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Towards a new sustainable mobility paradigm: The role and impacts of automated minibuses in the mobility transition

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Thèse préparée dans l'unité de recherche **Laboratoire Génie Industriel** (Université Paris-Saclay, CentraleSupélec), sous la direction de **Guy FOURNIER**, professeur, le co-encadrement de Danielle ATTIAS, Professeure Emérite et **Pascal DA COSTA**, Professeur

Thèse soutenue à Paris-Saclay, le 25 Novembre 2022, par

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Titre : Vers un nouveau paradigme de mobilité durable : Le rôle et les impacts des minibus automatisés dans la transition de la mobilité

Mots clés : véhicules automatisés, transport public, systèmes de mobilité, évaluation de la durabilité, mobilité durable, transition socio-technique.

Résumé : La mobilité est au cœur de notre société et fait partie de notre vie quotidienne. Cependant, le paradigme actuel de mobilité a atteint un point de basculement : on lui reproche de ne plus répondre aux besoins des passagers en matière de mobilité et de ne plus correspondre à l'agenda climatique. Parallèlement, le déploiement de technologies et de concepts innovants en matière de mobilité représente une tentative de fournir des alternatives plus durables. Le cœur de cette thèse porte donc sur les changements et les transitions dans le paradigme de la mobilité. La thèse vise à étudier le rôle et les impacts des véhicules électriques automatisés partagés et, plus spécifiquement, des minibus automatisés intégrés dans le système de mobilité, afin de soutenir la mobilité durable et la transition vers un nouveau paradigme de mobilité.

À cette fin, un ensemble d'indicateurs multidimensionnels pour mesurer les impacts des

véhicules électriques automatisés partagés est conceptualisé, dans un premier temps. Cet ensemble d'indicateurs est appliqué dans quatre études de cas, dans un second temps, afin de réaliser l'évaluation de la durabilité du déploiement des minibus automatisés dans la mobilité urbaine de villes européennes. Cette étape comprend l'évaluation de scénarios potentiels pour les minibus automatisés en fonction de leur niveau d'intégration dans le système de mobilité. Dans un dernier temps, la recherche est élargie en abordant l'intégration des véhicules automatisés et des minibus automatisés dans les systèmes de mobilité selon la perspective des différents groupes de parties prenantes et des citoyens. Les transitions vers un nouveau paradigme de mobilité sont analysées et interprétées à travers le prisme des transitions socio-techniques et de l'approche de perspective multi-niveaux.

Title : Towards a new sustainable mobility paradigm: The role and impacts of automated minibuses in the mobility transition

Keywords : automated vehicles, public transport, mobility systems, sustainability assessment, sustainable mobility, socio-technical transition.

Abstract : Mobility is at the heart of our society and a component of our everyday life. However, our current mobility paradigm has been reaching a tipping point, and it is criticised for no longer meeting the mobility passengers' needs, neither corresponding to the climate agenda. Meanwhile, the deployment of innovative technologies and concepts in mobility represents an attempt to provide more sustainable alternatives. The core of this thesis addresses the changes and transitions in the mobility paradigm. This thesis aims to investigate the role and impacts of shared automated electric vehicles (SAEV) and, more specifically, the automated minibuses (AM) integrated into the mobility system in order to support sustainable mobility and the transition to a future mobility paradigm.

For this purpose, at first, a multi-dimensional set of indicators to measure the impacts of SAEV is conceptualised. Secondly, the set of indicators is applied in four case studies in order to perform the sustainability assessment of the deployment of automated minibuses in the urban mobility of European cities. This step includes the assessment of potential scenarios for the AM according to their levels of integration in the mobility system. Thirdly, the research is broadened by addressing the integration of automated vehicles and automated minibuses into mobility systems according to the perspective of different stakeholder groups and citizens. The transitions in the mobility paradigm are analysed and interpreted through the lens of socio-technical transitions and multi-level perspective approach.

"A alegria não chega apenas no encontro do achado, mas faz parte do processo da busca. E ensinar e aprender não podem dar-se fora da procura, fora da boniteza e da alegria."

- Paulo Freire

"There is something infinitely healing in the repeated refrains of nature - the assurance that dawn comes after night, and spring after winter."

- Rachel Carson

SUMMARY

The transport of people and goods is a significant pillar of our society and economy. Conversely, the global rise in passenger demand and cargo transportation has a direct impact on the climate and quality of life in cities. Such impacts and challenges in the transportation sector are known as 'wicked problems', given their interconnectivity, complexity and the need for a systemic and interdisciplinary approach to tackle the challenges. For instance, the main impacts resulting from the transportation sector are greenhouse gas emissions, local air pollution, noise, accidents and traffic congestion.

Besides the global rise in the transportation sector activities and thus the increasing impacts, it is also important to consider that the nature of mobility is changing. A transition is envisioned towards a new mobility paradigm and more sustainable mobility systems as a response to the limits and impacts of the current mobility paradigm and the increasing demand for transportation activity. The changes and solutions in the mobility paradigm are driven by technological advances and new approaches to mobility. The technologies include, for instance, connected, automated, electric, and shared mobility. And new approaches in mobility refer, for instance, to new governance structures and models, the combination of policy instruments, urban planning and strategies for sustainability.

This thesis aims to investigate the role and impacts of shared automated electric vehicles, with a focus on automated minibuses (AM) in mobility systems in order to support sustainable mobility and the transition to a future mobility paradigm.

For this purpose, in a first step, a multi-dimensional set of indicators to measure the impacts of shared automated electric vehicles (SAEV) is conceptualised. In a second step, the sustainability assessment of the deployment of automated minibuses in the urban mobility of European cities is performed. The set of indicators is applied for the assessment of four case studies. This step includes the assessment of potential scenarios for the AM according to their levels of integration in the mobility system. In addition, the study develops premises and recommendations for the sustainable deployment of the AM within mobility systems according to Sustainable Urban Mobility Plan (SUMP) approach.

In a third step, the research is broadened by addressing the integration of automated vehicles (AV) and automated minibuses into the mobility systems according to the perspective of different stakeholder groups and citizens. The research method builds upon conceptual mapping and semi-structured interviews with the main stakeholder groups (n= 30) and a large-scale survey with citizens in four European cities (n= 1816). The changes and transitions in the mobility paradigm are analysed and interpreted through the lens of socio-technical transitions and multi-level perspective approach. As main outcomes, the study built a stakeholders map and identified the stakeholders' interactions concerning the automated driving and (public) transport provision. It identified the main drivers and barriers to deploying AV and AM, and pointed out mechanisms for a transition in mobility systems with the integration of AM.

This thesis concludes that the assessment of the deployment and performance of AV and AM within the mobility system is a key element to planning, monitoring and putting in practice sustainable mobility. At the current stage, the AM have yet limited performance concerning the different indicators assessed. The technology is under development, and the pilot trials are characterised by an

experimental nature. However, the automated minibuses prove to be feasible innovative mobility by offering new services, improving the transport network and supporting cities to achieve sustainable mobility under certain premisses aligned with the sustainable urban mobility plan (SUMP). The findings support the prospect that the automated minibuses - integrated into public transport and MaaS systems and coupled with other niche innovations and policy instruments – can be part of the solution to pave the way towards a socio-technical transition to a new mobility paradigm.

