOC	Non-methane volatile organic compounds
NO	Nitric oxide
OPEX	Operational expenditure
pkm	Passenger-kilometre
PM	Particular matter
PRM	People with reduced mobility
PTO	Public transport operator
PUDO	Pick-up and drop-off
QALY	Quality-adjusted life-year
RF	Risk factor
SAE	Society of Automotive Engineers
SAEV	Shared automated electric vehicle
SAV	Shared automated vehicle
SDG	Sustainable Development Goals
SUMI	Sustainable Urban Mobility Indicators
SUMP	Sustainable Urban Mobility Plan
TCM	Total Cost of Mobility
TCO	Total Cost of Ownership
TDM	Travel Demand Management
V2I	Vehicle to Infrastructure
Vkm	Vehicle-kilometre
VKT	Vehicle Kilometer Travelled
WBCSD	World Business Council for Sustainable Development
WP	Work Package
WTT	Whell to tank

Executive Summary

This deliverable presents the sustainability assessment of the AVENUE project and demonstrator sites. The goal of the sustainability assessment is to integrate and inter-relate the results of the social, environmental and economic impacts conducted on WP8 and to embed these results by applying the set of indicators for sustainability assessment of the automated minibuses within the AVENUE demonstrator sites. In addition, concepts such as externalities, scenarios for assessment and Sustainable Urban Mobility planning (SUMP) are also building blocks for the sustainability assessment. Thereafter, it is also part of the deliverable discussion on strategies and policy instruments for the integration of automated minibuses in urban mobility.

The study is structured into seven main chapters. Chapter 1 introduces the aims and context of AVENUE project, as well as the current operation and capabilities of automated vehicles. Chapter 2 contextualises the sustainability assessment and places it into the context of the Sustainable Urban Mobility Plans (SUMP). SUMPs are a cornerstone of European transport policy and are an important planning tool for municipalities and authorities in the EU. After an introduction of the SUMP concept and a critical review of the automated minibus service in the wider SUMP context, this section depicts the alignment of the AVENUE project and the SUMP concept. This alignment is constructed through a mutual embracement of new and alternative modes of transport and new concepts such as Mobility as a Service (MaaS), integrated and shared mobility, and multi and intermodal mobility. In a second major part of chapter 2, we contextualise this deliverable in the broader WP8 framework, the research approach and conclude with an overview of the main findings of the environmental, economic and social impact assessments.

Chapter 3 details the methodology and presents the final results of the multi-dimensional set of indicators for sustainability assessment of the automated minibuses. The results are illustrated via mobility radars for each pilot site of the AVENUE project. Next, chapter 4 presents the externalities impacts of different deployment scenarios for the automated minibus. Chapter 5 applies the set of indicators for assessment of future scenarios: integrated or competing with the transport system. Chapter 6 addresses strategies and recommendations for the deployment of automated minibuses according to the goals and principles of SUMP and the Green Deal. Ultimately, chapter 7 presents the conclusions.

1 Introduction

AVENUE aims to design and carry out full-scale demonstrations of urban transport automation by deploying, for the first time worldwide, fleets of Automated minibuses in low to medium demand areas of 4 European demonstrator cities (Geneva, Lyon, Copenhagen and Luxembourg) and 2 to 3 replicator cities. The AVENUE vision for future public transport in urban and suburban areas, is that Automated vehicles will ensure safe, rapid, economic, sustainable and personalised transport of passengers. AVENUE introduces disruptive public transportation paradigms on the basis of on-demand, door-to-door services, aiming to set up a new model of public transportation, by revisiting the offered public transportation services, and aiming to suppress prescheduled fixed bus itineraries.

Vehicle services that substantially enhance the passenger experience as well as the overall quality and value of the service will be introduced, also targeting elderly people, people with disabilities and vulnerable users. Road behaviour, security of the Automated vehicles and passengers' safety are central points of the AVENUE project.

At the end of the AVENUE project four-year period the mission is to have demonstrated that Automated vehicles will become the future solution for public transport. The AVENUE project will demonstrate the economic, environmental and social potential of Automated vehicles for both companies and public commuters while assessing the vehicle road behaviour safety.

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 around the world are defining strategies for the development of 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 very promising to the support of regional strategies for the development of public transport.

On-demand transport is a public transport service that only works when a reservation has been recorded and 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 takes care of the booking, planning and organization.

It is recognized that the use and integration of on-demand Automated vehicles has 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.

1.2 Fully Automated Vehicles

A self-driving car, referred in the AVENUE project as **a Fully Automated Vehicle** (**AV**), also referred as Autonomous Vehicle, is a vehicle that is capable of sensing its environment and moving 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 AVENUE we operate ***Fully Automated minibuses for public transport***, (previously referred as Autonomous shuttles, or Autonomous buses), and we refer to them as simply *Automated minibuses* or *the AVENUE minibuses.*

In relation to the SAE levels, the AVENUE project will operate SAE Level 4 vehicles.

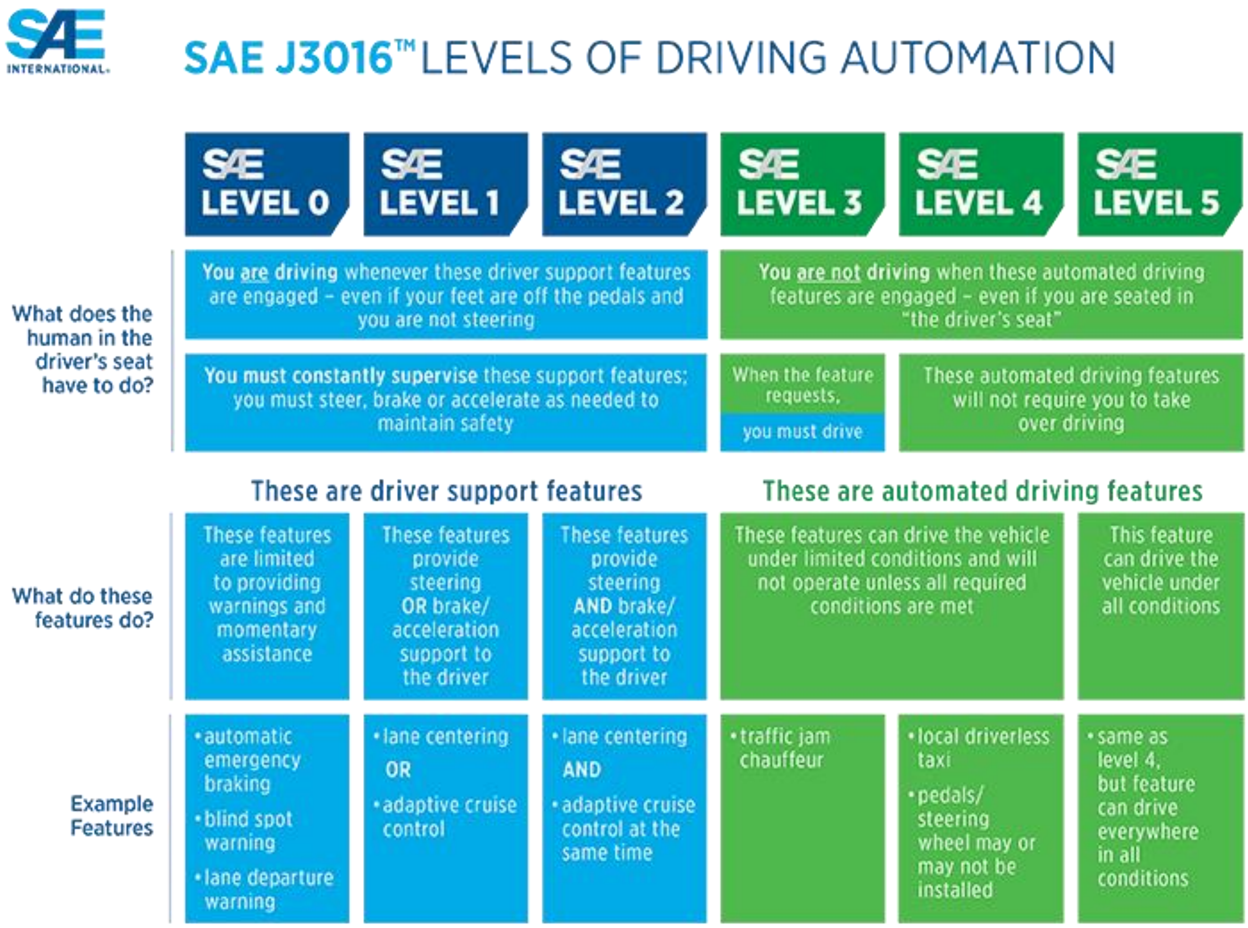

Table 1. SAE Driving Automation levels (©2020 SAE International)

1.2.1 Automated vehicle operation overview

We distinguish in AVENUE two levels of control of the AV: micro-navigation and macro-navigation. Micro navigation is fully integrated in the vehicle and implements the road behaviour of the vehicle, while macro-navigation is controlled by the operator running the vehicle and defines the destination and path of the vehicle, as defined the higher view of the overall fleet management.

For micro-navigation Automated Vehicles combine a variety of sensors to perceive their surroundings, such as 3D video, LIDAR , sonar, GNSS, odometry and other types sensors. Control software and systems,

integrated in the vehicle, fusion and interpret the sensor information to identify the current position of the vehicle, detecting obstacles in the surround environment, and choosing the most appropriate reaction of the vehicle, ranging from stopping to bypassing the obstacle, reducing its speed, making a turn etc.
For the Macro-navigation, that is the destination to reach, the Automated Vehicle receives the information from either the in-vehicle operator (in the current configuration with a fixed path route), or from the remote control service via a dedicated 4/5G communication channel, for a fleet-managed operation. The fleet management system takes into account all available vehicles in the services area, the passenger request, the operator policies, the street conditions (closed streets) and send route and stop information to the vehicle (route to follow and destination to reach).

1.2.2 Automated vehicle capabilities in AVENUE

The Automated vehicles employed in AVENUE fully and automatically manage the above defined, micro-navigation and road behaviour, in an open street environment. The vehicles are Automatically capable to recognise obstacles (and identify some of them), identify moving and stationary objects, and Automatically decide to bypass them or wait behind them, based on the defined policies. For example with small changes in its route the AVENUE mini-bus is able to bypass a parked car, while it will slow down and follow behind a slowly moving car. The AVENUE mini-buses are able to handle different complex road situations, like entering and exiting round-about in the presence of other fast running cars, stop in zebra crossings, communicate with infrastructure via V2I interfaces (ex. red light control).
The mini-buses used in the AVENUE project technically can achieve speeds of more than 60Km/h. However this speed cannot be used in the project demonstrators for several reasons, ranging from regulatory to safety. Under current regulations the maximum authorised speed is 25 or 30 Km/h (depending on the site). In the current demonstrators the speed does not exceed 23 Km/h, with an operational speed of 14 to 18 Km/h. Another, more important reason for limiting the vehicle speed is safety for passengers and pedestrians. Due to the fact that the current LIDAR has a range of 100m and the obstacle identification is done for objects no further than 40 meters, and considering that the vehicle must safely stop in case of an obstacle on the road (which will be “seen” at less than 40 meters distance) we cannot guarantee a safe braking if the speed is more than 25 Km/h. Note that technically the vehicle can make harsh break and stop with 40 meters in high speeds (40 -50 Km/h) but then the break would too harsh putting in risk the vehicle passengers. The project is working in finding an optimal point between passenger and pedestrian safety.
Due to legal requirements a **Safety Operator** must always be present in the vehicle, able to take control any moment. Additionally, at the control room, a **Supervisor** is present controlling the fleet operations. An **Intervention Team** is present in the deployment area ready to intervene in case of incident to any of the mini-busses. Table 2 provides and overview of the AVENUE sites and OODs.

	Summary of AVENUE operating sites demonstrators						
	TPG		Holo		Keolis	Sales-Lentz	
	Geneva		Copenhagen	Oslo	Lyon	Luxembourg	
Site	Meyrin	Belle-Idée	Nordhavn	Ormøya	ParcOL	Pfaffental	Contern
Funding	TPG	EU + TPG	EU + Holo	EU + Holo	EU + Keolis	EU + SLA	EU + SLA
Start date of project	August 2017	May 2018	May 2017	August 2019	May 2017	June 2018	June 2018
Start date of trial	July 2018	June 2020	September 2020	December 2019	November 2019	September 2018	September 2018
Type of route	Fixed circular line	Area	Fixed circular line	Fixed circular line	Fixed circular line	Fixed circular line	Fixed circular line
Level of on-demand service*	Fixed route / Fixed stops	Flexible route / On-demand stops	Fixed route / Fixed stops	Fixed route / Fixed stops	Fixed route/Fixed stops	Fixed route / Fixed stops	Fixed route / Fixed stops
Route length	2,1 km	38 hectares	1,3 km	1,6 km	1,3 km	1,2 km	2,3 km
Road environment	Open road	Semi-private	Open road	Open road	Open road	Public road	Public road
Type of traffic	Mixed	Mixed	Mixed	Mixed	Mixed	Mixed	Mixed
Speed limit	30 km/h	30 km/h	30 km/h	30 km/h	8 to 10 km/h	30 km/h	50 km/h
Roundabouts	Yes	Yes	No	No	Yes	No	No
Traffic lights	No	No	No	No	Yes	Yes	Yes
Type of service	Fixed line	On demand	Fixed line	Fixed line	Fixed line	Fixed line	Fixed line
Concession	Line (circular)	Area	Line (circular)	Line (circular)	Line (circular)	Line (circular)	Line (circular)
Number of stops	4	> 35	6	6	2	4	2
Type of bus stop	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed
Bus stop infrastructure	Yes	Sometimes, mostly not	Yes	Yes	Yes	Yes	Yes
Number of vehicles	1	3-4	1	2	2	2	1
Timetable	Fixed	On demand	Fixed	Fixed	Fixed	Fixed	Fixed
Operation hours	Monday-Friday (5 days)	Sunday-Saturday (7 days)	Monday-Friday (5 days)	Monday-Sunday (7 days)	Monday-Saturday (6 days)	Tuesday & Thursday Saturday, Sunday & every public holiday	Monday - Friday
Timeframe weekdays	06:30 – 08:30 / 16:00 – 18:15	07:00 – 19:00	10:00 – 18:00	7:30 – 21:30	08:30 – 19:30	12:00 – 20h00	7:00 – 9:00 16:00 – 19:00
Timeframe weekends	No service	07:00 – 19:00	No service	9:00 – 18:00	08:30 – 19:30	10:00 – 21:00	No Service
Depot	400 meters distance	On site	800 meters distance	200 meters distance	On site	On site	On site
Driverless service	No	2021	No	No	No	No	No
Drive area type/ODD	B-Roads	Minor roads/parking	B-Roads/minor roads	B-Roads	B-Roads	B-Roads	B-Roads/parking
Drive area geo/ODD	Straight lines/plane	Straight lines/ plane	Straight lines/ plane	Curves/slopes	Straight Lines/ plane	Straight lines/ plane	Straight lines/ plane
Lane specification/ODD	Traffic lane	Traffic lane	Traffic lane	Traffic lane	Traffic lane	Traffic lane	Traffic lane
Drive area signs/ODD	Regulatory	Regulatory	Regulatory, Warning	Regulatory	Regulatory	Regulatory	Regulatory
Drive area surface/ODD	Standard surface, Speedbumps	Standard surface, Speedbumps	Standard surface Speedbumps, Roadworks	Frequent Ice, Snow	Standard surface, Potholes	Standard surface	Standard surface

Table 2. Summary of AVENUE operating site (+ODD components)

1.3 Preamble

Within the scope of WP8, the AVENUE sustainability assessment integrates the environmental, economic and social assessment of the pilot trials of AVENUE. A step further adopts an interdisciplinary approach to conduct the analyses and to better understand the complexity of deploying a new form of mobility in urban areas and as part of the transportation system. The goal is to implement new mobility solutions that benefit the city and complement public transport. The findings from the social, environmental and economic impact assessments are embedded in a multi-dimensional set of indicators for sustainability assessment of the automated minibuses (AMs).

Hereinafter Chapter 2 describes the research approach for the sustainability assessment and comprises a summary of the main findings from the social, environmental and economic impact assessments.
Chapter 3 presents the sustainability assessment and the mobility radars of the AVENUE demonstrator pilot sites. Chapter 4 presents the sustainability impacts of deployment scenarios based on the concept of externalities. Chapter 5 assesses two scenarios of deployment of the automated minibuses: competing (Robotaxis) and integrated to urban mobility (AM in Mobility-as-a-Service).
Chapter 6 develops the strategies and policy instruments for the integration of automated minibuses in urban mobility. This chapter also relates to the AVENUE vision of future mobility with automated vehicles. Therefore, a short description of the automated minibuses in MaaS/ITS is presented as it is developed in AVENUE Work Package 9 'Transition Roadmap for Autonomous Vehicle in public transport'. Ultimately, Chapter 7 presents the concluding remarks.

2 The AVENUE approach to sustainability assessment

This chapter outlines the AVENUE sustainability assessment approach, starting with concepts of the Sustainable Urban Mobility Plan (SUMP) and the applied framework for assessment. Following, section 2.2 provides an overview of the main results of the WP8 tasks: insights from the environmental impact assessment, the economic impact assessment and the social impact assessment.

2.1 Concept and framework for assessing and planning sustainable urban mobility

2.1.1 SUMP as a framework

The concept of the Sustainable Urban Mobility Plan (SUMP) aims at a 'new planning paradigm' in mobility, which comprehends a shift from planning for motorised roads and infrastructure to planning for people (Arsenio et al. 2016). SUMP's approach has been widely recognised, targeting sustainable and integrative planning processes to deal with the complexity and dynamicity of urban mobility (Eltis 2021). Hence, it embraces new modes of transport, e.g. micro-mobility, automated and connected vehicles, and new concepts such as Mobility as a Service (MaaS), shared mobility and so on.

The concept of SUMP comprehends the integration of all modes of transport, public and private, motorised and non-motorised and a long-term planning vision. It targets to improve mobility accessibility, sustainability and citizens' well-being (European Commission 2013).