Part of the research of this thesis was developed within the AVENUE project (Autonomous Vehicle to Evolve to a New Urban Experience), a Horizon 2020 research and innovation program. Concerning future work, it is recommended to continue the data collection based on empirical data and the assessment of SAEV over time and considering different forms of deployment, contexts and larger-scale projects deploying a fleet of AVs. Future research could further develop the pathways for transition to the new mobility paradigm by using different lenses for analysis and interpretation, such as transition management, multi-level perspective, nested governance, socio-practice theory, responsible innovation, scenario planning and others. Future research on AV and AM may address new governance approaches and structures, participatory approaches, strategies for the AM to foster MaaS and intermodality and the combination of policy instruments and measures to provoke shifts in the mobility paradigm and enhance sustainable mobility.

RESUME

Le transport des personnes et des marchandises est un pilier important de notre société et de notre économie. Inversement, l'augmentation mondiale de la demande de passagers et du transport de marchandises a un impact direct sur le climat et la qualité de vie dans les villes. Ces incidences et ces défis dans le secteur des transports s'avèrent des 'problèmes complexes', en raison de leur interconnexion, de leur complexité et de la nécessité d'adopter une approche systémique et interdisciplinaire pour relever ces défis. Par exemple, les principaux impacts du secteur des transports sont les émissions de gaz à effet de serre, la pollution atmosphérique, le bruit, les accidents et le trafic.

Outre l'augmentation globale des activités du secteur des transports et donc de ses impacts, il est également important de considérer que la nature de la mobilité est en train de changer. Une transition est envisagée vers un nouveau paradigme de mobilité et des systèmes de mobilité plus durables en réponse aux limites et aux impacts du paradigme de mobilité actuel et à la demande croissante d'activités de transport. Les changements et les solutions dans le paradigme de la mobilité sont motivés par les avancées technologiques et les nouvelles approches de la mobilité. Les technologies comprennent, par exemple, la mobilité connectée, automatisée, électrique et partagée. Les nouvelles approches de la mobilité font référence, par ailleurs, à de nouvelles structures et modèles de gouvernance par exemple, à la combinaison d'instruments politiques, à une planification urbaine et des stratégies pour la durabilité.

Cette thèse vise à étudier le rôle et les impacts des véhicules électriques automatisés partagés, avec un focus sur les minibus automatisés dans les systèmes de mobilité afin de soutenir la mobilité durable et la transition vers un futur paradigme de mobilité.

À cette fin, dans une première étape, un ensemble multidimensionnel d'indicateurs pour mesurer les impacts des véhicules électriques automatisés partagés (SAEV en anglais, shared automated electric vehicles) est conceptualisé. Dans un deuxième temps, l'évaluation de la durabilité du déploiement des minibus automatisés dans la mobilité urbaine des villes européennes est réalisée. L'ensemble des indicateurs est appliqué pour l'évaluation de quatre études de cas. Cette étape comprend l'évaluation des scénarios potentiels pour les minibus automatisés (AM en anglais, pour Automated Minibus) en fonction de leur niveau d'intégration dans le système de mobilité. En outre, l'étude développe des prémisses et des recommandations pour le déploiement durable des minibus automatisés dans les systèmes de mobilité selon l'approche d'aménagement urbain ou de planification de la mobilité urbaine durable (SUMP en anglais, pour *Sustainable Urban Mobility Planning*).

Dans une troisième étape, la recherche est élargie en abordant l'intégration des véhicules automatisés et des minibus automatisés dans les systèmes de mobilité selon la perspective des différents groupes de parties prenantes et des citoyens. La méthode de recherche s'appuie sur une cartographie conceptuelle et des entretiens semi-structurés avec les principaux groupes de parties prenantes (n= 30) et une enquête à grande échelle auprès des citoyens de quatre villes européennes (n= 1816). Les changements et les transitions dans le paradigme de la mobilité sont analysés et interprétés à travers le prisme des transitions socio-techniques et une approche de perspective multi-niveau (*multi-level perspective*). Les principaux résultats de l'étude sont l'élaboration d'une cartographie des parties prenantes et l'identification des interactions entre les parties prenantes concernant la con-

duite automatisé et l'offre de transport (public). L'étude a identifié les principaux moteurs et obstacles au déploiement des véhicules automatisés et minibus automatisés, et a mis en évidence les mécanismes de transition des systèmes de mobilité avec l'intégration des minibus automatisés.

Cette thèse conclut que l'évaluation du déploiement et de la performance des véhicules automatisés et minibus automatisés dans le système de mobilité est un élément clé pour planifier, surveiller et mettre en pratique la mobilité durable. Au stade actuel, les minibus automatisés ont encore des performances limitées concernant les différents indicateurs évalués. La technologie est en cours de développement et les essais pilotes sont caractérisés par leur nature expérimentale. Cependant, les minibus automatisés s'avèrent être une mobilité innovante réalisable en offrant de nouveaux services, en améliorant le réseau de transport et en aidant les villes à atteindre une mobilité durable sous certaines conditions alignées avec le plan de mobilité urbaine durable (SUMP). Les résultats soutiennent la perspective que les minibus automatisés - intégrés dans les systèmes de transport public et MaaS et couplés à d'autres innovations de niche et instruments politiques - peuvent être déterminant pour ouvrir la voie à une transition sociotechnique vers un nouveau paradigme de mobilité.

Une partie de la recherche de cette thèse a été développée dans le cadre du projet AVENUE (Autonomous Vehicle to Evolve to a New Urban Experience) un programme de recherche et d'innovation Horizon 2020. En ce qui concerne les travaux futurs, il est recommandé de poursuivre la collecte de données empiriques et l'évaluation de véhicules électriques automatisés partagés dans le temps et en tenant compte de différentes formes de déploiement, de contextes et de projets à plus grande échelle déployant une flotte de véhicules automatisés. Les recherches futures pourraient développer davantage les voies de transition vers le nouveau paradigme de la mobilité en utilisant différentes optiques d'analyse et d'interprétation, telles que la gestion de la transition, la perspective multi-niveaux, la gouvernance imbriquée (en anglais, nested governance), la théorie des pratiques sociales, l'économie de la finalité (en anglais purpose economy), l'innovation responsable, la planification de scénarios, etc. Les recherches futures sur les véhicules automatisés et les minibus automatisés pourraient porter sur les nouvelles approches et structures de gouvernance, les approches participatives, les stratégies pour les minibus automatisés favoriser le MaaS et l'intermodalité et la combinaison d'instruments et de mesures politiques pour provoquer des changements dans le paradigme de la mobilité et améliorer la mobilité durable.

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LIST OF ABBREVIATIONS

ADS	Automated Driving System	NOx	Nitrogen oxides
AM	Automated Minibus	OEM	Original Equipment Manufacturer
API	Application Programming Interfaces	Pkm	Passenger-kilometre
AV	Automated vehicle	PM	Particular Matter
AVENUE	Autonomous vehicles to evolve to a new urban experience	PRM	People with reduced mobility
BEV	Battery electric vehicle	PSS	Product Service Systems
CAV	Connected and Automated Vehicle	PTA	Public Transport Authorities
CH ₄	Methane	PTO	Public Transport Operator
CO	Carbon monoxide	QALY	Quality-adjusted life years
CO ₂	Carbon dioxide	SAE	Society of Automotive Engineers
EIA	Environmental impact assessment	SAEV	Shared automated electric vehicle
EU	European Union	SAV	Shared automated vehicle
EV	Electric vehicle	SDG	Sustainable development goals
GHG	Greenhouse gas	SEA	Strategic environmental assessment
GIS	Geographic information system	SO ₂	Sulphur dioxide
GNSS	Global navigation satellite system	SPT	Social Practice Theory
HC	Hydrocarbons	STT	Socio-technical transition
ICEV	Internal combustion engine vehicle	SUMI	Sustainable Urban Mobility Indicators
ICT	Information and Communications Technology	SUMP	Sustainable Urban Mobility Plan
ID	Identification	TA	Technology Assessment
ITS	Intelligent Transportation Systems	TCM	Total Cost of Mobility
LaaS	Logistic as a Service	TCO	Total Cost of Ownership
LCA	Life Cycle Assessment	TDM	Transportation demand management
MaaS	Mobility as a Service	V2I	Vehicle to infrastructure
MLP	Multi-level perspective	VMT	Vehicle miles travelled
NGO	Non-governmental organization		
NMVOC	Non-methane volatile organic compounds		

PUBLICATIONS

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CHAPTER 1 GENERAL INTRODUCTION

1.1 GENERAL CONTEXT

'Mobility' refers to the ability of a person to move or to be easily moved, it is defined by Denmark (1998) as "the ease with which destinations can be reached", whereas 'transportation' refers to the act of moving people or goods (Shannon, 2006; McKay, 2019).

Mobility is a main activity of our everyday life, encompassing socio and economic impacts. The discussions addressing the current mobility paradigm have gained importance in the last decades, given the increasing demand for transportation of people and goods and, consequently, the increasing externalities of the transport sector. Between 1990 and 2019, annual transportation sector CO₂ emissions increased by roughly 80%, and currently, it accounts for 17% of global greenhouse gas emissions (Statista, 2022). In the EU, the transport sector is responsible for 27% of the total greenhouse gas emissions (European Environment Agency, 2019). Worldwide, road vehicles are the leading source of transportation emissions, with passenger cars accounting for 41% of global transportation CO₂ emissions in 2020 (Statista, 2022).

Conversely, in the last decades, we have seen an increase in the number of discussions, agreements, strategies and goals to reduce the GHG emissions of different sectors and tackle primarily climate change. For instance, some of these initiatives are the Sustainable Development Goals (SDG) launched by the United Nations (UN), particularly the SDG 11 'Sustainable cities and communities' which addresses sustainable transport, the Paris Agreement at the UN Climate Conference (COP21), Sustainable Urban Mobility Plans (SUMP), and more recently, the European Green Deal. The European Green Deal has set ambitious targets to reduce the transport impacts, for instance, reducing emissions from cars by 55% by 2030 (European Commission, 2022). Furthermore, in the European context, other specific European transport policies were set, such as the white paper 'Roadmap to a single European Transport Area – Towards a competitive and resource efficient transport system' (European Commission, 2011).

Beyond the climate impacts from the mobility sector, other externalities triggering social and environmental impacts are related to air pollution, accident, congestion, noise and oil dependence (Musso and Rothengatter, 2013; Jochem et al., 2016; Girardi et al., 2020). Road traffic is the largest source of noise pollution in Europe (EEA, 2020). The noise from road transport harms human health, it causes fatigue, hearing impairment, annoyance, sleep disturbance and stress (WHO, 2022). In terms of air pollution, at the local and regional levels, the main air pollutants from road transport are nitrogen oxides (NO_x), hydrocarbons (HC) and carbon monoxide (CO), sulphur dioxide (SO₂) and particulate matter (PM) (Santos et al., 2010). For instance, NO_x are associated with respiratory disease and eye, nose and throat irritation; in addition, PM is related to adverse health effects, such as respiratory symptoms and decreased lung function (Santos et al., 2010). Another main externality concerns accidents in road traffic, which can lead to injuries, impairments and fatalities, representing

a global social and public health challenge (Profillidis et al., 2014). Furthermore, traffic congestion results in additional production costs and loss of time and reliability (Profillidis et al., 2014).

Therefore, the criticism of the 'civil society of automobility' point to the overwhelming impacts of cars in the time-space of modern dweller (Sheller and Urry, 2000). Indeed, the current mobility paradigm is based on individual mobility, characterised by car ownership, individual rides, oil dependence and high CO₂ emissions (Fournier, 2017). The dominant mobility system is car-dependent and resistant to change (Geels et al., 2017). And this model has influenced how cities and streets are planned, infrastructure is built, and policies are designed (Banister, 2008). In the words of Sheller and Urry (2000): "Automobility is a complex amalgam of interlocking machines, social practices and ways of dwelling which have reshaped citizenship and the public sphere via the mobilization of modern civil societies."

Hence, by acknowledging the impacts and limits of our current mobility systems, the core of this thesis addresses the changes and transitions in the current mobility paradigm towards a new mobility paradigm. These changes in the mobility paradigm embrace transformations in the 'techno-economic paradigm' (Freeman and Perez, 1988) and socio-technical transitions and sustainability (Geels et al., 2017; Canitez, 2019). Thereby, the deployment of innovative technologies and concepts have been implemented in the pursuit of more sustainable mobility systems. For instance, the innovative technologies comprise automated, connected, shared and electric mobility (Janasz, 2018; Adler et al., 2019; Aksen and Sovacool, 2019; Litman, 2022). In addition, new concepts aiming at efficiency and decarbonisation of mobility encompass multi- and intermodal trips (Gebhardt et al., 2016; Willing et al., 2017), Mobility-as-a-Service (MaaS) (Kamargianni and Matyas, 2017; Sochor et al., 2018), mobility on-demand (Pavone, 2015; Liyanage et al., 2019), and sustainable urban mobility plans (Eltis, 2021; SUMP-Up project, 2022).

Among these innovations, this thesis investigates the shared automated electric vehicles (SAEV) and, more specifically, the automated minibuses (AM) integrated into the mobility system. Hence, the thesis investigates the role of automated minibuses and their current and potential future impacts on the mobility system in order to provide insights to support the cities' goals towards sustainable mobility as well as to better meet the citizens' mobility needs.

1.2 RESEARCH OBJECTIVE

Automated driving, coupled with other mobility innovations, has received greater attention from researchers and practitioners in the field. The emergence of such technologies and innovations are topic of numerous studies investigating their potential to trigger a paradigm shift towards better public transportation offers, mobility integration and intermodality, in addition to a more efficient, sustainable and environmentally friendly mobility (Nikitas et al., 2021; Litman, 2022).

However, the impacts of AVs (including SAEV) and their potential rebound effects rely on multiple variables; therefore, it could result in positive effects or aggravate even more the

mobility externalities (Soteropoulos et al., 2019). Such variables refer, for instance, to the type of deployment of SAEV, the level of their integration into the mobility system (e.g. competing or supporting public transport), regulations and policy instruments, urban and spatial planning, social acceptance, etc. (Merlin, 2017; Milakis and Müller, 2021; Thaller et al., 2021; Fournier et al., 2022).