SUMP is defined as:

> *"a strategic plan designed to satisfy the mobility needs of people and businesses in cities and their surroundings for a better quality of life. It builds on existing planning practices and takes due consideration of integration, participation, and evaluation principles." (Rupprecht Consult 2019)*

And it is guided by eight principles (Chinellato and Morfoulaki 2019):

1) Aim of sustainable mobility for the 'functional urban area.';
2) Assessment of current and future performance;
3) Long-term vision as well as a clear implementation plan;
4) Development of all transport modes in an integrated manner;
5) Cooperation across institutional boundaries;
6) Involvement of citizens and relevant stakeholders;
7) Arrangements for monitoring and evaluation;
8) Quality assurance.

Further, SUMP provides general guidelines for planning and implementation. It is composed of four main phases: i) Preparation and context analysis; ii) Strategy development; iii) Measure planning; iv) Implementation and monitoring.

SUMP has been implemented in a number of cities and countries and in diverse settings. For instance, in the city of Koprivnica, Croatia, the municipality carried out a status analysis of its mobility situation; for this, an extensive consultation process engaged a range of stakeholders and a public survey (Mobility Plans n.d.). In Cambridgeshire, UK, the Local Transport Plan (LTP) 2011 – 2026 defined indicators and targets to monitor progress towards the plan's objectives, which were aligned with the long-term strategy for transport (ibid).

Mück et al. (2019) describe the living labs as an innovative approach to fostering sustainable mobility planning in Munich. Such living labs aim to demonstrate innovative solutions for mobility, provide user experiences, and reduce potential gaps between long-term urban planning and the current development of mobility in the city (ibid).

Sampaio et al. (2020) carried out an economic and environmental analysis of measures from a SUMP in a small-sized city. The study compared the transport emissions and external costs of the baseline scenario with the status after the SUMP measures were implemented. The measures consisted of (M1) promoting cycling, (M2) modernisation of the local fleet, (M3) trucks logistic optimisation. According to the study, all measures presented a potential to reduce emissions, in particular the modernisation of the local fleet, with a potential reduction of CO_2 emissions by 9% and the reduction of external costs by 11%.

The study from Arsenio et al. (2016) reviewed a sample of forty case studies of SUMPs in Portugal, focusing on climate change goals and equity issues on accessibility. The main findings point out that SUMP guidelines remain very broad and general, and there is an absence of specific guidance. For instance, there are gaps in guidance on methods to account for GHG emissions and monitoring indicators to measure the progress on different issues.

Such examples illustrate the SUMPS adoption and implementation in different phases: decision and planning, developing vision and strategies with stakeholders, setting targets and indicators, and assessing the impacts of measures. Although, as mentioned by Arsenio et al. (2016), the next SUMP generations may address more specific guidance and methods to strengthen SUMP's implementation.

2.1.2 SUMP concept and the AVENUE project

The AVENUE project aims at deploying automated minibuses as an innovative and safe mobility solution to strengthen the public transport system of European cities. The automated minibus is electric and shared, and it is expected to improve accessibility, attractiveness and environmental performance of public transport (flexible on-demand, door-to-door services) to fill gaps in mobility and foster multi and intermodal mobility. The scope of the project also aims to critically assess the impacts of the introduction of these new technologies in the urban mobility system. The assessments investigate the potential environmental and climate emissions impacts, social acceptance of users and potential users, business model scenarios and economic impacts, safety and security issues, and the development of regulations, standards and policies for AVs.

AVENUE project and the SUMP concept are aligned by embracing new and alternative modes of transport and new concepts such as Mobility as a Service (MaaS), integrated and shared mobility, and multi and intermodal mobility. Such innovations could support the future shift from private car and individual trips to on-demand public transport and shared rides.

Furthermore, the AVENUE social, environmental and economic impact assessments will provide key findings to guide the integration and implementation of AV in the urban mobility system while endorsing the sustainable planning, strategies and goals of cities. The assessment studies are important to support a long-term vision, design and planning of mobility. Although the pilot projects are deployed on a small scale and with a technological focus, aspects of being strengthened are the citizens' participation (e.g.

citizen forums and discussions), as well as the active participation and partnership with the local municipality.

Moreover, the integration of automated minibuses in public transport has to be done accordingly to the specificities of each territory, and the different mobility needs, aiming to cover real gaps in mobility to a real contribution to better accessibility, affordability and environment-friendly mobility.

Finally, by aiming for a transition towards greener and sustainable transport, it is crucial that AVs deployment be consistent with the Sustainable Development Goals (SDG's), namely, SDG 9 targeting to build resilient infrastructure and foster innovation, SDG 11 on sustainable cities and communities and SDG 13 Climate Change (United Nations 2015).

2.1.3 AVENUE sustainability assessment framework

This deliverable presents the AVENUE sustainability assessment within the scope of WP8. The AVENUE sustainability assessment integrates the environmental, economic and social assessment of the trials of AVENUE. It adopts an interdisciplinary approach to better conduct different analyses. It also helps to better understand the complexity of deploying a new form of mobility in urban areas and as part of the transportation system. For instance, the results of the social and economic assessments provide important insights to predict scenarios for automated vehicles and calculate direct and indirect costs. Even more, the Life Cycle Assessment (LCA) is a source of environmental data that could be used to calculate environmental externalities. In addition, the findings from the social, environmental and economic impact assessments are embedded in the indicators for sustainability assessment. To better understand the different connections, the AVENUE assessment framework is presented in Figure 1.

The framework describes three major axes: first, the data input, methods and analysis; second, the social, economic, environment and sustainability assessments; and the connections with other Work Packages tasks.

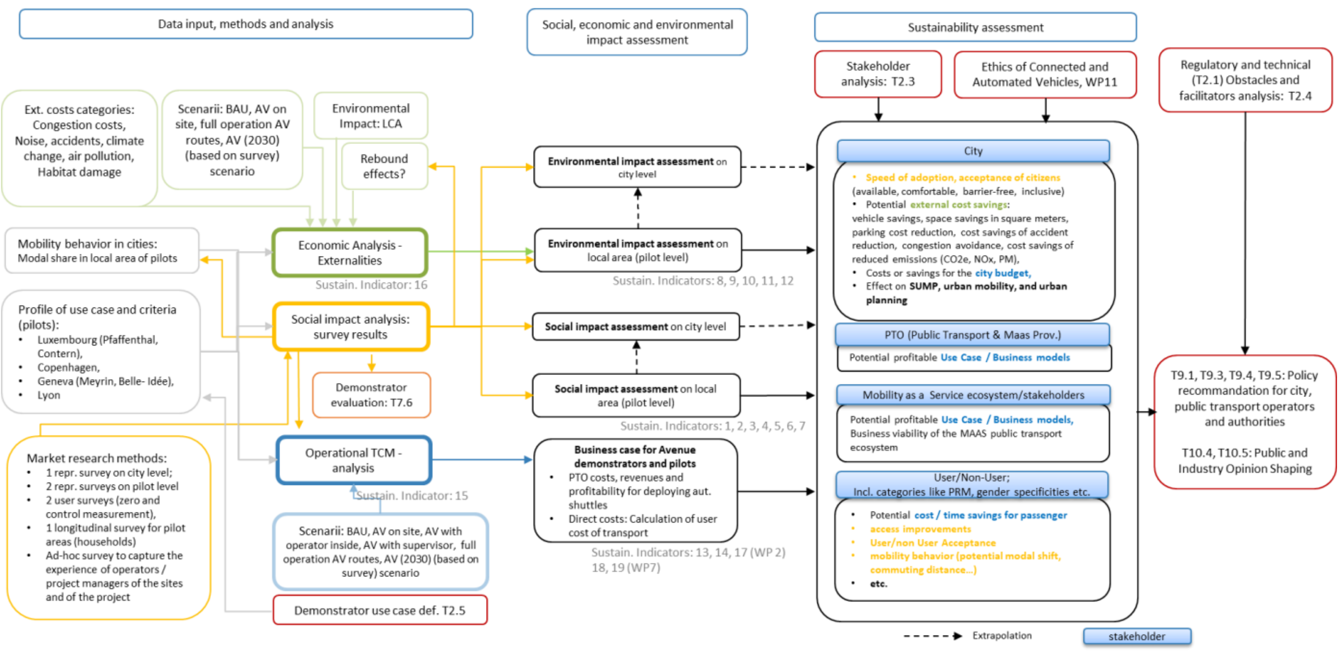

Figure 1. Framework from the AVENUE Work Package 8

Automated minibuses for public transport are expected to contribute to sustainable urban mobility. By combining automated, connected, shared, and electric technologies, the automated minibuses could improve transport accessibility, efficiency and reduction of greenhouse gases (GHG) (Jones and Leibowicz 2019). They have the potential to play a role in a shift from vehicle ownership to shared mobility services (Shaheen and Chan 2016) and to reduce transport externalities (Lim and Taeihagh 2018). Nonetheless, one cannot take for granted that the deployment of innovation and new technologies per se will contribute to sustainable mobility. It rather depends on certain premises, planning and policies to frame the automated minibuses deployment.

The study from Taiebat et al. (2018) points out main gaps concerning connected and automated vehicle impacts; for instance, the net effect of AVs technology on energy consumption and emissions in the long term remains uncertain. In addition, the broader society-level impacts and behavioural changes associated with AVs are also unclear. The study highlights that the 'synergetic effects of vehicle automation, electrification, right-sizing, and shared mobility are likely to be more significant than anyone isolated mechanism'.

AVs, especially for private use, could lead to an increase in vehicles kilometres travelled (VKT), reductions in public transport, and slow modes share (Soteropoulos et al. 2019). Whereas shared automated vehicles (SAV), when considering a high share, could reduce the number of vehicles for the current travel demand, resulting in less parking and more space in the cities (ibid). Yet, it is worth noting that the results of impact assessment for AVs are strongly dependent on model assumptions (Soteropoulos et al. 2019).

The integration of automated minibuses into the public transport of European cities also raises questions regarding their potential benefits and critical points to contribute to the sustainable urban mobility plan (SUMP) and goals towards sustainable mobility of the cities.

Hence, the goal of the sustainability assessment is to integrate and inter-relate the results of the social, environmental and economic impacts conducted on WP8 and to embed these results by applying the set of indicators for sustainability assessment of the automated minibuses within the AVENUE demonstrator sites. The SUMP and externalities concepts are also building blocks for the sustainability assessment. Figure 2 summarises the research approach for the sustainability assessment.

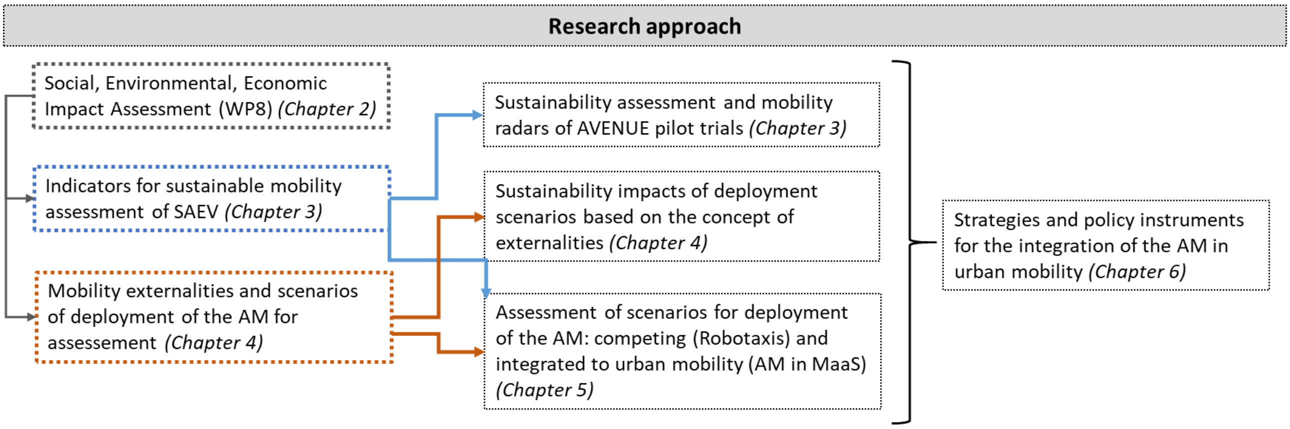

Figure 2. The AVENUE sustainability assessment approach

The next subsections summarise the main social, environmental and economic impacts associated with automated minibuses (WP8). The analysis is grounded on real-world data from the pilot test in the four European cities: Geneva, Lyon, Luxembourg and Copenhagen.

2.1.3.1 Indicators for sustainable mobility assessment

By aiming to achieve sustainable mobility, indicators are used to measure performance and progress towards established goals and objectives (Litman, 2007). Urban sustainability indicators are fundamental to support target setting, performance reviews and to enable communication among the policymakers, experts and general public (Shen et al. 2011; Verbruggen, H., Kuik O. 1991).
Hence, a set of indicators is applied for the sustainability assessment of the deployment of the automated shuttles in AVENUE pilot sites. The set of indicators was presented on D8.11 First Iteration Sustainability Assessment and in the article of Nemoto et al. (2021).
Chapter 3 details the indicators and presents preliminary indicators' radar for the pilot sites of Groupama (Lyon), Contern (Luxembourg), Pfaffenthal (Luxembourg), Nordhavn (Copenhagen).

2.1.3.2 Externalities concepts and applications to support sustainable mobility

Mobility Externalities represent the costs incurred by a third party and not borne by transport users. The negative externalities could help draft targeted public policies (i.e., urban planning and urban mobility policies) that addresses the negative effects of the transportation system (Chatziioannou et al. 2020). Using external cost estimates as a part of cost-benefit analysis helps weigh the benefits and drawbacks of introducing new policies or new forms of mobility such as automated minibuses (Jochem, Doll et Fichtner 2016). This tool relies on interdisciplinary assessment to monetise impacts such as air pollution, climate change, accidents, and congestion (European Commission 2003). These impacts have always been associated with the transportation system. The development of such systems plays an important role in government policies because transportation planning has overlapping effects on society. Thus, it should reflect potential negative externalities (Shiftan, Kaplan et Hakkert 2003). The internalisation of externalities leads to increased efficiency and reduction of negative effects of transportation. According to van Essen H.P. et al. (2008), the internalisation of these effects means incorporating them to transport users' decision-making process.
Policymakers seek to reduce the reliance on ICEV. The introduction of new modes of transport lead by electrification and automation technology presents a potential shift away from traditional and unsustainable mobility towards more sustainable options. The study of externalities leads to customised policies that address the specification of these technologies and the context of deployment (Buehler et al., 2017). The assessment depends on planning potential future scenarios of deployment and estimating the avoidance costs (of externalities), which present imputed costs of limiting the environmental damage by reducing the use of individual transport (OECD 2001; United Nations 1997). The avoidance costs (or savings) indicate if the specific scenario is recommended for future mobility. The scenario is imagined based on driving forces such as the development of the AV technology, the existing urban and mobility policies, and the modal shifts due to the minibuses (Krueger and Rashidi 2016). Thus, the externalities could orient policymakers towards the scenario to adopt and how to further reduce the environmental deterioration of the transport sector.
Moreover, other internalisation measures could help counterbalance the external costs. Trading emissions limits greenhouse gas emissions, such as the Cap & Trade scheme, where a limit is set for emissions with tradable emission rights. Also, Policy Packaging is a way to set taxes to balance the external costs like fuel taxes and road pricing. Another measure is the use of revenues (e.g. from policy packaging taxes) to make users accountable for the externalities they produce. The revenues will be directed towards

new infrastructure or improving public transport services as long as the pricing reform is conducted to increase efficiency and equity and is public acceptable (van Essen H.P. et al. 2008).

2.2 Insights from AVENUE research

As part of the WP8 assessment framework (Fig. 1), the sustainability assessment considers the main findings stemming from the three pillars and their deliverables[1]:

- 8.1 Environmental impact assessment, which presents the Life Cycle Assessment of the automated minibuses and their potential impacts considering different scenarios (Viere et al. 2022; Huber et al. 2022).
- 8.2 Economic impact assessment, based on Total Cost of Ownership (TCO) and Total Cost of Mobility (TCM) approaches and externalities cost calculations (Antonialli et al. 2022).
- 8.3 Social impacts assessment, which conducts assessments based on surveys with potential users and users, investigates social acceptance of the AM, service attractiveness, user experience and willingness-to-use (Korbee et al. 2022c).

As the fourth pillar, the 8.4 Sustainability assessment conceptualises (as presented in the D8.11 First Iteration Sustainability Assessment) and applies a set of indicators to assess the social, environmental, economic, governance, and technical impacts of the automated minibuses. The sustainability assessment also comprises the SUMP concept related to automated driving and automated minibuses for public transport.

2.2.1 Main findings from the environmental impact assessment

The investigation of the energy demand of automated driving technology and connectivity-related demand shows that, on the one hand, predictive, adaptive and information sharing through vehicle communication with infrastructure and other vehicles improves driving performance (e.g. braking performance) and, consequently, energy consumption. On the other hand, a highly connected vehicle means more data processing within and outside the vehicle, which may outweigh the V2X sustainability. Overall, the energy-saving potential of predictive driving functions is highly likely to outweigh the energy consumption for data transmission (Viere et al. 2022).

A Life Cycle Assessment (LCA) of the AM deployed within AVENUE shows that its automated technologies account for less than 5% of the total energy used. In a near-future use case, 59% of the AM impact stems from the use phase, while component production accounts for 39% (Huber et al. 2022). The use phase climate impacts are mostly due to the burning of fossil fuels to produce the electricity required for driving the AM. The global warming potential for each pkm is 78 g CO_2eq (Huber et al. 2022).

While the AM at the current pilot site deployment does not show significant environmental benefits, future use cases are very likely to improve substantially. In addition, the AM qualification as environmentally friendly depends on many factors such as occupancy, vehicle speed, mileage, and lifetime. Taking into consideration the perspective of the mobility system, the AM are seen as a complementary service in public transport (Viere et al. 2022). In combination with door-to-door, on-demand and driverless services, AM are expected to improve and strengthen public transport, hence bringing benefits by reinforcing shared, multi and intermodal mobility as well.

[1] AVENUE deliverables and publications at https://h2020-avenue.eu/public-delivrables/

2.2.2 Main findings from the social impact assessment

The social impact assessment studies (Korbee et al. 2022c) investigated the social impact of automated public transport systems and how this contributes to a changed mobility behaviour.

The results of the studies pointed out that there is no acute need for a complete substitution of current public transport offers in the perception of citizens. However, there are unfulfilled needs resulting from gaps in the current public transport offer and from individual mobility, which may be met by the automated minibuses. There are two major needs which could drive the willingness to use the automated minibuses: cognitive relief (the need for a reduction in stress and an increase in mental health) and a high level of flexibility.

The willingness to use is generally high. The analysis shows that goodwill is dominating. About half of the citizens – unreserved or sceptical goodwill – show willingness to use the automated minibuses. About a third of the citizens are still undecided but may be convinced by further communication and experience. Only a smaller part of about every fifth citizen feels reserved or is even explicitly refusing.

The results of a representative survey among 1,816 citizens (of which 1,526 have privately-owned vehicles) 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 own car to use AM to bridge the first and the last mile if this were available. If the service is on-demand and door-to-door, the acceptance could be even higher (Korbee et al. 2022a).

On the perceived concerns, we see a slightly more differentiated picture. Respondents show a high agreement with concerns regarding the functioning of the automated minibus and especially in these indicators an increase in fears of how the automated minibuses may interact with other traffic members is observed. As long as it is not really clear for many of the citizens how the automated minibuses may interact with other motorized or non-motorized traffic members, a supervisor is still expected to be very important.

The most important drivers for preference of transport systems are speed, travel time, and punctuality. It is therefore important that the automated minibus can compete with other means of transport regarding these three main factors.

Real experience in the automated minibus, has a generally positive effect on the trust in the system. A comparison of the results of the quantitative survey with potential users and the quantitative survey with users in Nordhavn shows that user experience is an important factor in reducing the perceived concerns and increasing acceptance of the automated minibus.

The AM in MaaS could better satisfy the needs of citizens and their acceptance of public transport and at the same time make transport in the cities more sustainable. Unpopular regulative or restrictive policies and measures (e.g. prohibition of vehicles) by transportation authorities could be avoided (Litman 2021a; Becker et al. 2020; Ajzen 1991; Zha et al. 2016; Fournier et al. 2022).

2.2.3 Main findings from the economic impact assessment

Based on the results presented in the final economic deliverable (Antonialli et al. 2022), the study analyses six different mobility scenarios for the integration of automated minibuses::

Sc1. Replacing all buses	Sc2. Replace all cars	Sc3. Robotaxis
Sc4. Expand network	Sc5. Targeted expansion	Sc6. AM in MaaS

A summary of the key points of the scenarios is presented in Table 3.

Table 3. Summary of the context and respective impacts of the six scenarios

Sc	Sc1	Sc2	Sc3	Sc4	Sc5	Sc6
Context	- flexible routes -fleet technologies -Policies to modernize PT -slow electrification of bus fleet - Users typical bus passengers	-on-demand, door-to-door -V2X capabilities -Policies to limit ICEV in cities -Traditional PT failing to meet passengers' demand -Users car drivers	On-demand and door-to-door -Developed fleet management and ticketing -Laissez-faire outcome -Robotaxi in competition with PT -PT failing to meet passengers' demand -Users prefer convenience and privacy	-seamless intermodal -mobility-on-demand technologies -Policies to improve PT services -limited public transportation offer -Users dependent on their cars,	-seamless intermodal -mobility-on-demand technologies -Policies to improve PT services -No suitable services in suburbia, buses running empty off-peak time -Users dependent on their cars, night workers, off-peak passengers	-On-demand first/last mile and mobility gap filler -MaaS, ticketing, API services -Public-private cooperation, sustainable mobility policies, car restrictions -Efficient long-distance PT -Users needing connections to train stations
Impact	-reduce air pollution and climate change emissions. -reduce car use and increases train ridership. -more pick-up and drop-off points city centre more attractive.	-reduce air pollution and climate change emissions. -reduce accidents rates and traffic congestion AM would be Better integration with long-distance transportation -might reduce the active mobility -less road space.	-better AV services: higher speeds, less waiting times, and more vehicles. -a mixed effect on the emissions rates. -significant reduction in accidents -improved traffic flow less active mobility and public transportation. -induced demand as a rebound effect -car-centric building environment	-increase PT modal share. -improved public transport network in suburban areas -increased population -urban sprawl -More mobility hubs to accommodate seamless and intermodal trips	-similar to Sc4 -more reduction in emissions	-increased in Public Transport (PT) ridership -reduced air pollution and climate change emissions. -reduced accidents rates and traffic congestion urban planning oriented towards more compact cities and mixed-land use -a reduction in road space.

In general, replacing all cars leads to the highest reduction in externalities (for all the external costs categories), but is highly unrealistic. People are reluctant to completely abandon their cars since cities and jobs are built around cars (Sensiba 2021). Much more realistic is the robotaxis scenario, which is defined as shared automated vehicles in numerous studies (see e.g., Fagnant and Kockelman 2018; Fournier et al. 2020). The analysis shows that the robotaxis scenario will lead to increases in external costs when deployed in competition with public transport, which is why it is also used in other deliverables as a negative scenario compared to AM in MaaS. While replacing all cars is a typical (not popular) push strategy which forbids cars in the city, AM in MaaS is a user-centric approach pull strategy.

However, for Copenhagen the most appealing scenario is the replacement of all car trips by the AM (a decrease of almost 95 million euros) (Antonialli et al. 2022). In contrast, in Lyon the emphasis should be on strengthening the public transport by deploying the AM serving seamless and intermodal trips, bridge first and last-mile gaps and enhancing connections to the rail stations. Geneva would benefit from the AM deployment in both scenarios 2 and 6 since it has the highest reduction in externalities. It could reduce car access to the city centre and introduce the AM to support public transport and replace all car trips in these areas. However, the scenario of replacing all cars is not really popular in the social impact assessment of the project, but following these surveys, the most realistic approach is to introduce the AM gradually, first as part of a MaaS service, where AM are filling existing mobility gaps rather than completely replacing individual mobility. As the users' acceptance increases, passengers would switch more and more to the AM instead of relying on their cars. If this introduction is accompanied by urban policies such as road pricing and no-car zones, it will further deter citizens from using their cars in the city centre, which would increase the modal shift to the AM, active mobility, and public transport. Finally, deploying the AM in Luxembourg also shows a reduction in externalities. This strategy fits with the canton's plans to reduce car use and improve connections to train stations to better serve cross-border travellers.

The analysis also revealed rebound effects that need to be considered in the overall context. AMs would provide passengers with a convenient, affordable and safe option. Thus, it could lead to more trips, as it provides more trips to people who were not commuting with vehicles in the first place, such as children or the elderly. In addition, it might cause a secondary modal shift after its implementation. It could reduce active mobility and public transportation shares even further than first predicted (Fagnant et Kockelman 2018). This might lead to a vicious circle of deploying more vehicles to meet the new demand. Then, as an unintended effect, more people shift to use the AM. Thus, the operators will need to deploy even more vehicles to meet the increasing demand. Thus, the AM would aggravate the traffic congestion and increase the environmental footprint. Hence, the rebound effect undermines the gains from reducing the use of individual mobility by causing new external costs because of reducing walking, biking, and public transport trips. Ergo, it is crucial that the deployment is accompanied by a regulatory framework to monitor the introduction of the AV in the transportation system and reduce potential rebound effects. These results of the externalities and scenarios model help orient policymakers to which strategies to adopt.

3 Final Sustainability assessment of the AVENUE demonstrator pilot sites

The sustainability assessment builds upon the set of indicators (Table 4) developed by Fournier et al. (2019) and Nemoto et al. (2021). This section presents the methods and the mobility radars for each pilot site based on the empirical data from the trials. The five sites assessed comprise Groupama (Lyon), Contern (Luxembourg), Pfaffenthal (Luxembourg), Nordhavn (Copenhagen). The assessment comprehends the mobility multi-dimensions: social, environmental, economic, governance and technical system performance.

Table 4. Set of indicators for sustainable mobility assessment of shared automated electric vehicles from Nemoto et al. (2021).

		Multidimensions				
Indicators	**Unit and methods of measurement**	**S**	**En**	**Ec**	**G**	**SP**
Accessibility	• Percentage of the city (area) coverage by the AM service • Percentage of the population that has convenient access (within 0.5 km) to the AM service					
	• AM digitally accessible (e.g. via apps)					
Accessibility for people with reduced mobility	• External environment facilities e.g., stops adaption for impaired/disabled people; tactile surfaces information • Internal environment facilities e.g., audible warning equipment for visually impaired people; facilities for wheelchair users					
	• Usability of the SAEV by people with reduced mobility (PRM) • Rating of users with reduced mobility concerning the AMexperience					
Safety	• Risk factor and number of accidents related to the AM (mild injuries, serious injuries, fatalities) considering internal risk (related to passengers) and external risk (related to other road users, pedestrians and cyclists)					
Security	• Number of criminal occurrences; nr/year					
	• Number of cybersecurity threats or attacks; nr/year					
Passenger's affordability	• The price of the ride on the AM					
Social acceptance	• User's perception about the readiness of the technology • User's willingness to pay • Safety feeling • Security feeling					
User satisfaction	• User rating concerning AM experience (comfort, speed, punctuality, information, frequency, connection to other means of transport)					
Energy efficiency	• Energy consumed for passenger per km (kWh/pkm)					
Renewable energy	• Use phase: Energy source and percentage of renewable energy sources (%)					
Air pollution	• AM emissions of air pollutants: PM levels (ug/m3), NOx, CO emissions					
Climate change	• AM GHG emissions: CO_2, N_2O, CH_4					
Noise pollution	• AM traffic noise (dB)					

Investments on mobility	• Public and private annual average investment on transport concerning automated vehicles (Euro/year), e.g. infrastructure, operational expenditures (cost of personnel, software system, etc.), investments in the vehicle R&D
Economic incentives for SAEV and sustainable mobility	• Incentives and subsidies for automated and sustainable mobility, e.g., shared, electric, automated, zero-emission, vehicles (Euro)
Economic profitability	• TCO (Total Cost of Ownership), TCM (Total Cost of Mobility), Cost/km/passenger, revenues (ticketing from passengers, subsides from authorities and companies), and payback period
External costs related to the AS	• AM impacts on congestion avoidance, accidents reduction, noise reduction, air pollution (PM, NOx) reduction, QALY (quality-adjusted life years) reduction, land/parking reduction, vehicle savings
Institutional development and innovation	• Existence of policies and regulations concerning automated vehicles • Regulations for open data and/or APIs for transport
Technical performance and reliability	• AM performance: . travel time: speed, frequency of departure or response speed for on-demand, travel-matching, punctuality. . on-demand availability . percentage of operational service . performance on different seasons/weather . vehicle occupancy (average passenger per km travelled) . the average lifetime of the vehicle . number of disengagements in the urban environment, number of km driven autonomously
System integration and efficiency	• AMV integration with mobility platform of the operator (planning, reservation, booking, billing, digital ticketing) • System and data interoperability and the existence of open data for the AM (access, static and/or dynamic real-time data, diffusion format, data quality, and open APIs for transport) • Intermodality: AM integration with other public or private means of transport or with a multi-modal platform for one intermodal trip (planning, reservation, booking, billing, digital ticketing)
Changes in total kilometres travelled in the transportation system	• Changes in per capita vehicle travelled induced by automated vehicles • Transportation demand management measures introduced congestion pricing, biking lanes, zoning measures, land-use policies

Acronyms AM: automated minibus APIs: Application Programming Interfaces dB: decibel Ec: economic En: environment G: governance	Nr/year: number per year NOx: nitrogen oxides Pkm: per kilometre PM: particular matter PRM: people with reduced mobility QALY: quality-adjusted life years	R&D: Research and Development SAEV: shared automated electric vehicle S: social SP: system performance TCM: Total Cost of Mobility TCO: Total Cost of Ownership

3.1 The indicators and methods

Hereinafter, for each indicator, we present a definition, parameter, description of the methodology, scale (min and max), and examples of the indicator value within a range from 1 to 5 – with 1 for the worst performance and 5 for the best performance.

The following guidelines provided the basis to develop and adapt the methods for the indicators in this deliverable:

- 'Sustainable Urban Mobility Indicators – SUMI' by the (European Commission 2020b)

- ‘Methodology and indicator calculation method for sustainable urban mobility’ by the (World Business Council for Sustainable Development 2015).

The normalisation step adjusts all indicators into a common scale (Saisana et al. 2019). The method of normalisation chosen is the re-scaling (EU Science Hub 2016) - defining max and min scale – and in some cases, categorical scales for more conceptual assessment (EU Science Hub 2016) – which defines categories - for instance, system integration and MaaS levels.

The disaggregated indicators reveal the strengths and weaknesses of each mobility indicator (World Business Council for Sustainable Development 2015). As graph representation, the radar (also known as spider chart) enables easy communication and visualisation of the results and comparison among case studies. As result, a mobility radar is built to illustrate the assessment of the AVENUE demonstrator sites.

Based on data availability, 14 out of 20 indicators are assessed. The indicators, units and scales of assessment are detailed in Table 5.

Table 5. Indicators, units and scales of assessment

Indicators	Parameter	Scale of assessent
Social acceptance	average rating reported concerning the i) willingness to use automated minibus; ii) perception about the readiness of the technology; iii) willingness to pay	City
User satisfaction	average rating satisfaction reported concerning the automated minibuses speed, comfort, punctuality, information, frequency of service, connection to other means of transport, and satisfaction with the last ride.	Local
Passenger's affordability	costs (Euro)passenger-km for passengers	City
Climate change	gCO2 eq/passenger-km	local and global
Air pollution	air pollutant emissions, particular matter, PM2,5 (g/km), and nitrogen oxides, NOx (g/km), from exhaust and non-exhaust.	Local
Noise pollution	vehicle noise in Decibels (dB)	Local
Renewable energy	percentage of renewable energy in the use phase of the mode of transport	Country
Energy efficiency	kWh/passenger-km	City
Economic profitability	costs (Euro)/passenger-km for operators	City
External costs	€-cent/pkm (with congestion)	City
Institutional development and openness to mobility innovations	ROAD index – ‘the Regulation Openness for Autonomous Driving’ index. It sets four variables to measure the level of readiness for the implementation of autonomous collective vehicles on open roads: 1. National Industrial policy 2. Local territories autonomy 3. National sustainable development policy and declination 4. Governance and integration at local level The score for each variable results in the Road Index for a city	City
Technical performance and reliability	assessment of i) average speed in km/h; ii) frequency or response speed in minutes of waiting time, iii) average occupancy as the average number of passengers on board at any given time and any place within a trip and iv) the percentage of kilometres driven autonomously.	Local
System integration and efficiency	Five levels of MaaS integration suggested by (Sochor et al., 2018).	City
Reduction of risk of induced demand	Percentage of motorised modes of transport – car and buses – that the automated minibuses are replacing based on the reference modal share.	City

3.1.1 Social acceptance

Definition: potential users' opinions, positionings and attitudes towards the automated minibuses.

Parameter: average rating reported concerning the i) willingness to use automated minibus; ii) perception about the readiness of the technology; and iii) willingness to pay.

Methodology: AVENUE representative survey. The questions have a 5 point Likert scale, with 1 corresponding to very low acceptance and 5 to very high acceptance.

Scale:

1 = very low acceptance

5 = very high acceptance

Calculation:

Social acceptance			
Indicator value	3,04		
Willingness to use the automated minibus as part of a seaml		1	5
Parameter value:	3,80	min scale	max scale
Indicator value	3,80	1	5
Perception about the readiness of the technology		1	5
Parameter value:	2,57	min scale	max scale
Indicator value	2,57	1	5
Willingness to pay		1	5
Parameter value:	2,75	min scale	max scale
Indicator value	2,75	1	5

Obs: Example of Groupama (Lyon)

Sources: Korbee et al. (2022c), D8.9 Social impact assessment

3.1.2 User satisfaction

Definition: users' experience, satisfaction and perceptions on-board the automated minibuses.

Parameter: average rating satisfaction reported concerning the automated minibuses speed, comfort, punctuality, information, frequency of service, connection to other means of transport, and satisfaction with the last ride.

Methodology: AVENUE users' survey. The questions have a 5 point Likert scale, with 1 for very poorly rated and 5 for very good rated.

Scale:

1 = very poorly rated/very dissatisfied

5 = very good rated/very satisfied

Calculation:

User satisfaction			
User rating concerning the ride experience		1	5
Parameter value:	3,96	min scale	max scale
Indicator value	3,96	1	5

Obs: Example of Nordhavn (Copenhagen)

Sources: Korbee et al. (2022c), D8.9 Social impact assessment

3.1.3 Passenger's affordability

Definition: Transportation affordability refers to 'household's ability to purchase basic mobility within its limited financial budget' (Litman 2021b). Therefore, in this study, the price of the ride on the automated minibus is assessed.
Parameter: costs (Euro) passenger-km for passengers
Methodology: price of the ride in the automated minibuses in comparison with other modes of transport. Currently, the ride in the automated minibuses is free of charge in all sites.
Scale: the scale range considers the costs (Euro)/ passenger-km for bus, minibus, car and van according to the study from Bösch et al. (2018), as well as free of charge public transport, as the case of Luxembourg (Zhen 2021).
1 ≥ 2.63 euros pkm (approximation from a midsize car, with 4 seats, urban, non-automated and non-electric)
5 = 0 euro pkm (free of charge)
Calculation:

Passengers' affordability			1	5
Parameter value:	0,00		min scale	max scale
Indicator value	5,00		2,63	0

Obs: Example of Pfaffenthal (Luxembourg)

Sources: Bösch et al. (2018), Antonialli, Mira-Bonnardel and Bulteau (2021) within the D8.4 Second Iteration Economic impact (Antonialli et al. 2021).

3.1.4 Climate Change

Definition: greenhouse gases emitted by the AM per passenger-km
Parameter: gCO_2 eq/pkm
pkm = passenger kilometres, a metric of transport activity: when a single passenger travels a single kilometre, the result is 1 pkm of travel.
gCO_2eq = grammes of CO_2 equivalent.
Methodology: the LCA study of the AM provided the GHG emissions (gCO_2 eq/pkm) (Huber et al. 2022). The LCA was developed under the Environmental Impact Assessment task within AVENUE project.
The scale was developed based on values reported on the average GHG emissions of different modes of transport on a well-to-wheel basis by the International Energy Agency 2020 and the LCA study from the AVENUE project (Huber et al. 2019). The study estimates the GHG emissions (gCO_2eq/pkm) for two/three-wheelers, buses and minibuses, small/medium and large vehicles as individual transportation or public transport.
Scale:
1 ≥ 273 gCO_2eq/pkm (average operation of large ICECAV - internal combustion engine connected and automated vehicle) (IEA, 2020)
5 ≤ 48 gCO_2eq/pkm (average operation of a battery electric bus - BEB) (Huber et al. 2019)
Calculation:

Climate Change			1	5	
Parameter value:	290,00		min scale	max scale	
Indicator value	1,00		273	48	gCO_2/pkm

Obs: Example of Pfaffenthal (Luxembourg)

Sources: Huber et al. (2022), International Energy Agency (2020)

3.1.5 Renewable energy

Definition: use of renewable energy for the mode of transport.