Furthermore, it is worth noting that the impacts of the mobility sector are known as 'wicked problems' given their complexity, knowledge gaps and uncertainties, the interconnectivity among problems and divergent perspectives on the same issues (Head, 2010; Ortúzar, 2019; Lyons, 2022). In addition, the 'wicked problems' need a systemic approach to be tackled (Ortúzar, 2019; May et al., 2020). Lyons (2022) argues that automated vehicles can be considered a 'wicked problem' by reasoning that: i) actors present divergent values and perspectives on this matter, ii) there are knowledge gaps and uncertainties concerning the pathways and future of AVs, iii) AVs entail complex relationships to other mobility challenges, e.g. technology-enabled innovations, public health, equity and sustainability issues. Indeed, automated driving may add more complexity to the mobility system of cities. For instance, the automated driving system encompasses a combination of technologies, such as lidar sensors, cameras, radars, global navigation satellite system (GNSS), automated driving algorithms, charging systems, etc. (Iclodean et al., 2020). In addition, automated driving can represent divergent effects on energy demand. On the one hand, it can represent energy savings through improved driving performance and enhanced traffic flows. On the other hand, it can represent additional energy demand due to extensive data processing and transmission (Lee and Kockelman, 2019; Prein, 2021).

Within a broader perspective, automated driving brings up new societal questions, which address, for instance: safety and the human-machine interactions, the potential synergies and conflicts between automated vehicles, non-automated vehicles and active travel, the cost and equity of access to mobility, health and wellbeing with the integration of AVs in mobility (Botello et al., 2019; Lyons, 2022). Other questions about AVs concern the social acceptance of automated driving (Kyriakidis et al., 2015; Fraedrich and Lenz, 2016). Further, it has also received attention the studies addressing new governance approaches to steer the new mobility technologies to provoke a shift towards more sustainable mobility systems instead of reinforcing the car society (Kemp and Rotmans, 2004; Tschoerner, 2016).

In fact, the studies on AVs, including SAEV, encompass diverse research perspectives, e.g. environment, economy, governance, travel behaviour, land use, traffic and safety (Narayanan et al., 2020). Consequently, the integration of automated driving in the mobility system and society poses multi-faceted topics for investigation and dichotomous perspectives. For instance, the dichotomy implicating AVs is addressed in the articles by Chase (2014) in 'Will a World of Driverless Cars Be Heaven or Hell?' and by Prein (2021) in "Autonomous Vehicles: Boon or Bane for Energy Efficiency?".

In the face of these challenging research topics and considering the uncertainties and knowledge gaps involving AVs, this thesis has as its object of study the shared automated electric vehicles and automated minibuses in mobility systems. The main research objective

of the present PhD thesis is to investigate the role and impacts of shared automated electric vehicles, focusing on automated minibuses in mobility systems, to better understand how they can contribute to sustainable mobility and support the transition to a future mobility paradigm. By sustainable mobility and the future mobility paradigm, it is meant a mobility system that is less car-based, less oil-dependent, with reduced externalities, better integrated, intermodal, efficient and environmental-friendly. Such concepts are detailed in the following section (Chapter 2).

According to the research objective, the first study explored how to measure the impacts of Shared Automated Electric Vehicles on the mobility of cities. As a result, a framework for assessment - the set of indicators for sustainability assessment of SAEV – was conceptualised. Subsequently, the second study applied the set of indicators to assess the current performance and impacts of AM integrated into public transport in cities. The study developed premises and recommendations for deployment of the AM according to Sustainable Urban Mobility Plan (SUMP) and presented the perspectives for future mobility systems with the AM.

Thereupon, the research perspective is enlarged by acknowledging the place of AVs in a socio-technical system. Hence, the third study investigated the stakeholders' perspectives on AVs and AM, the issues at stake, and the pathway and mechanisms for socio-technical transition in mobility with AV and AM.

The thesis builds upon both conceptual and empirical research:

- Concepts include sustainability assessment, technology assessment, indicators for assessment, automated driving, shared automated electric vehicles, mobility paradigm, sustainable mobility, sustainable urban mobility planning, socio-technical transitions and multi-level perspectives.
- Empirical data for the impact assessment of the AM based on case studies of pilot trials. In addition to surveys with citizens and interviews with multiple stakeholders.

1.3 OUTLINE OF THE THESIS

The thesis is organised into seven chapters. The present chapter 1 provides the general context and research objectives. Chapter 2 presents the background literature and conceptual foundation for the thesis. Chapter 3 reports the identified research gaps and corresponding research questions and methodologies applied in the thesis.

Chapters 4, 5 and 6 present the main contributions of the thesis. Chapter 4 addresses how to measure the impacts and externalities of shared automated electric vehicles (SAEV) on urban mobility. It consists of a literature review to contextualise the current mobility paradigm and mobility innovations and presents concepts and definitions of sustainable mobility, sustainability assessment, and technology assessment. The research method consists of: i) an integrative literature review on methods and frameworks to assess sustainable mobility, ii) an in-depth analysis and frequency of indicators, and iii) the discussion and validation of the indicators with experts. The main outcome is the

conceptualisation of a set of indicators for the sustainability assessment of SAEV. The multi-dimensions of mobility assessed comprise five axes: social, environmental, economic, governance and technical system performance. The conceptualisation and analysis of the study are grounded on real cases of AVENUE project, in which automated minibuses are deployed in pilot trials in four European cities. The proposed method allows an evaluation and comparison of SAEV in different types of deployment and to different means of transport. The assessment over time supports strengthening scientifically based recommendations for transportation policies with innovative mobility.

Chapter 5 performs the sustainability assessment of four case studies from pilot trials. The trials are deploying automated minibuses in the urban mobility of three European cities: Lyon, Luxembourg and Copenhagen. In addition, the potential scenarios of AM deployment are also assessed. The conceptual background explores the concepts and definitions of AVs, the potential impacts of AVs on urban mobility, and the Sustainable Urban Mobility Plan (SUMP) concept. The research method applies the framework for sustainability assessment developed previously in Chapter 4 to assess the four case studies for pilot trials testing automated minibuses. Primary data and studies related to the impact assessment of the pilot trials are used for the sustainability assessment. The results from the sustainability assessment are discussed under the SUMP approach, which includes the premises and recommendations for sustainable deployment of the AM.

Chapter 6 broadens the perspectives of the study by analysing the potential changes in the mobility paradigm with the integration of automated vehicles and automated minibuses into the mobility systems. The analysis and interpretation are carried out through the lens of socio-technical transitions and multi-level perspectives. Therefore, the conceptual background presents the concepts of socio-technical transitions, multi-level perspective (MLP), and the relation between automated driving and socio-technical transition. The research method builds upon conceptual mapping and semi-structured interviews with the main stakeholder groups (n= 30) and a large-scale survey with citizens in four European cities (n= 1816). The study analyses the integration of automated vehicles and automated minibuses into the urban mobility systems from the perspective of different stakeholder groups and citizens. As main outcome, the study builds a stakeholders map and identifies the stakeholders' goals, interactions and perceptions concerning automated driving and (public) transport provision. It analyses the socio-technical transitions in the mobility sector with the integration of AVs and AMs through a multi-level perspective (Landscape, Regime and Niche). In addition, it identifies the main drivers and barriers to deploying AV and AM, and the mechanisms for a transition in mobility systems with the integration of AM.