Parameter: percentage of renewable energy in the electricity mix for the use phase of the mode of transport.

Methodology: the measurement takes into account the use of renewable fuels according to the energy sources for the mode of transport. The automated shuttle is a battery electric vehicle (BEV). Therefore, the electricity mix of each country may influence the percentage of renewable energy used in the vehicle use phase.

For the calculation, it was considered the share of energy from renewable sources in gross electricity consumption 2018 (%) according to the countries of the pilot tests (The Federal Council 2019; Eurostat 2020).

Scale:

1 = 0%

5 = 100%

Calculation:

Renewable energy			1	5	
Parameter value:	21,2		min scale	max scale	
Indicator value	1,06		0	100	% renewable energy

Obs: Example of Groupama Stadium (Lyon)

Sources: Eurostat (2020), The Federal Council (2019), European Environment Agency (2016), Litman (2019).

3.1.6 Noise pollution

Definition: noise emission by the (motorised) mode of transport.

Parameter: vehicle noise in Decibels (dB) at 20km/h.

Methodology: Considering the uncertainty and variations among noise emissions studies, we describe here in more detail the noise measurement for this indicator.

> *"The noise from vehicles comes mainly from two different sources, the propulsion and the contact between the tyres and the road. The tyre/road noise increases more with increasing speed than the propulsion noise, and therefore the tyre/road noise dominates the propulsion noise at high speeds." (Marbjerg 2013).*

Hence, the difference in noise emissions between BEVs and ICEVs strongly depends on the vehicle speed (European Environment Agency 2018).

A study by Jochem et al. (2016a) pointed out that taking into account the background noise and traffic density, EV does not differ from ICEV in the usual traffic, except for urban traffic during the night at low-speed areas. Moreover, the extent of noise reduction will also depend strongly on the proportion of BEVs in the vehicle fleet (EEA, 2018).

To simplify the measurement of noise emission, the study from Marbjerg (2013), 'Noise from electric vehicles - A literature survey', provided the basis for comparing the noise emissions from different modes of transport (ICE, hybrid and electric vehicles) at different speed levels.

Considering that the automated shuttle drives at an average speed of 10-18km/h in areas with a speed limit of 30km/h, the noise difference reported for different vehicles was considered at 20km/h (Dudenhöffer, Hause 2012; Lelong and Michelet 2001; Marbjerg 2013; Cai 2012). The noise emission for the automated minibus was considered similar to a BEV, at 50 decibels at a constant speed of 20km/h.

Scale:

1 ≥ 65dB

5 ≤ 50 dB

Calculation:

Noise pollution		1	5	
Parameter value:	50	min scale	max scale	
Indicator value	5,00	65	50	Decibels at 20km/h

Sources: European Environment Agency (2018), Marbjerg (2013), Jochem et al. (2016a), Cai (2012), Dudenhöffer, Hause (2012), Lelong and Michelet (2001).

3.1.7 Air pollution

Definition: air-polluting emissions by the modes of transport in the use phase.

Parameter: air pollutant emissions, particular matter, $PM_{2,5}$ (g/km), and nitrogen oxides, NO_x (g/km), from exhaust and non-exhaust.

Methodology:

Particulate matter (PM) and nitrogen oxides (NO_x) are the main transport air pollutant emissions, along with carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs) and sulphur oxides (SOx). The emissions from road transport are mainly exhaust emissions arising from fuel combustion, and non-exhaust releases contribute to NMVOCs (from fuel evaporation) and primary PM due to tyre- and brake-wear and road abrasion (European Environment Agency 2019). Further, transport is responsible for more than half of all NOx emissions (ibid).

The automated shuttle is a BEV, and during the use phase, BEVs have zero exhaust emissions, e.g. NOx and PM (European Environment Agency 2018). However, BEVs emit PM locally from road, tyre and brake wear, like other motor vehicles (European Environment Agency 2018). And it is important to mention that air pollutant emissions from BEVs occur for the electricity generation to charge BEV batteries. Nonetheless, the emissions from power stations tend to occur in less densely populated areas, provoking less human exposure to air pollution than in urban areas (ibid). At the same time, the local emissions from combustion engine vehicles in cities provoke greater human exposure and potential health harm.

Considering this factor, we limited the impact measurement for air pollutant emissions to the use phase and local area. And we considered the assumption that the automated minibus presents similar air pollutant emissions as an electric car.

Values from $PM_{2,5}$ (g/km) from exhaust and non-exhaust and NO_x (g/km) by mode of transport are provided by the excel tool 'Air pollutant emissions indicator' on Sustainable Urban Mobility Indicators (SUMI) (European Commission 2020b).

Scale:

$PM_{2,5}$

1 ≥ 0.005 $PM_{2,5}$ g/km

5 = 0 $PM_{2,5}$ g/km

NO_x

1 ≥ 0.08 NO_x g/km

5 = 0 NO_x g/km

$PM_{2,5}$ Non exhaust

1 ≥ 0.0474 $PM_{2,5}$ g/km

5 = 0 $PM_{2,5}$ g/km

The Euro 6 standards for light-duty (cars, vans) were considered to establish the maximum values in the scale (European Commission 2020a). The emission limits are presented in Table 19.

Table 6: The light-duty Euro 5 and Euro 6 vehicle emission standards (g/km)

Pollutant	Euro 5 Light-Duty		Euro 6 Light-Duty	
	Gasoline	Diesel	Gasoline	Diesel
CO	1.0	0.5	1.0	0.5
HC	0.1[a]		0.1[e]	
$HC+NO_x$		0.23		0.17
NO_x	0.06	0.18	0.06	0.08
PM	0.005[c]	0.005	0.005[c]	0.005
PN (#/km)		6.0×10^{11}	6.0×10^{11} [d]	6.0×10^{11}

[a] and 0.068 g/km for NMHC; [c] applicable only to DI engines, 0.0045 g/km using the PMP measurement procedure; [d] applicable only to DI engines, 6 x 1012 #/km within the first three years of Euro 6 effective dates.

Source: Williams and Minjares (2016)

Calculation:

Air pollution

Indicator value	4,68

PM 2,5

			1	5	
Parameter value:	0,00		min scale	max scale	
Indicator value	5,00		0,005	0	PM 2,5 g/km

NOx

			1	5	
Parameter value:	0,00		min scale	max scale	
Indicator value	5,00		0,08	0	NOx g/km

Non exhaust

			1	5	
Parameter value:	0,01		min scale	max scale	
Indicator value	4,03		0,0474	0	Non exhaust PM2,5 g/km

Sources: European Environment Agency (2018), Jochem et al. (2016a), (European Commission 2020a), European Commission (2020b), European Environment Agency (2019).

3.1.8 Energy Efficiency

Definition: energy consumption (kWh) by the AM per passenger-km

Parameter: kWh/pkm

kWh = kilowatt-hour

pkm = passenger kilometres, a metric of transport activity: when a single passenger travels a single kilometre, the result is 1 pkm of travel.

Methodology: data on the energy consumption (kWh/km) for the AM was collected per pilot site.

The scale was developed based on values of the methodology for 'energy efficiency' indicator from the World Business Council for Sustainable Development (WBCSD, 2015), which also considered the energy use by urban transport per passenger-km.

Scale:

1 ≥ 0.97 kWh/pkm

5 ≤ 0.14 kWh/pkm

Calculation:

Energy efficiency			1	5	
			min scale	max scale	
Parameter value:	0,18				
Indicator value	4,81		0,97	0,14	KWh/pkm

Obs: Example of Pfaffenthal (Luxembourg)

Sources: WBCSD (2015).

3.1.9 Economic profitability

Definition: the ability of the transport operator to generate profits (more revenues than costs) through its operations.

Parameter: costs (Euro)/vehicle-km for operators

Methodology: the Total cost of ownership tool (EASI-AV©) for the automated shuttles was developed by Antonialli, Mira-Bonnardel and Bulteau (2021) within the D8.4 Second Iteration Economic impact (Antonialli et al. 2021). The study calculated the TCO of the four demonstrator cities.

Scale: the scale range considers the costs (Euro)/ vehicle-km for bus, minibus, car and van according to the study by Bösch et al. (2018).

1 ≥ 3.40 EUR vkm (Van Urb PT-P N. aut N. elec)

5 ≤ 0.46 EUR vkm (Midsize Urb PT-NP Aut Elec)

Calculation:

Economic profitability			1	5	
Parameter value:	11,23		min scale	max scale	
Indicator value	1,00		3,4	0,46	costs(Euro)/vkm

Obs: Example of Groupama (Lyon)

Sources: Bösch et al. (2018), Antonialli, Mira-Bonnardel and Bulteau (2021) within the D8.4 Second Iteration Economic impact (Antonialli et al. 2021), Friedrich and Hartl (2016), Hazan et al. (2016).

3.1.10 External costs of deployment scenarios

Definition: Marginal external costs “are the additional external costs occurring due to an additional transport activity” (CE Delft 2019). The external costs analysis monetises impacts such as air pollution, climate change, accidents, and congestion, given the context and scenario of deployment of the AVs in the mobility system.

Parameter: €-cent/pkm

Methodology: the assessment of the marginal external costs for different scenarios of deployment of the AM was developed by Jaroudi (2021). The scenarios here considered are: i) AM in MaaS and ii) Robotaxis.

Scale:

1 – external costs value €-cent/pkm (estimate for individual mobility for car petrol/diesel)

5 – external costs value €-cent/pkm (estimate for bus/coach)

Sources: Jaroudi (2021), CE Delft (2019)

3.1.11 Institutional development and openness to mobility innovations

Definition: development of regulations and policymaking processes at the national and local level for the implementation of automated collective vehicles on open roads.

Parameter: ROAD index – ‘the Regulation Openness for Autonomous Driving’ index developed by Mira-

Bonnardel and Couzineau (2021).
Methodology: The ROAD index set of four variables to measure the level of readiness for the implementation of autonomous collective vehicles on open roads:
"1. National Industrial policy (share of Government investment into the Gross Domestic Expenditures in Research and Development (GERD) to measure the strength of national industrial policy)
2. Local territories autonomy (Keuffer's local autonomy assessment, European Commission scoring methodology)
3. National sustainable development policy and declination (Government Effectiveness, Regulatory Quality)
4. Governance and integration at a local level (assessment of governance arrangements)"
The assessment is performed for the four AVENUE demonstrators' cities: Copenhagen, Lyon, Luxembourg and Geneva. The table below presents the score for each variable, resulting in the Road Index score for each city.

Table 3.3 The ROAD index for the four cities

Cities	Copenhagen	Lyon	Luxembourg	Geneva
Variables				
Local territories autonomy	2	4	3	5
National Industrial policy strength	2	3	2	2
National sustainable development policy and local declination	5	4	5	4
Governance – Integrator policy bodies at local level	3	5	4	5
Road Index per city (score out of 20)	12	16	14	16

Source: Mira-Bonnardel and Couzineau (2021)
Scale: each of the four variables is assessed on a 1 to 5 scale (1 minimum and 5 maximum).
Source: Mira-Bonnardel and Couzineau (2021), How to Assess Regulation Openness for Autonomous Driving in Public Transport? The ROAD Index.

3.1.12 Technical performance of the vehicle

Definition: technological maturity and performance of the automated minibus assessed by average speed, frequency or response speed for on-demand, average occupancy (very important in terms of environmental performance and efficiency), and kilometres driven autonomously.
Parameter: i) average speed in km/h; ii) frequency or response speed in minutes of waiting time, iii) average occupancy as the average number of passengers on board at any given time and any place within a trip and iv) the percentage of kilometres driven autonomously.
Observation: the number of disengagement can be used as a unit of measurement, but for AVENUE this measure is not assessed considering that the vehicles are driving in cities and complex environments, different from the tests in the US on highways and with low traffic or in cities build for cars.
Methodology: average of performance for the four variables described below.
Scale: the following scales for assessment were established:

i) Speed

1 ≤ 6km/h
5 ≥ 25km/h (25km/h is the current maximum operating speed of the minibus. In addition, they are running in areas of about 30km/h)

ii) Frequency

1 ≥ 40 minutes (It takes into account that in some areas the minibus complements bus services running every 30 minutes, also in order to be competitive with on-demand services a minimum of 5 minutes is settled in comparison with taxis services, with an average of waiting time of 4:32minutes (Bischoff et al. 2017)

5 ≤ 5 minutes

iii) Average occupancy

1 ≤ 1

5 ≥ 6 passengers

iv) Km driven autonomously

1 ≤ 60%

5 = 100%

Calculation:

Technical performance

Parameter value:	3,1
Indicator value	3,14

Speed

			1	5	
Parameter value:	17		min scale	max scale	
Indicator value	2,89		6	25	km/h

Frequency or response speed for on-demand

			1	5	
Parameter value:	15		min scale	max scale	
Indicator value	3,57		40	5	minutes

Average occupancy rate

			1	5	
Parameter value:	2,84		min scale	max scale	
Indicator value	1,84		1	6	passengers on board

Km driven autonomously

			1	5	
Parameter value:	94		min scale	max scale	
Indicator value	4,25		60	100	% km drive autonomously

Obs: Example of Pfaffenthal (Luxembourg)

3.1.13 System integration

Definition: Integration of various modes of transport offered by different mobility providers in one platform that allows the planning, reservation, booking, billing, and ticketing.

Parameter: five levels of MaaS integration suggested by (Sochor et al. 2018).

Methodology: categorical scale based on the MaaS levels conceptualised by Sochor et al. (2018)

Scale: 1) No integration - single, separate services

2) Integration of information - multi-modal travel planner, price info

3) Integration of booking & payment - single trip, find, book and pay

4) Integration of the service offer - bundling/subscription, contracts, etc.

5) Integration of societal goals - policies, incentives, etc.

Calculation:

System integration

Mobility Integration

			1	5
Parameter value:	1		min scale	max scale
Indicator value	1,00		1	5

Obs: Example of Contern (Luxembourg)

Source: Sochor et al. (2018)

3.1.14 Reduction of risk of induced demand

Definition: potential increase of vehicle kilometres travelled in the transportation system due to the offer of new mobility services by the automated minibus.
Parameter: percentage of motorised modes of transport – car and buses – that the automated minibuses are replacing based on the reference modal share.
Methodology: Gorham (2009) describes four characteristics of induced travel:

i) Induced travel at the metropolitan level is concerned with travel as a whole, not trip-making per se;

ii) The concept of induced travel applies to the entire transportation sector, not just to one mode;

iii) Induced travel is not the only source of growth in the demand for travel.
Besides induced travel due to improvements in transportation conditions (e.g. better infrastructure, roads, better technologies), it can also occur due to “natural demand growth” due to changes in population, employment, income, socio-demographics, for instance;

iv) Induced travel can only be understood with reference to a hypothetical “base” case or counterfactual.

The measurement of induced demand triggered by the integration of the automated minibus is complex, and for this study, it presents significant limitations due to the small scale of the tests, therefore, not representing meaningful mobility impacts. In addition, there is no available accurate data on the mobility behaviour on the local scale of the pilot sites. Therefore, the assessment is simplified to the potential risks of induced vehicle travelled caused by the automated minibuses according to the means of mobility that they have replaced. The data is provided by the AVENUE users’ survey.
Scale:
1 = 0% replacement of individual cars or buses
5 = 100% replacement of individual cars or buses
Calculation:

Reduction of risk of induced demand	
Parameter value:	27
Indicator value	1,36

1	5
min scale	max scale
0	100

Obs: Example of Nordhavn (Copenhagen)

3.2 Pilot sites assessment and results

The indicators were applied for the sustainability assessment of four different demonstrator sites. The description of the sites and respective mobility radar are presented hereinafter. The indicators present a value from 1 to 5 – with 1 for the worst performance and 5 for the best performance, therefore, the outside part of the radars represent the optimal results.
It is worth noting that the data availability and sample vary from site to site. Table 7 summarises the main information on the pilot sites.