Finally, chapter 7 provides a general discussion, limitations of the studies, future research and conclusion. Figure 1 provides an overview of the thesis structure.

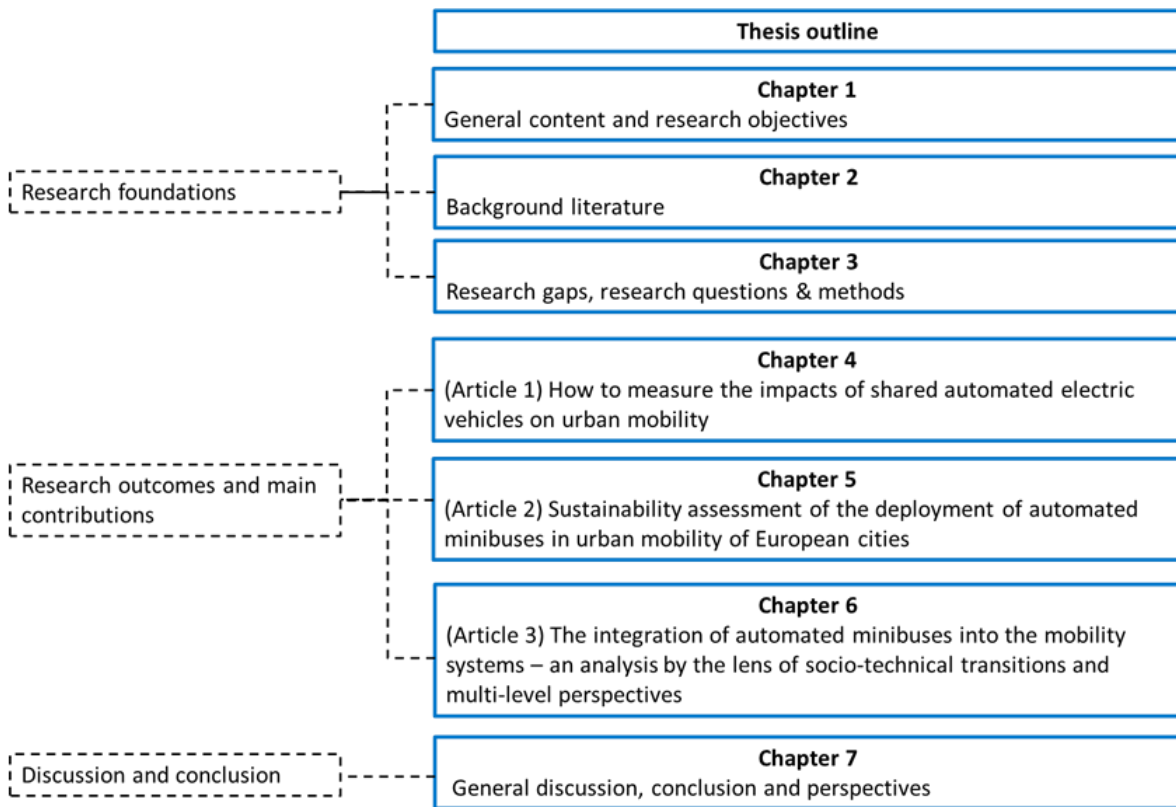


Figure 1. Thesis structure

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CHAPTER 2 BACKGROUND LITERATURE

This chapter presents the concepts and definitions that served as building blocks for the research work of the thesis. It starts by introducing the notions of sustainable mobility, and afterwards by presenting the concepts and definitions of AVs, and what they represent as innovation. The concepts on socio-technical transitions are presented afterwards, followed by the perspectives and elements of the transition from the current to the future mobility paradigm. Subsequently, the potential impacts of AVs on urban mobility are addressed, considering that these topics are the main subjects of research in this thesis.

2.1 CONCEPTS OF SUSTAINABLE MOBILITY¹

Cities are challenged with increasing mobility demands, congestion, air quality deterioration and increasing greenhouse gas (GHG) emissions. Pursuing human-centred mobility requires rethinking the paradigm by which mobility and city planning is guided (GIZ, 2019). In this regard, different concepts and definitions of sustainable mobility address more liveable, safe, affordable, accessible, and environmental-friendly mobility systems.

The Avoid-Shift-Improve (A-S-I) approach (GIZ, 2019) focuses on the demand side, meaning the mobility needs of people. 'Avoid' refers to reducing motorised travel, the trip length and travel needs through transport-oriented and compact development of cities. 'Shift' refers to modal shifts to more environmentally friendly modes, such as active mobility and public transport. 'Improve' focuses on vehicle and fuel efficiency and the optimisation of the operational efficiency of public transportation. The A-S-I approach serves as guidance to structure policy measures, and it suggests a hierarchy with: "avoid" measures to be implemented first, secondly "shift", and finally the "improve" measures.

The A-S-I approach is in line with Banister's (2008, 2011) argumentation when addressing the 'sustainable mobility paradigm'. The author argues that the sustainable mobility approach requires measures to reduce the need to travel, land use planning to reduce trip lengths, policy measures to encourage modal shifts and soft modes of transport, and technology innovation for greater efficiency in the transport system. Avoided journeys and moderating travel demand could be achieved, for instance, through online services, distance learning, and remote work (Lah et al., 2019; Miskolczi et al., 2021).

Sustainable mobility focusses on the reduction of transport externalities to improve urban resilience and citizens' quality of life. Sustainable mobility is a broad term, operationalised differently by diverse organisations. The narrowest conceptualisation is the pure focus on environmental sustainability, operationalised as renewable resources by the OECD (1997),

¹ This section realocates part of the theoretical background defining 'sustainable mobility' of the publication: Nemoto, E. H., Issaoui, R., Korbee, D., Jaroudi, I., & Fournier, G. (2021). *How to measure the impacts of shared automated electric vehicles on urban mobility. Transportation Research Part D: Transport and Environment*, 93, 102766. <https://doi.org/10.1016/j.trd.2021.102766>

for instance. A comparable conceptualisation, considering the reduction of greenhouse gasses, is proposed by Axsena et al. (2019). However, they add the notion of affordability and accessibility to all people to it. Broader definitions also include system diversity, smart growth, land use development, efficient transport pricing, and diverse transport modes in a city (Litman, 2007; ICLEI 2019).

A second stream of operationalisation addresses on the needs of society to '...access to safe, clean, and affordable transport for all' HABITAT III (2015). Sustainable transport should provide transport without "...sacrificing other essential human or ecological values, today or in the future" (World Business Council for Sustainable Development, 2015). The European Union concept of Sustainable Urban Mobility Plans (SUMP) aims to improve the overall quality of life for residents and the accessibility of urban areas in order to provide "high-quality and sustainable mobility and transport to, through and within the urban area" (European Commission, 2017). UITP (2017), which analysed the integration of automated vehicles in the city, sees "affordable, sustainable and convenient mobility options to all citizens including less mobile persons, the elderly, children and people living in suburban or rural areas".

Finally, it is important to stress that digitalisation is an enabler to lever the benefits (and risks) for sustainable urban mobility (Creutzig et al., 2019). Digitalisation, in fact, influences the optimal dispatch and routing of fleets (Creutzig et al., 2019) and is the key to informing and providing the users with the right (intermodal) mobility offer on-demand. Thus, this optimisation of fleets leads to an optimisation of travel where the passengers' needs are met in a way that reduces unnecessary kilometres travelled but also as a second option to more sustainable forms of mobility such as walking and biking. Hence, digital approaches are more efficient when accompanied by transportation demand management (TDM) measures. Public policies and urban governance can ensure the provision of possible benefits (Creutzig et al., 2019). The axes of new and sustainable mobility could be complementary or opposing. Lyons' (2018) paper explains that new mobility is more than digital solutions (akin to smart city concepts). It should be "affordable, effective, attractive, and sustainable". Thus, the dichotomy between smart and sustainable should be avoided. This hinges on TDM measures and public policies.

Taking all these concepts and definitions into account, sustainable mobility in this study is addressed as mobility that: encompasses innovative mobility alternatives, digital and governance approaches integrating all modes of transport in order to provide an efficient, reliable, safe, affordable, accessible and economically viable transport system that reduces transport externalities (GHG, particulate matters, NO_x, Qaly - Quality Adjusted Life Years, free up vehicle spaces) for a liveable and sustainable city.

Sustainability reflects the intent to create a positive and durable legacy; therefore, sustainability planning aims to ensure that local and short-term decisions are consistent with society's long-term goals (Litman, 2007). A step further, the concept of Sustainable Urban Mobility Planning (SUMP) tackles the need for more sustainable and integrative planning processes to deal with the complexity of urban mobility (Eltis, 2021). SUMP provide principles

and guidelines to support practitioners in adapting and planning mobility in a constantly evolving field. SUMP embraces new modes of transport, e.g. micro-mobility, automated and connected vehicles, and new concepts such as Mobility as a Service (MaaS) and shared mobility. 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. The SUMP guidelines for planning and implementation are composed of four main phases: i) Preparation and context analysis; ii) Strategy development; iii) Measure planning; iv) Implementation and monitoring.

Further in this thesis, chapter 4 explores the use of indicators for sustainability assessment. And chapter 5 further explores the concept of Sustainable Urban Mobility Plan (SUMP) in order to develop premises and recommendations for sustainable deployment and perspectives for the future mobility system with AM.

2.2 AUTOMATED VEHICLES CONCEPTS AND DEFINITIONS

An Automated Driving System (ADS) is equipped with hardware and software systems capable of performing part or all of the dynamic driving tasks on a sustained basis (SAE, 2018). Conventionally, six levels of driving automation are described, ranging from no driving automation to full driving automation. The five levels are named (SAE, 2018):

- Level 0 - No Driving Automation
- Level 1 - Driver Assistance
- Level 2 - Partial Driving Automation
- Level 3 - Conditional Driving Automation
- Level 4 - High Driving Automation
- Level 5 - Full Driving Automation

Levels 1 and 2 of automated driving functions perform the so-called assisted mode, for instance, assisted braking, steering, and car lane centring. Automated vehicles with level 3 are currently entering regular production; they can drive independently to some degree, with the driver taking over the driving functions upon request and with advance notice (Buchholz, 2021). AVs with levels 4 and 5 can drive independently; however, they are not yet available on the market (Buchholz, 2021).

AVs are in the test phase in different countries, and they are the object of study to be deployed in different forms, such as private AVs, or shared AVs as robotaxis, or AM integrated into public transport and MaaS (Pettigrew and Cronin, 2019). Furthermore, vehicle automation, in combination with shared mobility services and vehicle electrification, are seen as the three main mobility revolutions (Sprei, 2017; Sperling, 2018). Hence, the synergies among emerging technologies such as the shared automated electric vehicles (SAEV) are the object of study to improve sustainability in the mobility sector (Martinez and Viegas, 2017; Shaheen and Bouzaghrane, 2019; Taiebat and Xu, 2019; Dlugosch et al., 2020).

SAEV in the form of robotaxis and AM could offer a variety of services, ranging in space (line, corridor, area, urban, suburban), time (fixed scheduled or on-demand), and function (first

and last-mile, door-to-door, integrated into the transport network). In addition, SAEV business models may vary according to two main factors: vehicle ownership and who controls the network operations (Stocker and Shaheen, 2017).

Narayanan et al. (2020) describe the typology of SAEV according to:

- i) Booking type: on-demand, reservation-based
- ii) Integration type: independent system (without connection to other modes), integrated into public transport
- iii) Sharing system: mixed system, ride-sharing, car sharing

Földes and Csiszar (2018) depict four shared AV service types: taxi (independent car-sharing system), shared taxi (independent ride-sharing system), feeder pod and fixed-route pod (as feeder system integrated public transport). Further, MOQO (2020) distinguish between 'goods sharing' such as carsharing, and 'service sharing' such as ridesharing, ridepooling and ridehailing.

The present thesis addresses the impacts of shared automated electric vehicles, and in a second stage, it focuses on the impacts of automated minibuses, also known as 'autonomous shuttles' in the literature (Nordhoff et al., 2018; Grahle et al., 2020; Bucchiarone et al., 2021). In this regard, the name 'minibus' is considered more appropriate than shuttle in this research work, considering that shuttle services are limited to fixed stops and one line service. In contrast, the minibus could serve an area and provide on-demand and door-to-door services. Worldwide many pilot projects have been deploying the AM at reduced speed, small-scale nature, monitored by a safety driver, with on-demand ride services or in controlled environments, and with the aim to deploy a shared and fully automated fleet (Stocker and Shaheen, 2017).

The AM serving public roads are currently characterised by Levels 3 and 4 of automated driving. They are battery electric vehicles with a maximum capacity of 15 passengers, and most of the trials are free of charge, serving routes through airports, industrial zones, and commercial areas (Iclodean et al., 2020). The main models and manufacturers of the AM are EasyMile EZ10 (EasyMile, Toulouse, France), Navya Arma and Autonom® Shuttle Evo (Navya, Lyon, France), Olli (Local Motors, MD, USA), and Apollo Baidu (Baidu, China) (Iclodean et al., 2020). Currently, the deployment and scaling up of the AM are still constrained by technical, operational, social and legal obstacles. Such limitations entail continuous improvements aiming at technology maturity, social acceptance and legal developments (Nemoto et al., 2021).

Beyond technological innovation, SAEV and AM represent an innovation from the perspective of Product Service Systems (PSS) (Antoniali et al., 2018; Tian et al., 2018; Wang et al., 2018) and Innovation Ecosystem (Kim et al., 2022; Sherwani, 2022).

SAEV and AM can be featured from the lens of PSS, which is characterised as a set of products and services designed and combined to fulfil the users' needs and cope with reducing resource consumption and environmental impacts (Tukker, 2004; Qu et al., 2016).

PSS are provided by a single company or a conjunction of companies (M. Goedkoop et al., 1999). Further, the alliance among different companies relates to the concept of innovation ecosystem.

The concept of innovation ecosystem addresses joint value creation, and it is featured by alliances for developing new technology and solutions, which leads to the emergence of an innovation ecosystem (Pushpanathan and Elmquist, 2022). The emergence of an innovation ecosystem consists of actors (automotive firms, new entrants, and non-automotive) co-creating value (Attias, 2017; Pushpanathan and Elmquist, 2022). In this case, the automotive industry is currently witnessing a period of technological change with automated driving, connected, shared economy and battery electric vehicles (Adam Stocker and Susan Shaheen, 2017; Pushpanathan and Elmquist, 2022).