Table 7. Description of the demonstrator sites

City	Pilot	Characteristics of route	Type of passenger	Deployment

Lyon	Groupama Stadium	Fixed route with stops 1.3 km. Will become an on-demand, door-to-station service	regular workers, people with reduced mobility (medical centre nearby)	November 2019 - April 2022
Copenhagen	Nordhavn	Fixed route with stops, 1,2km, will become an on-demand, door-to-door service	Residents of the area, tourists	September 2020– April 2022
Luxembourg	Contern	Fixed route with stops, on-demand. 2.2 km	Employees working at Campus Contern	September 2018 - April 2022
	Pfaffenthal	Fixed route with stops, on-demand 1.2 km	Workers, tourists, residents, and visitors of Luxembourg city	September 2018 - April 2022

Figure 3 presents the sustainability mobility radars from AVENUE pilot sites. The following subsections discuss the features of each pilot site. Followed by the acknowledgements about the limitations of the assessment (section 3.3) and the general discussions and conclusions concerning the assessment of all the pilot sites (section3.4)

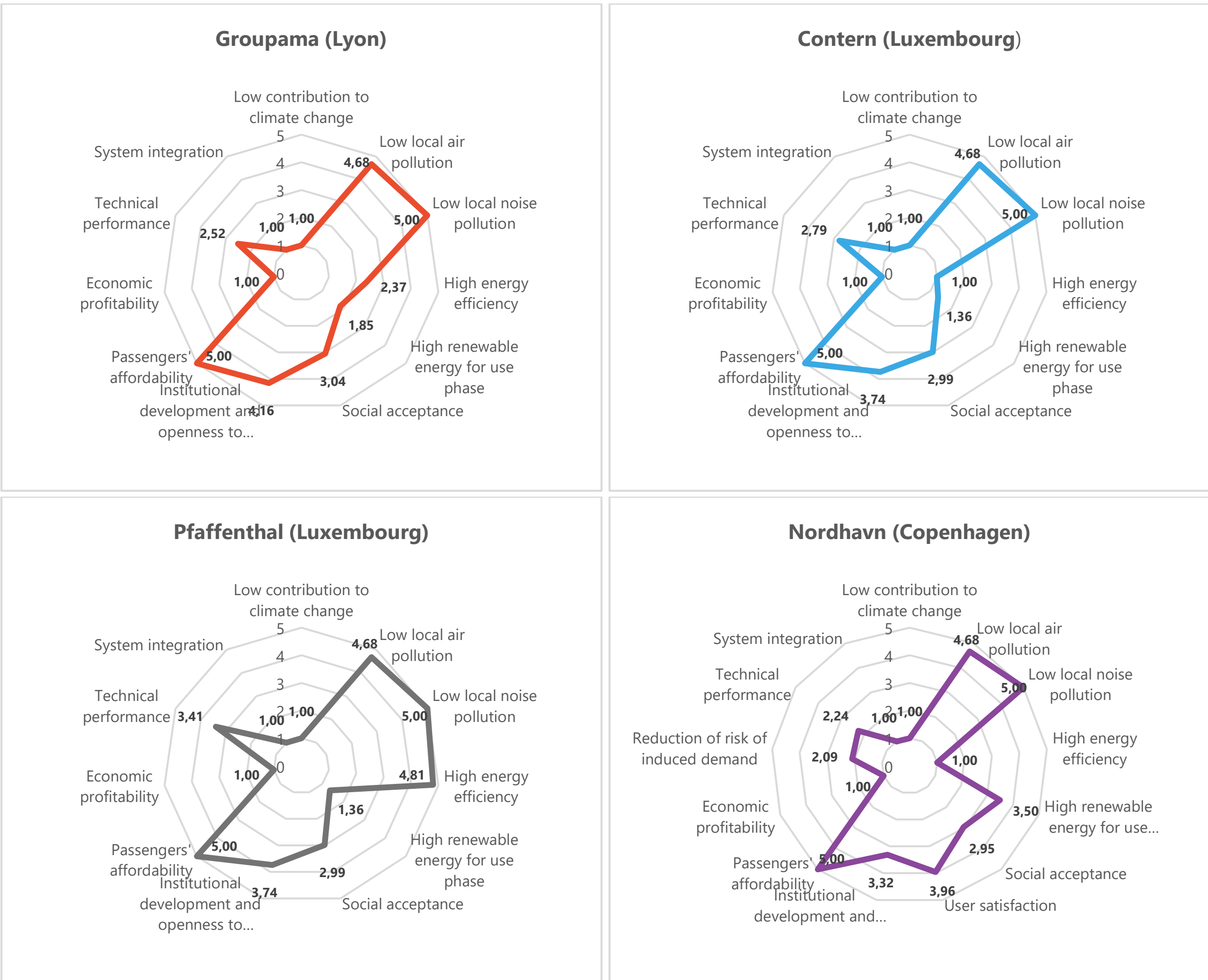

Figure 3. Sustainability mobility radars from AVENUE pilot sites – with 1 for the worst performance and 5 for the best performance (a) Groupama (Lyon); (b) Contern (Luxembourg); (c) Pfaffenthal (Luxembourg); (d) Nordhavn (Copenhagen)

3.2.1 Groupama Stadium (Lyon)

Groupama Stadium, also known as Parc Olympique Lyonnais is a football stadium. The area is a high traffic district, and it attracts visitors going to the football games, people working in offices, medical centre, leisure centre, hotels, and restaurants.

To access the Groupama Stadium by public transport, the area is served by the Tramway 3 line and a bus every 30 minutes to connect the area. The automated minibuses route is parallel to the bus line, and the service is complementary to the bus (Zuttre 2019). The automated minibuses route comprises crossroads and roundabout with the vehicle to infrastructure (V2I) intersections (Zuttre 2019). For the near future, it is envisaged on-demand and door-to-door services in Parc Olympique Lyonnais.

In Groupama trial, as in other pilot sites as well, the environmental indicators such as low contribution to climate change and energy efficiency score low mainly due to the low passenger occupancy. The social acceptance towards the AM in Lyon scores medium to high, reflecting the willingness to use the automated minibuses (3,80), the willingness to pay (2,75) for most of the respondents is equivalent to the public transport fee for the automated minibuses services, and the perception about the readiness of the technology (2,57). The technical performance is affected by the low speed (10km/h) and low occupancy, but with 84% km driven autonomously.

According to the ROAD Index (Mira-Bonnardel and Couzineau 2021), the city of Lyon scores high concerning the 'Institutional development and openness to mobility innovation' (4,16). It means a good performance according to the variables: local territory autonomy; national industrial policy strength; national sustainable development policy and local declination; governance – integrator policy bodies at a local level. Other common aspects among the pilot sites are discussed in section 3.4.

3.2.1 Pfaffenthal (Luxembourg)

Pfaffenthal is a residential area located in a valley between the historical centre of Luxembourg City and Kirchberg, the business district of Luxembourg City. During the peak hours, work commuters move through Pfaffenthal, and throughout the day, local residents and a vast number of tourists (Reisch 2019). The automated minibuses route in Pfaffenthal connects the public elevator, which provides access to the city centre, a multi-modal station and the residential area (Reisch 2019).

Among all the sites, Pfaffenthal scores the highest in technical performance, with 15km/h speed, 94% of km driven autonomously, and average occupancy of 3 passengers. The higher vehicle occupancy also reflects a higher energy efficiency (kWh/passenger-kilometre). Other common aspects among the pilot sites are discussed in section 3.4.

Currently, the ride on the AM is free of charge in all sites, therefore, the passengers' affordability performs good. In addition, as in Luxembourg public transport is free for everyone, the passengers' affordability may remain to perform good. Other common aspects among the pilot sites are discussed in section 3.4.

3.2.1 Contern (Luxembourg)

Contern is an industrial zone with different companies located around 10 km east of Luxembourg city. The traffic in Contern consists of industrial vehicles, such as trucks and individual cars (Reisch 2019). A railway station and a bus are located on the border of the industrial zone of Contern; however, the area is not served by public transport. Thus, the companies employees use mainly private cars to commute to work and to move inside this area (Reisch 2019). The route of the automated minibuses connects public transport to the industrial zone.
Contern pilot trial presents the highest speed, with 17km/h. The social acceptance towards the AM in Luxembourg points to a medium to high willingness to use the AM (3,53), and lower perception about the readiness of the technology (2,44). As in Luxembourg public transport is free for eveyone, the passengers' affordability may remain to perform good. Other common aspects among the pilot sites are discussed in section 3.4.

3.2.1 Nordhavn (Copenhagen)

Nordhavn is an active industrial port, which is expected to be Copenhagen's new international waterfront district, with residential and commercial buildings (Guldmann et al. 2019). The area hosts eco-friendly initiatives such as the use of renewable energy, and recycling of resources (Guldmann et al. 2019).

Nordhavn area is served by a tram station about 1km away and bus stops located near the train station; however, there are no buses or trains running directly in the area, which creates an opportunity for automated minibuses services to connect the area.

An interesting point from Nordhavn is the social acceptance; it points high willingness to use the automated minibuses among potential users (3,82). In addition, the real users pointed to high satisfaction with the ride (4,50), and evaluated well the speed, comfort, punctuality, information, frequency and connection (3,96). An important point assessed concerns the 'risk of induced demand'. The user surveys pointed out that currently, the automated minibuses have been replacing high percentages of walking and cycling (17% and 45%, respectively). In parts, this can be explained due to the vehicles' low speed. However, in the future, the goal is the replacement of other motorised modes of transport and to foster mobility intermodality by deploying automated minibuses. In addition, the technical performance of the vehicle is affected by the low vehicle speed (8km/h).

According to the ROAD Index (Mira-Bonnardel and Couzineau 2021), the city of Copenhagen performs lower than Lyon and Luxembourg concerning the 'Institutional development and openness to mobility innovation' (3,32). Of the four variables, Copenhagen scores low in 'local territory autonomy' (2, on a scale from 1 to 5) and 'national industrial policy strength' (2, on a scale from 1 to 5). Other common aspects among the pilot sites are discussed in section 3.4.

3.3 Limitations of the assessment

As this study analyses pilot trials, the sustainability assessment in this study is limited to a local and small-scale deployment, in addition to the technological limitations due to the development of the automated minibuses (Level 3 and 4 of driving automation) and software. The assessment is also limited to just one type of vehicle provided by the same vehicle manufacturer.

Further, the application of the indicators is limited to data availability and data asymmetry from the pilot sites. For instance, the AVENUE representative and user surveys among the four demonstrator cities have different samples (n), hence, varying their representativeness.
It is also important to note that all the pilot tests within AVENUE project have been directly affected by the Covid-19 pandemic. The trials had interruptions, the number of passengers dropped, as had happened to public transport in general, and in some trials, the maximum number of passengers was limited to four in order to keep the social distance. For these reasons, the data collection and data availability for assessment was affected by the Covid 19- pandemic.
For some indicators, the assessment was simplified considering standard units of measurement available in the literature and commonly applied to other modes of transport.

3.4 Discussion and concluding remarks

The results from the sustainability assessment reveal strong and weak points of the deployment of the automated minibuses. Some common results among the sites pointed out that the automated minibuses score poorly on ‘energy efficiency’ (with the exception of Pfaffenthal) and ‘low contribution to climate change’ due to the low vehicle occupancy. With the exception of Pfaffenthal (Luxembourg), all sites presented very low occupancy. This result can be an indication of low demand for the offered mobility services. However, we should be cautious in this conclusion due to the unknown impacts of the Covid-19 restrictions. In addition, the energy efficiency could also be affected negatively in case the automated minibuses were equipped with more hardware and technical features, such as sensors, cameras, Lidars and communications.
As electric vehicles, automated minibuses seem to be a good alternative to tackle ‘local air pollution’. However, they are not a significant solution to tackle ‘local noise pollution’, as their noise level does not differ that much from other motorised modes of transport from 30km/h speed. It considers that the background noise and traffic density, EV does not differ from ICEV in the usual traffic, except for urban traffic during the night in low-speed areas (Jochem et al., 2016).
As temporary pilot trials, the automated minibuses present low system integration. Nonetheless, they present a high potential in the near future to have information, booking and payment integration within the public transport services, considering that in most cases, they are already deployed by public transport operators. In addition, it is expected that in the future, the AM could be integrated into MaaS systems.
Concerning the technical performance elements (speed, frequency, occupancy rate, and km driven autonomously): all sites struggle with low speed and low occupancy rates. The percentage of fully automated driven kilometres is 80 to 94%. The manual interventions that took place were mainly caused by wrongly parking cars and trucks.
The use of renewable energy for the use phase varies significantly according to the electricity mix of each region or country. In this case, Nordhavn in Copenhagen has the best score (with 62,4% of renewable sources in the electricity mix), and Contern and Pfaffenthal in Luxembourg are the lowest.
Currently, the ride on the AM is free of charge. Therefore, passengers’ affordability performs high. In the future, it is envisaged to integrate the AM in the ticketing of public transport.
Overall, the economic profitability is still low due to the elevated costs with feasibility studies and legal authorisations; infrastructure works; high annual depreciation and salaries for on-board safety drivers impact as detailed in the second iteration economic Impact assessment (Antonialli et al. 2021).
Concerning the indicators of social acceptance, respondents show goodwill to use the AM (scoring 3,80 in Lyon and Copenhagen, and 3,5 in Luxembourg), while the perception of the readiness of the technology is lower (2,5 In Lyon, 2,4 in Luxembourg, and 2,5 in Copenhagen). Based on real experiences, the users in

Copenhagen pointed a good satisfaction (3,96) with the ride and the AM services (comfort, information, punctuality, speed).

The indicator on 'reduction of risk of induced demand' scored low in Nordhavn; this is explained by the users' survey, which shows that the automated minibuses have been replacing walking and cycling (17% and 45%, respectively). In parts, this can be explained due to the vehicles' low speed.

All in all, the indicators reflect an incipient phase of deployment and development of the technology. In the short-term, key factors for improvement are:

i) the minibuses' occupancy, a key factor in fostering environmentally-friendly mobility. The automated minibuses should be deployed to cover real mobility gaps and to provide rides with great potential to replace private cars. These factors are crucial to guarantee higher occupancy and reduction of the risks of induced demand and increase in vehicle kilometres travelled.

ii) better mobility services integration, as the integration of information, booking & payment

iii) offer of permanent lines/services, on-demand services and higher speed as a factor to improve flexibility and reduce travel time

iv) monitoring and planning the deployment in order to replace car trips.

In the medium and long term, the economic profitability of deploying the automated minibuses should become more attractive with the development of a legal framework and lower costs with feasibilities studies, authorisations, and exemption of safety drivers.

Concerning the SUMP concept, it is worth noting that automated vehicles and minibuses will not be sustainable per se, but rather their mode of deployment is very important, and factors such as shared mobility, ride-matching capacity and efficiency, system integration and means of transport it will replace proper policies and regulations. The automated minibuses should be integrated into urban public transport or within MaaS perspective and fundamentally aligned with the city's goals, planning and strategies for sustainable mobility. Also significant is to keep an integrated vision of the mobility system. And as highlighted by SUMP approach, to develop all modes of transport in an integrated manner. Thus, the automated minibuses are a piece within the mobility ecosystem that could support intermodality, MaaS, mobility hubs and the use of soft modes of transport.

Concerning SUMP principles, the deployment of this new mode of transport and new mobility technologies require more than ever long-term vision and planning, development of all transport modes in an integrated manner, cooperation across institutions, stakeholders and citizens' participation, performance assessment and monitoring towards established sustainability goals.

Therefore, SUMP principles and four steps guidelines are a valuable tool for planning and implementing automated minibuses aiming at people's mobility needs and better quality of life. In this regard, the indicators are a tool to measure and monitor the progress and achievement of sustainable mobility planning and goals.

Thereafter, chapter 6 presents and discusses in detail the policy instruments, strategies and recommendations to deploy AVs considering urban and spatial development as well as sustainable mobility goals.

4 Sustainability impacts of deployment scenarios

As a second tier of the sustainability assessment, we assess the sustainability impacts of possible deployment scenarios. For this assessment, the method of scenario planning helps outline deployment strategies of the automated minibuses in the future. The avoidance costs (externalities savings or costs from introducing the minibuses) provide insights on the recommended strategy to adopt to reduce the environmental deterioration of the transport system and promote sustainable mobility. Accordingly, internalization policies and TDM measures could be implemented in line with the SUMP guidelines.
A summary of the scenarios analysed on the city level is presented in section 2.3.3.
Hence, we focus on the impact on the transportation system (on the other modes of transportation and consequent modal shifts, on the mobility demand -overall Vkm) and the impact on the infrastructure. This qualitative analysis is supported by the externalities calculations.
The analysis will prove valuable for cities to opt for which deployment strategy based on their context and the environmental and social goals they desire to achieve.

4.1 Summary/Main findings from the scenarios and externalities studies

The description follows the methodology of scenario planning, specifically the Intuitive Logics Approach (ILA). It presents different futures in the form of stories of how the AM might be deployed (Dator 2019). It is reached through a deliberative process with the AVENUE experts as well as a literature review (Antonialli et al. 2021). The most plausible scenarios are drafted based on the key factors and driving forces. A detailed analysis is present in D8.6. In the following part, we present a brief description of the six scenarios and the main results from calculating the externalities of introducing the AM in the AVENUE cities.

4.1.1 Scenario impacts

A brief description of the scenarios main key points and impacts was presented in 2.2.3. It is important to note that the externalities increases and decreases were determined in comparison to reference scenarios or business as usual scenarios. For the urban scenarios, we compare the scenario total externalities and the total reference externalities. The external costs impacts are air pollution, climate change, noise, production emissions, well-to-tank emissions, congestion, and accidents. For the reference case, there are no AV on the roads, thus, the externalities are caused by car and buses. The total external costs for the reference scenario for Geneva 2015, were estimated to be around 481.56 million euros, while those for the second suburban scenarios were 81.74 million euros. For more details, see appendix A.
Moreover, it is important to note that the deployment of privately-owned AV is an important scenario to account for, however, in this study, we focus on shared forms of AV. Private AV would aggravate negative externalities and worsen social equity since the costs of automation would be accessible just to a very small fraction of the population (Fournier et al. 2020).

The decrease or increase in externalities for each of the scenarios compared to the status quo was calculated in D8.6. Table 8 below includes a summary of the calculations for Geneva. The assumptions and references for the scenario assessment are in Appendix B.

Table 8. Summary of externalities for scenarios for Geneva

	Scenario	Setting	The modal share of AV	The scenario modal shift	Sources used for modal shift	Decrease (-) or increase (+) in external costs in million euros	Savings in Parking space in km²	Equivalent number of parking spaces
1	Replacing all buses	urban	12 %	-Replace all bus trips in city center => 12% of all trips		+ 12.11	-	-
2	Replace all cars	urban	23 %	-Replace all car trips in city center => 23% of all trips		- 307.95	0.65	64,824
3	Robotaxis	urban	18 %	-Replace 7% of bus trips=>1% of all trips -Replace 20% of car trips => 4.5% of all trips -Replace 13% of all trips (from walking modal share)	(Ward et al. 2019)(May et al. 2020) (Clewlow et Gouri S.Mishra 2017) (Heineke et al. 2019)	+ 161.8	0.16	15,800
4	Expand network	suburban	12 %	-Replace the car trips from daily car users who would give up their car - 26% of car trips => 11.5% of all trips	- representative survey	-12.94	0.01	1,367
5	Targeted expansion	suburban	13 %	-Same for car trips from Sc4 => 11.5% from all trips -Replace all trips on night buses and empty-running buses-12% form all bus trips => 1.2% from all trips	- representative survey Mancret-Taylor and Boichon (2015), Adra et al. (2004)	-14.86	0.01	1,367
6	AM in MaaS	urban	11 %	-same for car trips from Sc4 - Replace car last/first mile trips to connect to a rail station => 6.5% of all trips -Replace walking last/first mile trips to connect to a rail station => 3% of all trips -Replace biking last/first mile trips to connect to a rail station => 1.7% of all trips	- representative survey (Paydar et al. 2020), (Giansoldati et al. 2020) Gebhardt et al. (2016)	-83.38	0.04	4,160

The results of the scenario planning and the externalities calculations give important insights into the deployment of the AM and its potential impacts. The six scenarios show different AV penetration rates varying from 5% to 26% (for the 4 cities, urban and suburban setting). Out of the six scenarios, the two scenarios of "robotaxis" and "Replacing all buses" record increases in externalities. Both show that replacing traditional public transportation (or with a laissez-faire outcome) would have a negative impact on cities.