Such innovations may also trigger societal changes to the mobility scene, which comprises: i) user-centred services (Cornet et al., 2019), ii) personal and tailored mobility services with public transport and Mobility-as-a-Service (Fraedrich et al., 2015), iii) accessibility and social inclusion for instance for elderly people and people with reduced mobility (Milakis and van Wee).

Taking into account the magnitude of such innovations and engendered changes, one can state that automated vehicles (AVs) represent a socio-technical transition (STT) of the mobility system (Geels et al., 2017; Milakis and Müller, 2021). STT addresses the co-evolving of technological functions with social functions (Hodson and Marvin, 2010), and it was chosen in this thesis as the primary approach to analyse and interpret socio-technical changes in mobility with the integration of AV and AM. Hence, the next section explores the concept of STT and the nexus with AVs and related innovations.

2.3 SOCIO-TECHNICAL TRANSITIONS IN MOBILITY SYSTEMS

Transitions are structural changes in society (Rotmans et al., 2000). It is marked by transformation processes in which society changes in a fundamental way over an extended period (Rotmans et al., 2000; Kemp and Rotmans, 2004). The socio-technical transition (STT) approach refers to the co-evolving of technological functions with social functions and social interests (Hodson and Marvin, 2010). STT deals with the interdependent and co-evolving processes of technological, social, institutional and economic changes (Patterson et al., 2017). The concept addresses the system changes that entail new technologies, infrastructures, changes in markets, supply chains, user practices, regulations, policy and cultural meanings (Geels, 2004, 2010; Geels et al., 2017).

Another prism of analysis of transformations concerns the 'techno-economic paradigm' (Freeman and Perez, 1988). The concept sheds light on the notion of technological revolutions within a neo-Schumpeterian perspective to understand the innovation process and the interplay and influences that transform the economy (Perez, 2010). It is important to acknowledge that the theory of economic development by Schumpeter (1934) and his studies on innovations and business cycles (Schumpeter, 1939) have enlightened and influenced following approaches as the 'techno-economic paradigm' (Freeman and Perez,

1988), and innovation and transitions theories.

Transitions are described as disruptive, contested, and non-linear processes (Geels et al., 2017). Disruptive because they threaten the present economic positions and business models; contested because actors may disagree about the desirability of the solutions and technologies implemented; and non-linear because innovations can face advances and setbacks (Geels et al., 2017). Further, Geels and Schot (2007) develop a typology of transition pathways: transformation, reconfiguration, technological substitution, and de-alignment and re-alignment.

The concept of 'Socio-technical transitions' is part of the 'transitions approaches' in research that shed light on long-term societal change (Patterson et al., 2017). The research in socio-technical transitions emerged in the early 2000s in the field of innovation studies (Raven et al., 2012; Li et al., 2015; Geels, 2019). This approach is largely applied in diverse fields such as mobility, energy, agriculture, water, public health, and sustainability studies (Markard et al., 2012; Whitmarsh, 2012; Geels, 2019).

Understanding how socio-technical transitions might occur is an interdisciplinary research challenge (Li et al., 2015). In this regard, a variety of conceptual approaches have been applied to interpret and analyse socio-technical transitions, for instance, transition management (Rotmans et al., 2001), technological innovation systems (Carlsson and Stankiewicz, 1991; Markard and Truffer, 2008), multi-level perspective (Geels and Schot, 2007; Geels, 2010, 2011), social-ecological systems (Berkes and Folke, 2000), sustainability pathways, transformative adaptation.

In the mobility sector, examples of current innovations that may create the momentum for low-carbon and sustainability transitions are (Geels, 2020):

- i) Technical innovation: battery electric vehicles, biofuel cars, automated vehicles
- ii) Social innovation: car and bike sharing, modal shift to soft modes of transport, teleworking, teleconferencing
- iii) Business model innovation: sharing services, mobility services (e.g. MaaS)
- iv) Infrastructural innovation: intermodal mobility systems, mobility hubs, compact cities

Automated vehicles can be analysed through the prism of 'techno-economic paradigm' (Freeman and Perez, 1988) and as part of the socio-technical transition of the mobility system (Milakis and Müller, 2021). AVs entail changes in infrastructure, industrial networks, policies, market and mobility behaviour and habits (Fagnant and Kockelman, 2015; Hopkins and Schwanen, 2018; Milakis and Müller, 2021). Automated driving, along with vehicle electrification, is expected to change the mobility system; in addition, the combination of shared economy and information technology may enable new mobility services (Becker et al., 2020).

2.4 THE TRANSITION FROM THE CURRENT TO THE FUTURE MOBILITY PARADIGM ²

The discussion addressing the mobility paradigm has raised attention in the last decades due to the increasing externalities in the transport sector and the acknowledgement of the limitations of car dependence and the car-dominant mobility system (Bouton et al., 2015; Fournier, 2017).

The current mobility paradigm, as it evolved, is based on individual mobility, featured by car ownership, individual rides, cheap fossil fuel and, consequently, high CO₂ emissions and mobility externalities (Fournier, 2017). This model has influenced how cities and streets are planned, infrastructure is built, and policies are designed (Nemoto et al., 2021).

Banister (2008) points out two critical principles of conventional mobility. The first principle is 'travel as a derived demand', meaning that the act of moving is not necessary as an action that people wish to undertake; however, it is justified by the value of the activity at the destination. The second principle is travel cost minimisation through the arrangement between the costs and time of travel. According to Banister (2008), these two principles from conventional mobility explain some implications for the current mobility paradigm, such as faster and longer distance travel and greater use of the car to the detriment of local public transport, cycling and walking. Such processes of car dependence and increased decentralisation of cities are difficult to reverse (Banister, 2008). Alike, Hupkes (1982) argues that expanding mobility is based mainly on increasing private motor car use.

Furthermore, Geels et al. (2017) explain that the current and dominant mobility system is car-dependent and resistant to change. It is maintained and incrementally improved by actors and institutions in the 'socio-technical regimes'. In addition, the preferences and habits of car drivers are reinforced by cultural and status associations of the car with freedom, prestige and individual identity (Attias, 2017; Geels et al., 2017). Figure 2 illustrates the socio-technical system of conventional car-centred mobility.