First, the results of Replacing the buses scenario results is similar to the ITF study of replacing buses with shared AV in Helsinki (ITF 2017). Preferably, AM should replace low occupancy buses during off-peak hours like in scenario 5 "targeted expansion". Ideally, to update the bus service, it is recommended to replace the fleet with electric buses. Second, the robotaxis without ridesharing services would negatively influence the transportation system as it would repeat a model of individual mobility. Furthermore, Replacing all cars scenario shows the highest decrease in external costs out of the 6 scenarios. This is in line with current urban strategies to restrict car use in city centres (Duarte and Ratti 2018; McCallum 2020; ITF 2015, 2017). The AM in MaaS scenario also shows a consistent decrease in externalities (in the Geneva, Copenhagen, and Lyon). As a mobility gap filler, it is easier to integrate with the transportation system and could provide better results accompanied by TDM measures to promote walking and biking. Another interesting side of the analysis is the focus on the suburban scenarios, both have positive impact. This shows the need to strengthen the transportation network in less dense areas.

If we were to focus on the externalities categories, the congestion would record the biggest reduction in external costs (Sc 2, 4, 5, and 6) or the biggest increases (Sc 1 & Sc 3). It reflects the transport pricing and value of time. Replacing buses that usually operate within specific lanes with AM would potentially slow down the traffic flow, whereas deploying more individual vehicles like robotaxis would affect the traffic congestion. This is incremental for policymakers as it showcases the perils of traffic jams as it worsens the traffic flow, which affects daily life and air pollution and GHG emissions. Reducing congestion is a leading cause of externalities gains in our scenarios. Dominating congestion externalities are aligned with Jochem et al. (2016b), and van Essen et al. (2019) results for road traffic congestion. The categories of accidents, air pollution, production, and climate change show savings across the 6 scenarios. Hence, any introduction of AV, whether AM or robotaxis, will have positive impacts on accidents rates and air pollution GHG emissions. The air pollution and GHG emissions externalities during the WTT (whell to tank) phase, on the other hand, shows negative results for all urban scenarios. This is explained by the fact that the production of electricity for battery charging is strongly energy-intensive, and it involves air emissions, thus causing a not negligible environmental burden, as proved by Pero et al. (2018). Furthermore, the introduction of AV in the city will, in general, lead to savings in parking spaces. The table also shows the savings in parking space, which would influence the urban planning of cities because of the free space.

Subsequently, in chapter 5 the scenario 'AM in MaaS' and 'Robotaxis' are assessed according to the indicators presented in chapter 3. Thereafter, chapter 6 addresses the strategies and recommendations for the integration of automated minibuses in urban mobility and urban development.

5 2030 Scenario assessment for the automated minibuses

Considering the six scenarios assessed in Chapter 4, in this chapter, we selected two specific potential scenarios of deployment of AVs: AVs deployed as Robotaxis (therefore competing with public transport), and AMs integrated into Mobility-as-a-Service and public transport. The aim is to assess how the two integration levels can affect the impacts of AVs.

These two scenarios are the backbone of the AVENUE Work Package 9 'Transition Roadmap for Autonomous Vehicle in public transport'. The first scenario focuses on the automated minibuses in an integrated transport system and MaaS, it is called AM in Maas/ITS. The second provides a reference point as it considers the potential effect of robotaxis as a car-sharing fleet on mobility as well as cities (in the form of externalities mostly). Hereinafter, the scenarios are described and assessed accordingly to the indicators presented in Chapter 3.

5.1 AV deployed as Robotaxis

Robotaxis are described as shared automated vehicles in numerous studies (Alazzawi et al. 2018; Fagnant and Kockelman 2018; Litman 2021a; Jones and Leibowicz 2019). Although they might be comparable to the AM in terms of services (on-demand, door-to-door, MaaS), they differ in the vehicle size, occupancy factors, speed, and integration with public transport (PT). The AM is a bigger vehicle that could carry up to 15 passengers, it rarely provides single-ride trips, and it requires longer waiting times for pick-up. On the contrary, the robotaxis (or shared AVs) are destined mostly for single ridership, even though, they could provide ridesharing services such as Uber Pool. It is assumed that robotaxis are mostly operated by private stakeholders, that they can drive faster, and they have reduced waiting times. They are convenient, especially if the passenger privileges privacy (UITP 2017).

For this scenario, the robotaxis serve the city centre as well as the connection to the suburbs. They do offer door-to-door and on-demand trips but no ridesharing services. They are competing with public transport, replacing more than one mode of transport (cars, buses, and walking).

Higher technological development facilitates the deployment of the robotaxis fleet, such as recharging, platooning, and eco-driving. The regulatory conditions can best be described as a “laissez-faire” outcome. This means that there are no policies to regulate the AV market. Private stakeholders are seeking to maximise their profit which would have unpredictable consequences on sustainable mobility and people's welfare (in terms of accessibility, safety and security, etc.). The regulatory conditions also translate into a deteriorating public transport offer that manifests in a high dependency on individual motorised mobility. It could be considered that this scenario is citizen-centric and thus satisfies the best individual mobility.

The trend of AV-markets driven by shareholders' interest would create a race to optimise the services: higher speeds, less waiting times, and more vehicles. This leads to a mixed effect on the emission rates. Therefore, it is anticipated that it will result in a reduction of greenhouse gases (GHG) during the well-to-wheel phase, an insignificant effect on air pollution, and an increase in the tank-to-wheel, production and disposal emissions. The robotaxis deployment will positively impact road safety, causing fewer accidents and consequently improving traffic flow (ITF 2015). Nevertheless, the interaction between robotaxis and non-connected vehicles would limit the full accident-reduction potential (Maurer et al. 2016). Even more, it would limit the gains in the congestion externality if not aggravate it. Moreover, an increase in overall vehicle travelled km "VKM" is expected.

The long-term consequences of this scenario on the mobility system are the modal shift from active modes of transport and public transportation. The proliferation of the robotaxi fleet complicates the biking and movement of pedestrians. Thus, this scenario is expected to cause induced demand as a rebound effect, and it could even reduce public transport ridership as it is very convenient (Niles 2019; Litman 2022; UITP 2017). Furthermore, urban planning follows car-centric strategies, where the building environment is designed to accommodate private vehicles rather than the people. The spread of AV means new roadway design features such as improved lane markings, signs designed to be read electronically, and wireless repeaters in tunnels to provide internet access.

5.2 AM in Mobility-as-a-Service

The AM are deployed within MaaS to better provide on-demand services that bridge the first and last mile and provide seamless and intermodal trips. They are deployed in highly dense areas such as city centres or the connecting points with the suburbs.

Their introduction aims to support PT. They are positioned to influence more than one mode of transport (cars, walking, and biking). The technological innovations in AVs are similar to the previous scenario. However, there are significant advancements in digital on-demand services, interoperability, ticketing, utilising mobile apps, the cloud, ride-pooling and routing algorithms. The regulations to support this deployment strategy rely on public and private collaboration for MaaS services, platform management, open API, and data sharing; and other regulations such as the sustainable urban mobility Plan (SUMP) and smart city initiatives. They adopt fuel and parking measures and push and pull regulations (in line with transport demand management (TDM)) to prevent the use of internal combustion engine vehicles (ICEVs) and reduce the environmental and societal impact.

Even though the public transportation offer is efficient and reliable, there are gaps connecting travellers to mobility hubs (e.g. tram and metro stations). Thus, the AM seeks to capture first and last-mile travellers that would have driven, walked or biked to reach a train/tram station or other destinations. The modal shift to be studied in this scenario concerns the share of journeys within an intermodal trip that connect to or from a train/tram station or other destinations. In addition, the AM can of course also connect the city centre with the suburbs, supporting existing public transport routes or filling gaps. Since fewer AM are needed to meet the travel demand in comparison to the robotaxis scenario, this leads to an increase in road capacity and thus a decrease in road traffic, especially during peak hours. Nevertheless, it is considered that for the AM to meet the travel demand and remain competitive, the waiting time is less than 4 minutes. Hence, there is an increase in VKM due to pooling, rerouting to pick-up and drop-off passengers due to a large fleet (ITF 2020; Milakis et al. 2017a; Jones and Leibowicz 2019; Moreno et al. 2018).

The long-run consequences of this scenario are: an increase in PT ridership, as the AM provide seamless intermodal and last-mile trips and is considered as a mobility gap filler. This improves the connectivity to other PT modes. However, the convenience of the service could replace more short-distance trips from walking and biking. In terms of urban impacts, urban planning is predicted to evolve towards more compact cities (more walkable and developed around mobility centres) and mixed land use (residential, commercial and business in the same area). The scenario would lead to a reduction in road space. And if the city adopts a sustainability agenda, it could repurpose this space to benefit the citizens. The city could become more attractive, thus urban density increases, and by a consequence, the jobs rate increases. These effects are also attributed to an increase in access and accessibility of all inhabitants.

5.3 The mobility radar for the scenarios

Accordingly to the scenarios' description and assumptions, Figure 4 presents the mobility radar for assessment of the two scenarios. This is an explorative approach, these future perspectives need further research, and the enclosed developed hypothesis will be deepened on sites in the EU-funded ULTIMO project (2022-2026).

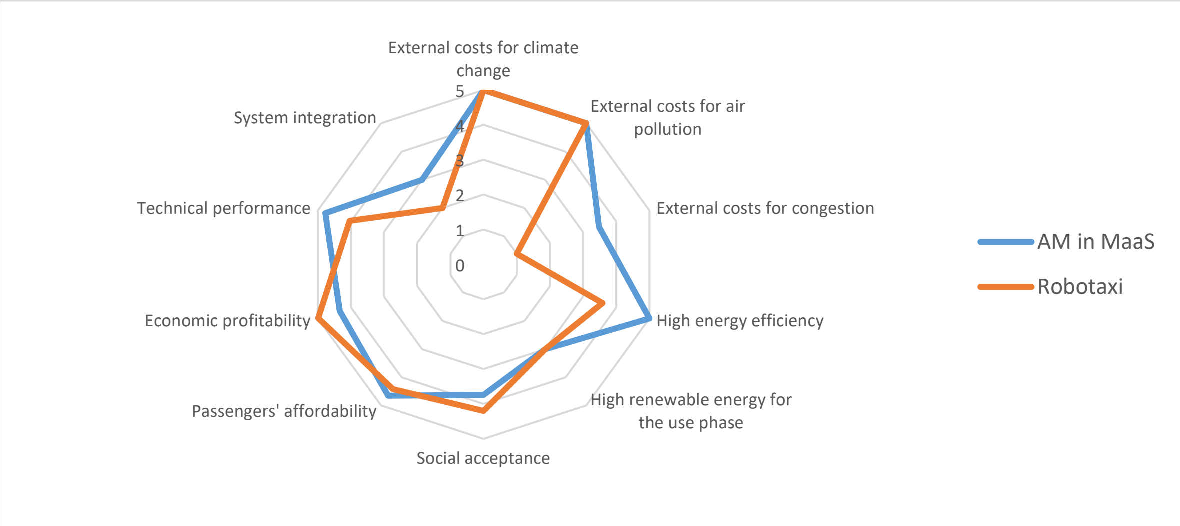

Figure 4. Sustainability mobility radars for scenarios deploying AM in MaaS and Robotaxis.

The assessment suggests that, overall, AM in MaaS tend to present a better performance than AM deployed as Robotaxis. As electric vehicles, the external costs for climate change and air pollution of both scenarios score high. Whereas AM in MaaS scores much better in terms of external costs for congestion and energy efficiency, considering that the average occupancy and sharing rate for AM in MaaS are higher. The calculation of the external costs is detailed in 'Deliverable 8.6 Final Economic Impact Assessment' (Antonialli et al. 2022), and it comprises air pollution, climate change, well-to-tank, noise, accidents, and congestion (Jaroudi 2021).

The social acceptance for robotaxis could be higher than the AM in MaaS, since they are akin to individual mobility; they could be a faster option (shorter waiting time), cheaper, and no intermodal. Therefore, the social acceptance could be higher; nonetheless, this form of deployment would be less sustainable. The robotaxis are very attractive for users and compete with public transport. The passenger traffic would thus be displaced from public transport to robotaxi and increase congestion (WEforum 2020).

The economic profitability is assessed according to the costs (Euro) per vehicle-km, therefore in VKM the operation of robotaxis is cheaper than AM, however, when it comes to costs (Euro) passengers-km, the price for the AM services are more attractive and affordable (Bösch et al. 2018).

Regarding the technical performance, robotaxis are expected to have a higher speed, with less waiting time, however, the AM would present higher occupancy. And in terms of system integration, the AM would be integrated in MaaS for data, information, booking, ticketing, billing for different mobility services etc. On contrary, robotaxis would present a lower level of integration. This means that the integration of data, information and the related partners within the transport system is low, and no synergies or positive externalities can be enabled.

The sustainability assessment of the scenario is in line with MaaS and SUMP approaches, reinforcing that mobility system integration is crucial to fostering intermodality and sustainable mobility. Additionally, the development of policy instruments and push and pull measures are levers for a mobility shift from private and individual mobility towards public transport centred MaaS. Hence, the next chapter focuses on policy instruments and strategies targeting sustainable mobility and the integration of the AM in mobility systems in order to serve the general interest.

6 Strategies and recommendations for the integration of automated minibuses in urban mobility

The results from indicators assessing the current performance of deployment of automated minibuses coupled with the externalities scenarios studies are seen as complementary, and they will underpin recommendations following SUMP concept and guidelines aiming at strategies and planning sustainable urban mobility with automated shuttles. Therefore, section 6.1 addresses strategies and policy instruments to deploy AVs and AMs integrated into urban mobility systems aiming to meet the needs of citizens and sustainable mobility goals of the cities. Section 6.2 addresses the future vision of AM integrated into ITS and MaaS, this topic is presented in detail on AVENUE Work Package 9 'Transition Roadmap for Autonomous Vehicle in public transport', task 9.3 'Roadmap for cost-attractiveness'.

6.1 Strategies and policy instruments for the integration of automated vehicles in urban mobility

"Well-designed public policy is needed to foster the right outcomes to maximize public and private value" (Eliot and Fagan 2021)

AVs and AMs are new technology to be implemented into the transportation network of cities. Therefore, the development of a policy framework and strategies for the deployment of AVs and AMs is crucial to ensure that this mode of transport can complement the current transportation system and bring benefits for passengers and likewise to the sustainability goals of cities.

Policy makers and urban planners are key stakeholders in steering the deployment of AVs and AMs through the development of policy instruments, as well as strategic planning and infrastructure to meet the needs of citizens and sustainable mobility. Based on the literature, hereinafter, we develop insights for AVs' policy formulation.

Li et al. (2019) review in their paper the importance of AV policy formulation and discuss three methods. They underline the importance of controlling uncertainties and implementation of this new technology and the difficulty of the development of common frameworks or methodologies because traditional laws and regulations are based on human drivers and not, as for AVs, on machines. The three methods they discuss for policy formulation were already used for existing transport systems, namely:

i) *The backcasting method* uses scenario building for the desired future and then looks backwards on how to achieve it. It helps, therefore, to determine AV objectives and the pathway. It has already been used in several cities to analyze how transport systems can become more sustainable.

ii) *The dynamically adaptive method* is often used when dealing with great uncertainties, it´s based on having a specific goal that doesn´t change but adapting policies as needed along the way, thereby continuously learning and adapting. Policy makers would take immediate actions but within a framework that allows adaptions and to respond to changes over time.

iii) *The policy transfer and migration method* is based on using existing knowledge and policies from another time or place and use them to develop the respective policies needed. It distinguishes between adaptation and mitigation, adaptation concentrating more on local, short-term actions and mitigation maintaining a global, long-term view.

When transitioning from human drivers to AVs, adaptations in mobility regulations and standards are needed. The backcasting approach was, for example, used in Staricco et al. (2020) for the Italian city of Turin for the year 2050. In this paper, the authors use this approach to try to define a policy pathway to transition to automated vehicles with the background objectives of sustainability and livability in the city. They developed 33 key actions clustered into 6 categories (road hierarchy, restriction to vehicle circulation, parking, public transport, sharing and active mobility) that were defined with the SUMP as the key planning tool for the actions. It is stated that backcasting is often mentioned as an appropriate method for the transition towards autonomous driving in literature, quoting Li et al. (2019) and González-González et al. (2019) but that there can be some difficulties while using it in real-world case studies, mainly because of its complexity, uncertainty and many stakeholders involved.

The study from Thaller et al. (2021) reviews sustainable transport in Austria to develop disruptive policy packages and gives more detailed suggestions on how to design such policies. They distinguish between three different policy categories

i) the first being *pricing instruments* like congestion pricing or tolls. They argue that those measures are relatively easy and quick to implement and have shown to be very effective in changing transport behaviour.

ii) The second category is additional *restrictive measures*, for example, quotas or bans. They were mentioned as being important but merely difficult to implement because of the acceptance of the population, therefore, additional incentives could be useful.

iii) The last category is the *soft policy approach*, which consists of raising awareness within the population to increase acceptance and understanding and thus support restrictive policies regarding mobility. This could be done with media reports, for example.

All in all, the authors support the idea of designing policies that serve two goals, first disruptiveness (quick and effective) and second implementation (acceptance and costs); policy packages, therefore, should include measures from both dimensions. They argue that mostly the dimension of implementation is considered by policy makers, concentrating on acceptance and technology innovations because of the lack of acceptance of the public for disruptive policies and fear of losing voters of political parties. Lastly, they stress the fact that spatial planning and infrastructure are crucial to consider because they build the foundation for policies.

In the following subsections, the reviewed literature concentrates on five axes when suggesting new policies, all five being interconnected: reducing CO_2 emissions and electromobility, reducing congestion, incentivizing the use of public transport and urban planning models, social equity, levers for AVs and AMs.

6.1.1 Reducing CO_2 emissions and electromobility

By targeting the reduction of CO_2 emissions in mobility, Axsen et al. (2020) provide insights into possible policy development. They suggest the implementation of quotas for low CO_2 emissions fuels, zero-emission vehicles, and electric vehicles. The authors also suggest having limits on CO_2 emissions for passenger vehicles.

Thaller et al. (2021) argue that electromobility should be encouraged, but being attentive to the energy sources. In addition, they express that the use of hydrogen vehicles should also be promoted to reduce pollution. Ezike et al. (2019) provide three policy recommendations for the implementation of AVs, based on the statement that AVs will increase congestion and pollution when used as single-occupancy vehicles. Their last policy recommendation is to have AVs powered by electricity to reduce pollution and therefore also construct more EV charging stations. The authors stress the fact that it is important to start now with the planning and not wait until AVs are getting implemented to make sure the new vehicles meet the needs of the municipality and not just benefit the car makers.

6.1.2 Reducing congestion

Fagan et al. (2021) developed five different mobility policy actions regarding AVs that can already be taken now to be ready when they are being implemented. Their third action to prepare for AVs is to manage and reduce congestion. AVs, if used as TNC (Transport network companies) single passenger model, will probably make congestion even worse, so cities need to prepare models to counteract. This could be, for example, with financial penalties for vehicles with only one passenger or adjusting the toll depending on the number of people using it. Some cities are already using the congestion pricing model, which charges a fee for entering the urban area of the city with a private vehicle. This can encourage people to travel by public transport if the city provides adequate public transportation. Steps they propose to take to do so would be the following: i) profile existing traffic patterns and congestion to understand the current traffic problem and what the goal should be, ii) learn from existing programs and establish objectives, iii) define your guiding set of core principles for the design of the program, iv) develop a congestion pricing strategy and communications plan to win over the public, v) improve transit uptake and performance with for example contacting major employers and offering some kind of discount for public transport as incentives for new employees, vi) and finally to design a pilot, learn and scale.

To avoid congestion, it can also be interesting to take a look at TDM (Transportation Demand Management), a set of strategies aimed at maximizing traveller choices. Ferguson (1990) describes TDM as a method to change mobility behaviour to avoid the expansion of a transportation network; it is focused on the travel demand rather than transportation supply. The author mentions that the most common approaches used are efforts to change the travel mode and time. General actions categorized under TDM are to eliminate trips entirely by providing substitutes (e.g., online shopping, home office), shifting trips to less congested destinations (e.g., zoning restrictions), shifting trips to higher-occupancy vehicles (e.g., increasing parking fees, incentives for carpooling, guaranteed to ride home programs), shifting trips to less congested routes (e.g., permanent or temporary street barriers to remove traffic in residential areas), shifting trips to a less busy time of the day (e.g., alternative work schedules).

Part of TDM is also to increase carpooling and ride-sharing. Brownstone and Golob (1992) state that some effective methods to incentivize it are to provide guaranteed rides home, to implement high-occupancy vehicle lanes, to subsidize ridesharing, and to guarantee reserved parking. A newer study from France by Delhomme and Gheorghiu (2016) found that carpoolers are more likely to be female, to have children, to be environmentally conscious and to have a positive attitude towards public transport. Following this study, the main incentives for car pooling are financial gains, environmental protection and time-saving. Consequently, policy makers should make those gains obvious, for example, by highlighting positive effects like less congestion. van der Waerden et al. (2015) also found in their study for the Netherlands that time and cost-related attributes are the main influential factors for ride-sharing. They also add that flexible working hours and difference in parking situation of solo riders and shared rides are important incentives.

Conceição et al. (2017) reviewed the option of having dedicated zones only for AVs to minimize congestion. Because of their calculation method, they supposed static traffic assignments, which is not realistic, but despite those limitations, they found out that dedicated zones might be an option as it reduces travel time. Ezike et al. (2019), basing their three policy recommendations on the statement that AVs will increase congestion and pollution when used as single-occupancy vehicles, recommend prioritizing the movement of people over vehicles by motivating pooling. They suggest expanding high-occupancy vehicle lanes and other congestion pricing strategies.

6.1.3 Incentivizing the use of public transport and urban planning models

The first action Fagan et al. (2021) suggest municipalities should take to prepare for AVs is to foster mobility as a service (MaaS), to combine all trip planning, booking and payment of different transportation methods in one single platform. To implement a MaaS system, AVs are not necessary, but having a MaaS system in place when introducing AVs might attract travellers who use a private vehicle to shift to multimodal transportation. The steps they propose to develop a MaaS system are the following: build or foster data-sharing and interoperability requirements, improve coordination of existing public transportation services and ensure MaaS aligns with regional mobility goals.

The second action to take following the steps of Fagan et al. (2021) is to rethink curb design and street space allocation. The authors mention that cities should implement restrictions for pick-up and drop-off (PUDO) zones, especially for AVs, as they may always respect the traffic rules. To discourage the use of private vehicles in the city centres parking should be made more difficult with for example elevated parking costs and/or reduced parking space. Steps to take for this approach could be the following:

i) mapping the curb to understand how it is used today,
ii) establishing a prioritization framework that supports the municipality´s long-term vision and reflects the city´s needs,
iii) piloting alternative curb uses and PUDO zones to test whether the planned change results in the desired outcome and to understand possible future problems,
iv) and lastly, establishing a curb-use and street space allocation master plan.

Moreover, behavioural economics could be used to nudge passengers to use more public transportation and reduce private car ownership and use more public transport (Narayanan et al. 2020). Non-financial incentives such as travel vouchers could promote the use of sustainable transportation (Byerly et al. 2018). Furthermore, land use is also an important point in González-González et al. (2019), to restrict motorized access, implement new parking policies, green infrastructure, and active mobility as well as equal access to housing in the city. Milakis et al. (2017b) indicated that AV would affect existing transport infrastructures such as road planning and design, intersection design, parking infrastructure, public transport and transit services, cycle lanes and paths, sidewalks, and pavement. Indeed, AV could have a positive impact on mobility due to an increase in road capacity (Cordera et al. 2021).

Ezike et al. (2019) also suggest adapting the street design to have more PUDO zones and less parking as their first policy recommendation. Their second policy is to enhance other public mass transport options so that AVs and other public transport can complement each other, to improve first- and last-mile connections. Thaller et al. (2021) take the view that policies need to influence the mobility behaviour of the population to nudge them into more sustainable mobility for reducing CO_2 emissions. They address an interesting idea that was not really mentioned in the other reviewed papers, which is the transition of city structures, suggesting a complete change from the current car-centred structure into spaces where daily life can be lived within short distances, where the need for cars disappears. Nevertheless, they admit that this requires a deep restructuring process and is not something that can be implemented short term. Urban planning models such as compact city (an urban design model that relies on high-density areas with mixed land use) could reduce trips distance, improve public transport, promote active modes, and deter travellers from daily use of cars (Heinrichs 2016; Rogatka and Ramos Ribeiro 2015)

In general, most projections of the city of the future do account for the potential of disruptive innovation in the transportation system like the AV, AM, and MaaS. For instance, Heinrichs (2016) formulates different effects of AV on land use based on future cities. One prediction sees the dominance of mobility hubs (a multimodal station that connects a variety of transportation modes); the city will be designed in a polycentric manner around these hubs where most likely, pick-up and drop-off points for AM will be located (Heinrichs 2016; Intertraffic 2021). Another scenario focuses on the spread of highly dense urban centres and the development of suburban parts, it focuses on swarms of AV circulating on exclusive guided routes for the AV. Another alternative implies that AV in the transportation system would lead to low-density settlements and increased urban sprawl (Angel 2012).

These effects are dependent on the form of AV introduced, whether private, taxis competing or supporting public transport, or microtransit integrated into public transport. Another important aspect of the AV influencing land use would be parking space. For private AV, there might be an increase in the number of needed parking spots, but this would be realized by optimising the parking space to fit more vehicles compared to the current layout and by relocating them outside the urban areas, which would increase the number of empty trips (Mitchell et al. 2010). However, if AV are integrated in public transport such as the AM, parking spaces could be significantly reduced since the vehicles would mostly be on service looking to pick up passengers (Fagnant and Kockelman 2015). Thus, AV positive impacts on land use depend highly on its integration in public transport and on how (private, robotaxi, AM) and where (urban, suburban) it would be introduced.

Therefore, to start, public transport needs to be expanded to reduce the need for private car transport, to connect cities with suburbs or other neighbouring communities, to expand first and last mile transport options and to build more bike lanes to incentivize active transport. In addition to that, to get people to really use public transport travel times and costs should be reduced, so that public transport can compete with private car transportation.

6.1.4 Equity/ Social Sustainability

Equity is a very important topic when talking about the implementation of AVs. Emory et al. (2022) analysed this topic in the United States. They state that AVs, implemented correctly, can increase transportation access for disadvantaged groups and therefore reduce inequality but can also easily increase inequality if implemented incorrectly. Security should be taken more seriously in the planning of driverless AVs to provide access to vulnerable people to harassment and assault (e.g., women, racial minorities, trans people), who may avoid those vehicles if security is not given. It is also important to mention that with driverless vehicles, former drivers will lose their job. Those people are in the US mainly from minority groups, and they will be the ones especially harmed by the implementation of AVs. The government should therefore have employment strategies and new jobs ready for them. According to United Nations (2013), accessibility is at the heart of achieving cities that are sustainable, environmental-friendly, and socially equitable and accessibility is achieved through a high efficiency-transport system that promotes active mobility and public transportation while reducing individual car dependency. AV deployment could ensure an efficient transportation system if the vehicles are integrated with public transport. Thus, AV hold the key to achieving social equity and sustainability in cities. However, if introduced as a competitor to public transport, AV would worsen social mobility. It would further reinforce social segregation models. Another concern regarding equity is that AVs will mainly be implemented in wealthier neighbourhoods and therefore disadvantage lower-income neighbourhoods, a critical point that is also mentioned (Fagan et al. 2021). Moreover, AV use would require a level of "technological competence" thus excluding those deemed less technological advanced from the mobility system (Bissell et al. 2020).

AVs are revolutionary to the transportation sector; therefore, it is critical that policymakers understand the importance of this to create a network of inclusion instead of increasing inequalities. They need to include groups that suffer mobility obstacles actively in their planning and set frameworks. This can be done with reviewing how other countries and municipalities are developing their policies but at the same time considering their own local needs. They also must be aware of possible unintended consequences of their policies. Fagan et al. (2021) furthermore urge to consider the equity impacts of MaaS systems. If implemented as an app, everyone who wants to use it should have a smartphone, which especially some older and low-income residents might not have.

They also explain why it is important to carefully implement different payment systems; a monthly pass to use all transportation systems could be unfair to lower-income users because they might not be able to pay upfront while wealthier users are able to save money. Equity is also an important topic when thinking about where to prohibit cars and reduce parking space. Usually, cities would implement those limitations in dense urban areas as this would make sense considering congestion and efficiency, but on the other hand, those areas are often homes for lower-income residents, so they would be affected disproportionately. When congestion pricing strategies are implemented, and it becomes more attractive to live at a shorter distance to work because of the travel costs, lower-income residents might be at risk for displacement. Ezike et al. (2019) mention that it is important that whenever changes should occur, all people impacted by those changes should have a say in it and make sure that AVs are also accessible for people with disabilities.

González-González et al. (2019) also stress the importance of social sustainability. Very similar to Emory et al. (2022), they urge to increase accessibility for all social groups instead of only the wealthy and therefore increase equity and inclusiveness. Additionally, they mention that the promotion of multimodal public transport is important, that funds for public transport must not be cut and that MaaS system implementation can be very useful to ensure equal access for all.

6.1.5 Levers for AVs and AMs

Another action, according to Fagan et al. (2021), is to establish data-sharing guidelines and agreements, a point that is also mentioned in Die Bundesregierung (2015). As AVs will collect a lot of information when implemented (with cameras facing the inside and outside of the vehicle, traffic information, data about the weather, street conditions etc.), thus it is crucial to define who owns that data and who needs to have access. AV operators are hesitant to share their collected information, fearing that their competitors will have an advantage.

Steps to implement those guidelines could be the following: determine data needs and wants, draft data-sharing guidelines considering transparency, inclusion, public value, and others, begin implementing with existing mobility providers and evaluate the value of information sharing and refine guidelines. The last action that should be taken for the implementation of AVs in accordance with Fagan et al. (2021) is to reposition revenues. Municipal governments rely on income through private vehicles with tax gas, parking fees or driving/ parking violations. With the above-mentioned actions and implementation of AVs, those revenues will decline, and the government, therefore, needs to find other revenue generation methods, for example, transportation charges and land use or property taxes. Steps to implement this could be the following:

i) understanding the revenues and policy levers that municipalities can pull
ii) identifying existing curb demand and areas for flexible curb space
iii) ensuring all loading zone signage is specific, visible, and managed
iv) confirming the current tax code does not incentivize parking lots and
v) determining appropriate areas for eliminating parking minimums.

All five actions developed by Fagan et al. (2021) were applied in another paper of the HARVARD Kennedy School of Eliot and Fagan (2021) during a policy development simulation.

In Die Bundesregierung (2015), the German government published a paper regarding their strategy for implementation. It describes the situation they would like to live in a few years, however not so much what kind of policies they would need to implement to get there. Nevertheless, it shows an important inside from a governmental side as the other papers reviewed are all researchers´ points of view. It includes five topics: Infrastructure, Legislation, Innovation, Interconnectivity and Cyber security and data protection. Concerning infrastructure, they envision implementing a digital infrastructure with high-speed data transmission and basic universal coverage with minimum speeds and intelligent roads. Legislation should be based on an international and national regulatory framework, as well as driver training and international level type approval and technical inspections for the automotive industry. Innovations mean, on the one hand, opening possibilities for trialling those new technologies in Germany but also research funding. With interconnectivity, the German government stresses the importance of interaction between vehicles and infrastructure and collecting and especially sharing and consolidating mobility and spatial data to provide real-time information for the vehicles, as also mentioned in Fagan et al. (2021). They also plan interlinking traffic signs to optimize traffic flow and develop a high-precision map system. The last point mentioned by them is about vehicle safety and the protection of personal rights. They plan on standardizing cyber security throughout Europe and want to implement a general data protection law that includes anonymization and pseudonymization techniques.

To better support the deployment of AV and its integration within the public transport network, there must be engagement from all key stakeholders. the collaboration between different actors (especially citizens) would uphold a citizen-centric model that is beneficial to the city and the environment while ensuring financial gains and transport efficiency. Furthermore, implementing pull measures using nudges would incentivize passengers to adopt sustainable forms of AV such as AM in MaaS (PwC 2017; Narayanan et al. 2020; Kosters and van der Heijden 2015).

Finally, table 9 summarises the instruments and measures discussed in this chapter.

Table 9. Summary of policies and strategies for sustainable mobility.

	Push measures	Pull measures
Planning instruments (infrastructure provision and spatial planning)	. Spatial planning (e.g. reducing road space, car limited zones, parking policies)	. Infrastructure for BEV/AM charging . Defining a common API for system interoperability and positive externalities . Mobility hubs . Attractive active transport (biking lanes, pedestrians zones) . Attractive public transport (bus rapid transit, better connections) . Shared mobility and high occupancy vehicle lanes . Mode integration, Mobility-as-a-service, . Intelligent Transport Systems (ITS)
Command-and-control (regulations, restrictions and standard settings)	. Pricing policies (road pricing, carbon pricing, congestion charging) . Congestion management . Speed reductions . Taxation (carbon tax, parking tax) . Transport restrictions (Low emission zones, car limited zones)	. High service frequency . Public transport priorities . Technology improvements (automated, connected, increasing fuel efficiency)
Incentives (financial incentives/subsidies to support specific behaviours)		. Soft policies/awareness-raising . Commuter solutions (Corporate mobility management, teleworking) . Alternative fuels and power trains (electric, biogas, biofuels, hydrogen)

Source: developed by the authors, based on TUMI (2018), Thaller et al. (2021)

6.1.6 Final considerations on policies and strategies to deploy AM in urban mobility

Considering the diverse policies and strategies described in the sections above, one can state that an integrative approach and a combination of different measures are needed for the integration of AVs and AMs in urban mobility. Policy instruments and pull and push measures are key elements for system innovation and a shift from private mobility to a mobility that serves the general interest.
However, we do emphasise that the AM in MaaS can combine and enhance different pull measures and avoid some unpopular push measures. The combination of pull measures is also crucial to pave the way for mobility transitions and incentivize people to adopt new and sustainable mobility. From the perspective of a combination of pull measures, the AM adds technological improvements and innovations in mass transit, such as automated, electric, connected, on-demand, and door-to-door services. AM deployed within a multimodal and intermodal mobility system can also boost the attractivity of soft modes of transport and public transport, see Table 10.

Table 10. Pull measures for AM in MaaS

Pull measures for AM in MaaS
Levers for AM in MaaS: . Infrastructure for BEV/AM charging . Defining a common API for system interoperability and positive externalities . Mobility hubs **AM in MaaS as a lever for:** . Attractive active transport (biking lanes, pedestrians zones) . Attractive public transport (bus rapid transit, better connections) . Shared mobility and high occupancy vehicle lanes . Mode integration, Mobility-as-a-service . Intelligent Transport Systems (ITS)

A step further, we focus on the AM integrated with MaaS and ITS as it is considered as a positive model of deployment based on 5.2. This deployment strategy could improve the attractiveness of public transport by offering better connections, flexibility and better accessibility. Furthermore, the integration of the AM in MaaS systems and ITS could improve mobility efficiency and intermodality (section 6.2 develops these elements). The new technologies attributed to AM would attract passengers since it provides convenient and efficient services. It would be further as flexible as private cars but at affordable costs. As mentioned before, approximately 45% of the potential user are ready to give up their car if we could provide AM in MaaS services. The implementation of the AM in Maas would integrate pull measures on multiple levels to address the entirety of the transportation ecosystem and not just the AM. This would promote sustainable mobility and attract passengers to use the AM as an intermodal mode instead of cars.

Another aspect addressed by Audouin and Finger (2019) is the importance of new governance structures and new governing approaches from public authorities to develop MaaS schemes and target sustainability transitions. The study points out the importance of having national and local government participation in order to have a shift from a ‘governing by doing’ and ‘laissez-faire’ approach to a ‘governing by enabling’ approach. Hence, national and local governments set regulations and standards, for instance, data-sharing policy aiming for greater efficiency of mobility systems and open API (Application-Programming-Interface) as a key enabler for interoperability among transport systems, since open APIs can create open ecosystems for both users and providers of mobility services.

Following the context and goals towards sustainable mobility of each city, innovative modes of transport combined with policy instruments can enable system innovation and offer intermodal mobility as attractive as private and individual mobility.

6.2 Vision: Sustainability impacts of AM in ITS/MaaS

In deliverable ‘D9.3 Roadmap for cost-attractiveness of the AVENUE project’, the future vision of automated mobility for the year 2030 is presented. In the following, we present a brief summary as this vision shows the path of the AVENUE project towards more integrated and sustainable mobility.

As mentioned before, automated vehicles (AVs) could play a crucial role in the transition to a more sustainable transport system. However, their actual contribution depends on different factors, such as:

i) Technical issues (Zinckernagel 2021)

ii) Environmental performance of AVs according to average utilisation, lifetime and total mileage, the electricity mix used, the substituted means of transport, energy savings and demand (Viere et al. 2022)

iii) Social acceptance, accessibility and greater inclusion of PRM (Korbee et al. 2022b)

iv) Their operation and integration with other means of transport and the use of data and AI (see WP9 vision, economic assessment and bellow), and last but not least

v) The governance (see above) to enable positive externalites and avoid negative externalities

Hence, the vision focuses mainly on the integration of AVs and AMs into a multi and intermodal mobility system. The integration of (road-bound) AVs into intelligent urban transport systems can be envisioned in different ways (UITP 2017): AV could be deployed as
a) privately-owned cars,
b) shared fleet of vehicles competing with public transportation (e.g. robotaxis) or as
c) a fleet of shared vehicles integrated into public transportation (AM in MaaS).
The concept of automated minibuses (AM) operating in a Mobility as a Service (MaaS) system and in a later stage in a (self-learning) Intelligent Transport System (ITS) has been selected as a promising option for a more sustainable future mobility. Thereby, AM as first and last mile and mobility gap filler could provide an on-demand, door-to-door service in which trips are pooled (i.e., multiple trips of users are combined) and connected to other complementary private and public means of transport. This vision of integrating AM into a citizen-centred MaaS system and its integration into an ITS uses a holistic approach and is based on three main theoretical expected benefits:
1. Innovations into the transport system have to focus on citizen centrality in order to increase the attractiveness for passengers in terms of mobility offer, time and usability.
2. A sustainable transport system will have to avoid a situation in which value is captured by a single actor through the system of the 'winner takes it all' and a dominant market position, such as a monopoly.
3. The aim is to enable positive externalities and lower negative externalities through intermodality and interoperability, thus serving the general interest of society.
The mobility paradigm of the last decades was based on cheap fossil fuel energy, high CO2 emissions, individual mobility and a linear economy (Goehlich et al. 2020). Altering this mobility paradigm requires social transformations in addition to technical innovations (such as AM and MaaS/ITS). The socio-technical transformation is expected to impact passengers, transport operators and related companies, technology providers, governance etc., and therefore the whole mobility system and partly the society itself. This transformation process has further to be managed to avoid and overcome diverging interests and resistances.
Thereby, AM in MaaS can be a promising game changer. The AM, deployed on-demand and door-to-door and combined with other means of transport, will provide an individualised, affordable and inclusive transport as convenient as privately-owned cars. An innovative coopetition governance on local, national and European level, as well as open data, open interfaces and protocols are further key factors for fair competition and more sustainable mobility. In addition, AVs coupled to ITS and AI (artificial intelligence, see as examples the seven loops in **Fehler! Verweisquelle konnte nicht gefunden werden.**5 are expected to make a self-learning transport system which is more reliable, safe, efficient and flexible (a concept called ambidexterity, see e.g. Raisch and Birkinshaw (2008), combining incremental and disruptive innovations, and thus antinomic goals. As a result, AM and ITS have the potential to make the transport system citizen-centric, resilient and sustainable by enabling positive externalities and lowering negative externalities. The citizen-centric approach could thus become purpose centric, serving the general interest to the best for all stakeholders. However, this innovative vision of the future is not only of a technical nature, as shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**5. This vision is not even achievable only with changes in governance, citizen-centric also means that the whole society will change, even has to change, in the process.

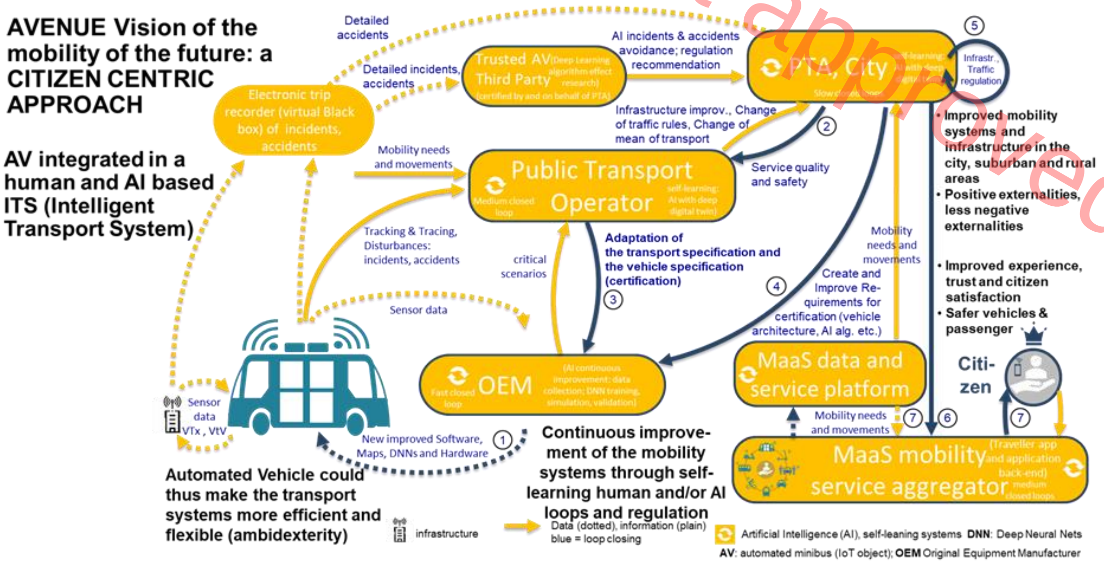

Figure 4. The mobility of the future: a citizen centric approach by integrating AV in an ITS

7 Conclusions

The sustainability assessment embedded the results from the AVENUE WP8, which targets the social, environmental and economic impact assessment, as well as it brings forward further sustainability analysis and recommendations for the deployment of AM in mobility systems. The cornerstones concepts for this assessment are: sustainable urban mobility planning, indicators for sustainability assessment, scenarios for assessment, externalities, policy instruments for mobility transitions.

A step further, the sustainability assessment conceptualised a set of indicators to assess the social, environmental, economic, governance and technical impacts of the implementation of AM in the transport system of European cities. Following this framework, the assessment of the pilot trials and scenarios of deployment for the AM is developed. It is worth noting that the small scale of deployment, the newness of the technology and Covid-19 pandemic restrictions posed some limitations to the current performance of the AM. The assessment of the pilot trials points out that at the current stage, the AM does not fulfil all the premises for sustainable mobility. However, the AM prove to be feasible as new alternative mobility and with the potential to support cities to achieve sustainable mobility under certain premises (e.g. technological improvements, vehicle usability and occupancy, integration into the mobility systems and intermodality, policies and strategies for sustainable mobility).

Further variables and questions will influence the performance and assessment of the AM in urban mobility, such as which modes of transport it will replace; what will be the occupancy rate; how fast the technology and policies development will occur; at to which extent AM will be integrated into the mobility system, and under which policies and incentives.

Regarding the externalities assessment scenarios for the deployment of AM in mobility systems, the study pointed out that 'robotaxis' and 'replacing all buses' record increases in negative externalities. 'Robotaxis' without ridesharing services would negatively influence the transportation system as it would repeat a model of individual mobility. Replacing all buses with AM would create more congestion since more vehicles are needed on the road to compensate for one bus. Furthermore, 'replacing all cars' scenario shows the highest decrease in external costs out of all scenarios, which is in line with the potential advantages of eliminating ICEV in cities. The AM in MaaS scenario also shows a consistent decrease in externalities (in the Geneva, Copenhagen, and Lyon). As a mobility gap filler, it is easier to integrate the AM within the transportation system and could provide better results accompanied by pull measures to promote walking and biking. Another interesting side of the analysis is the focus on the suburban scenarios; both have a positive impact. This shows the need to strengthen the transportation network in less dense areas.

If we were to focus on the externalities categories, the congestion would record the biggest reduction in external costs (Sc 2, 4, 5, and 6) or the biggest increases (Sc 1 & Sc 3). It reflects the transport pricing and value of time. Dominating congestion externalities are aligned with Jochem et al. (2016b), and van Essen et al. (2019) results for road traffic congestion. Alternatively, other studies, such as Fournier et al. (2020) demonstrate that accidents could be the main cause determining the increase or decrease in externalities.

The sustainability assessment of the scenarios (AM in MaaS and Robotaxis) pointed out that overall, AM in MaaS tend to present a better performance than AM deployed as robotaxis. This result is in line with MaaS and SUMP approaches, reinforcing that mobility system integration is crucial to fostering intermodality and sustainable mobility. Additionally, the development of policy instruments are levers for a mobility shift from private and individual mobility towards public transport centred MaaS.

Those elements are key for system innovation, and it comprises changes in governance, from a laissez-faire approach to a 'governing by enabling' approach.

Finally, the perspective is that AM could be integrated into urban mobility to improve the transport network, cover mobility gaps, and foster intermodality by substituting motorised vehicles, and offering on-demand and door-to-door services. The AM can be seen as a game-changer by improving mobility services and offering attractive private mobility, being part of the mobility innovations that target a system innovation and a shift from private to a mobility that serves the general interest. Indeed, AM could support MaaS approach, electrification, and shared mobility, and accordingly to the recommendations in our study, they can foster SUMP and the sustainable agenda of cities.

Appendix A:

Urban Geneva,2015

	Mode of transportation	
Externality type	Car	Bus
Air pollution	6.09	2.94
Climate change	12.72	1.70
Wtt	4.09	0.74
Noise	18.67	3.27
Accidents	13.13	6.30
Congestion	382.22	25.29
Production	3.68	0.71
Total externalities per mode of transport	440.61	40.95
Total externalities – reference scenario	481.56	

Suburban Geneva (second suburan ring), 2015

Externality type Mode of transportation	private vehicles	buses
air pollution	1.50	0.56
climate change	3.14	0.33
wtt	1.01	0.14
noise	4.61	0.62
accidents	3.24	1.20
congestion	61.22	3.12
Production	0.91	0.14
Total externalities per mode of transport	75.64	6.11
Total externalities	81.74	

Appendix B

<table>
<tr><th colspan="3">Assumptions and references for 2030 scenarios assessment</th></tr>
<tr><th></th><th>Assumptions</th><th>References</th></tr>
<tr><td>Climate Change</td><td>AM near future performance 77gCO2eq/pkm
RT as a medium BECAV 140gCO2eq/pk</td><td>Reference: Huber, Viere, Nemoto, Jaroudi, Korbee & Fournier (2021) Climate and environmental impacts of automated minibuses in future public transportation. Transportation Research Part D. Currently under minor revisions.</td></tr>
<tr><td>Renewable Energy</td><td>The measurement takes into account the use of renewable fuels according to the energy sources for the mode of transport. The AM and RT are considered as a battery electric vehicle (BEV). Therefore, the electricity mix of each country may influence the percentage of renewable energy used in the vehicle use phase. Estimates of future electricity mix in the EU is considered. THe REmap scenrio is used (50% of renewable energy by 2030 in the EU)
2010 – EU28 20% of renewable energy in electricity generation
2030 – EU28 40% (Reference case scenario)
EU28 50% (REmap scenario)</td><td>IRENA (2018). Renewable Energy Prospects for the European Union. Based on REmap analysis conducted by the International Renewable Energy Agency in co-operation with the European Commission</td></tr>
<tr><td>Noise Pollution</td><td>Assuming that the AM is an electric vehicle and drives around 30km/h and the robotaxis are electric vehicles driving at 50km/h.</td><td>Marbjerg, Gerd (2013): Noise from electric. a literature survey. Vejdirektoratet. Available online at https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwiG37W-1LHtAhUJhRoKHT1KDQ4QFjADegQIBRAC&url=https%3A%2F%2Fwww.vejdirektoratet.dk%2Fapi%2Fdrupal%2Fsites%2Fdefault%2Ffiles%2Fpublications%2Fnoise_from_electric_vehicles_0.pdf&usg=AOvVaw1ksLoAa2OmmfiYsj1WTR_O.
Lelong, J.; Michelet, R. (Eds.) (2001): Passenger cars. Power unit and tyre-road noise, driving behaviour: what are the stakes? Inter-noise. The Hague.</td></tr>
<tr><td>Air pollution</td><td>Assumption that AM and Robotaxis will be electric, the values for Evs were used for assessmen</td><td>European Environment Agency (2019): Emissions of air pollutants from transport. Available online at https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-air-pollutants-8/transport-emissions-of-air-pollutants-8.
Jochem, Patrick; Doll, Claus; Fichtner, Wolf (2016): External costs of electric vehicles. In Transportation Research Part D: Transport and Environment 42, pp. 60–76. DOI: 10.1016/j.trd.2015.09.022.
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European Commission (2020b): Sustainable Urban Mobility Indicators (SUMI). Available online at https://ec.europa.eu/transport/themes/urban/urban_mobility/sumi_en.</td></tr>
<tr><td>Energy efficiency</td><td>"This corresponds to the EAM manufacturer's specifications for energy consumption of 520 Wh/km." (HUber et. al, 2022)
Assumption that robotaxis will be electric, occupancy 1,2 (similar to taxis, with individual trips, it depends on the sharing mode), AM in Mass occupancy of 5 ("the near-future use</td><td>Huber, Dominik; Viere, Tobias; Horschutz Nemoto, Eliane; Jaroudi, Ines; Korbee, Dorien; Fournier, Guy (2022): Climate and environmental impacts of automated minibuses in future public transportation. In Transportation Research Part D: Transport and Environment 102, p. 103160. DOI: 10.1016/j.trd.2021.103160.</td></tr>
<tr><td>Social acceptance</td><td>Estimates based on social acceptance studies from Korbee et al (2022) and</td><td>Liu, Mingyu; Wu, Jianping; Zhu, Chunli; Hu, Kezhen (2020): A Study on Public Adoption of Robo-Taxis in China. In Journal of Advanced Transportation 2020, pp. 1–8. DOI: 10.1155/2020/8877499.
Korbee, Dorien; Naderer, Gabriele; Dubielzig, Markus; Mathe, Linda; Helfer, Laurent (2022a): D8.9 Social impact assessment. Available online at https://cordis.europa.eu/project/id/769033/results.</td></tr>
<tr><td>Passenger affordabili</td><td>Bösch et al. (2017) Cost-based analysis of autonomous mobility services
1) AM in MaaS: Minibus Urb PT-P Aut Elec - 0.24 CostPassKM [CHF] = 0.23 CostPasskm(EUR)
2) Robotaxi: Midsize Urb PT-NP Aut Elec - 0.39 CostPassKM [CHF] = 0.38 CostPasskm(EUR)</td><td>Bösch, Patrick M.; Becker, Felix; Becker, Henrik; Axhausen, Kay W. (2018): Cost-based analysis of autonomous mobility services. In Transport Policy 64, pp. 76–91. DOI: 10.1016/j.tranpol.2017.09.005.</td></tr>
<tr><td>Economic profitability</td><td>Bösch et al. (2017) Cost-based analysis of autonomous mobility services
1) AM in MaaS: Minibus Urb PT-P Aut Elec 0.98 Cost VKM [CHF] = 0,95 Cost VKM(EUR) 21/03/2022
2) Robotaxi: Midsize Urb PT-NP Aut Elec - 0.48 Cost VKM [CHF] = 0,47 Cost Vkm(EUR) 21/03/2022</td><td>Bösch, Patrick M.; Becker, Felix; Becker, Henrik; Axhausen, Kay W. (2018): Cost-based analysis of autonomous mobility services. In Transport Policy 64, pp. 76–91. DOI: 10.1016/j.tranpol.2017.09.005.</td></tr>
<tr><td>External costs related to the AM</td><td><table>
<tr><th colspan="5">External costs estimates</th></tr>
<tr><td>Vehicle</td><td>Bus/Coach</td><td>Car petrol/diese</td><td>Robotaxi</td><td>AM in MaaS</td></tr>
<tr><td>Air pollution</td><td>0,73</td><td>1,18</td><td>0,07</td><td>0,05</td></tr>
<tr><td>Climate change</td><td>0,44</td><td>1,22</td><td>0,00</td><td>0,00</td></tr>
<tr><td>wtt</td><td>0,15</td><td>0,40</td><td>1,11</td><td>0,54</td></tr>
<tr><td>Noise</td><td>0,24</td><td>0,59</td><td>2,56</td><td>0,30</td></tr>
<tr><td>Accidents</td><td>0,80</td><td>1,41</td><td>0,00</td><td>0,00</td></tr>
<tr><td>Congestion</td><td>3,18</td><td>29,31</td><td>64,67</td><td>13,10</td></tr>
<tr><td>TOTAL</td><td>5,54</td><td>34,11</td><td>68,40</td><td>13,99</td></tr>
</table></td><td>Antonialli, F.; Boos, A.; Fournier, G.; Jaroudi, I.; Mira-Bonnardel, S.; Thalhofer, M. (2022): Deliverable 8.6: Final Economic Impact Assessment. AVENUE – Automated Vehicles to Evolve to a New Urban Experience, European Union Horizon 2020 research and innovation programme under grant agreement No 769033.
CE Delft (2019): Handbook on the external costs of transport. Version 2019. CE Delft. Delft (EUR. Scientific and technical research series).
Jaroudi, Ines (2021): What is the potential impact of the transition from traditional transport to new mobility (electric automated minibuses) in European cities? Gerpisa colloquium, Paris. Available online at https://gerpisa.org/node/6370.</td></tr>
<tr><td>Technical performanc</td><td>Assumptions:
Speed AM 30km/h, RT 50km/h
Waiting time AM 6min, RT 3min
Occupancy AM 5, RT 1,2
AD level 5 AM and RT</td><td></td></tr>
<tr><td>System integration</td><td>Levels of integration
1) No integration - single, separate services
2) Integration of information - multi-modal travel planner, price info
3) Integration of booking & payment - single trip, find, book and pay
4) Integration of the service offer - bundling/subscription, contracts, etc.
5) Integration of societal goals - policies, incentives, etc.

AM in MaaS - level 3
Robotaxis - level 2</td><td>Sochor, J., Arby, H., Karlsson, I. C. M., Sarasini, S. (2018): A topological approach to Mobility as a Service: A proposed tool for understanding requirements and effects, and for aiding the integration of societal goals, Research in Transportation Business & Management 27 (2018): 3-14.</td></tr>
</table>

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