² *This section is written using as basis the theoretical background of the publication: Nemoto, E. H.; Jaroudi, I.; Fournier, G. (2021): Introducing Automated Shuttles in the Public Transport of European Cities: The Case of the AVENUE Project. Nathanail E.G., Adamos G., Karakikes I. In: Nathanail E.G., Adamos G., Karakikes I. (eds) Advances in Mobility-as-a-Service Systems. CSUM 2020. Advances in Intelligent Systems and Computing: Springer, Cham (1278).*

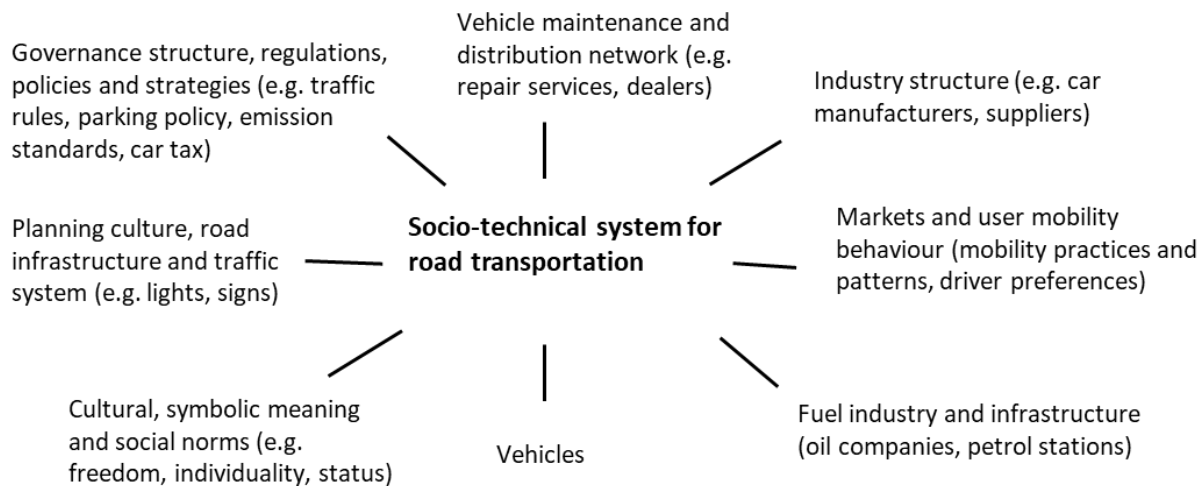


Figure 2. *Socio-technical system of conventional car-centred mobility, adapted by the author by Geels et al. (2017) and Canitez (2019).*

By acknowledging the limits and impacts of the current mobility, potential pathways for mobility transition are envisioned. These pathways target sustainable mobility and a new mobility paradigm (Banister, 2008; Sheller and Urry, 2016; Merriman, 2020).

Merriman (2020) portrays a 'new mobility paradigm', described by "the significance of mobility and mobilities in the modern world; and second, but less commonly, the emergence of new forms of mobile practice and technology which are reconfiguring social and economic life."

Sheller and Urry (2016) state that the new mobility paradigm presents intersections among public policy, planning and applied research, which embeds complexity in mobility systems. According to the authors, the research about the new mobility paradigm enlarges the field of transportation research to investigate built environments and urban design, environmental externalities, mobility justice, low-carbon energy transitions and paths for the transition to sustainable mobility. Further, Sheller and Urry (2016) describe a shift toward a "new mobility paradigm" occurring nowadays led by sharing, connectivity and accessibility. These are seen as socio-technical transitions that aim to decrease the use of automobiles and prepare for a post-auto mobility transition.

Regarding this transition, Banister (2008, 2011) argues that sustainable mobility provides an alternative paradigm to explore the complexity of cities. The author suggests four types of actions aiming 'sustainable mobility paradigm': i) Reducing the need to travel - substitution; ii) Transport policy measures - modal shift; iii) Land-use policy measures - distance reduction; iv) Technological innovation - efficiency increase (Nemoto et al., 2021). In addition, the author states the importance of the participation and support of stakeholders along the transition process.

Miskolczi et al. (2021) describe four scenarios for future urban mobility by 2030, and they vary according to the role and potential of emerging mobility solutions:

- 'Grumpy old transport' scenario: is very similar to the present mobility. It is pictured

by the predominance of privately owned cars, shared mobility remains in a narrow segment, and automation developments do not entail breakthroughs. Congestion, environmental pollution and other externalities are aggravated by the increase of the number of private cars and vehicle kilometres travelled.

- 'At an easy pace' scenario: presents moderate changes, privately-owned cars remain dominant, EVs gain better diffusion, whereas shared mobility and automation spread slow. In this path, environmental and traffic problems still remain serious and unsolved.
- 'Mine is yours' scenario: shared mobility and EVs are more spread and play a role in reducing to a certain extent the traffic problems and the negative impact of transport on the environment. However, the development of automation remains limited. The role of private cars decreases and intermodal and integrated solutions gain space.
- 'Tech-eager mobility' scenario: a high level of automation becomes widely available. In addition, shared, automated and electric vehicles are combined, strengthening each other's market position and minimising environmental impacts of mobility. Connect mobility enables optimising traffic flow, travel time and minimising congestion, ICT-based mobility solutions provide MaaS applications, e-ticketing, and real-time information. Public transport remains significant, and the environmental impacts are reduced.

Miskolczi et al. (2021) state that the most likely pathways are the 'At an easy pace' or the 'Mine is yours' scenarios. The study suggests that by 2030 mainly incremental advances, such as a slow shift towards automated driving, electric and shared vehicle use, are predicted.

The study by Marletto (2019) suggests three transition pathways to automated driving: i) the 'individual transition pathway' led mainly by automotive companies, ii) the 'shared transition pathway' led by the cooperation between leaders of the internet system, artificial intelligence and managers of shared and collective transport systems, iii) the 'smart transition pathway', driven by energy agents, who integrate AVs and smart grids based on the argument of energy efficiency and sustainability. Furthermore, it is crucial to sustain a systemic view when envisioning a transition to more sustainable mobility systems and a new mobility paradigm. It means that the mentioned technologies (shared, electric, automated, connected, ICT-based solutions) will play a relevant role in improving, optimising and reducing environmental impacts on mobility. Likewise, policies, regulations, urban and spatial planning, and new cooperation among stakeholders will also play a relevant role in implementing more sustainable mobility systems (Fagnant and Kockelman, 2015; Sprei, 2017; Litman, 2021a).

In summary, the transition to a new mobility paradigm is envisioned according to different paths, scenarios, actors' leads and speed of transformation. In this regard, some of the 'unknowns' and knowledge gaps concern the arrival of new stakeholders, the set of new interactions and new paths to lead transformations within the mobility sector with automated driving (Marletto, 2019). Hence, an in-depth understanding of the new stakeholders' constellation and new interactions within the mobility sector with AVs and AM is one of the knowledge gaps addressed by this thesis. In addition, the literature sustains

that the studies about transitions in mobility require a broader vision that goes beyond the technical nature of AVs. A broader picture should include the perspective of citizens and diverse groups of stakeholders (Pettigrew and Cronin, 2019; Milakis and Müller, 2021) and multi-level perspectives (Geels, 2011) to better understand the issues at stake and to draw the paths and mechanisms for a socio-technical transition in mobility with AVs. These gaps are also addressed within the research work in this thesis and detailed in the next section, in Chapter 3.

2.5 THE POTENTIAL IMPACTS OF AUTOMATED VEHICLES ON MOBILITY SYSTEMS

Automated vehicles, combined with other mobility innovations, are expected to lead a paradigm shift in transportation. Hence, the potential impacts of automated vehicles are the object of study from different angles, such as economy, environment, governance, travel behaviour, traffic and safety, transport supply, and land use (Narayanan et al., 2020).

The sharing economy, automated driving and electrification are major developments in the transport sector (Sperling, 2018; Dlugosch et al., 2020). In addition, connectivity, multimodality, and mobility-on-demand services enabled by automated driving may lead to a shift toward smaller, more flexible and right-sizing vehicles instead of large buses (Dlugosch et al., 2020; Nikitas et al., 2021). The synergies and combination of such innovations are emphasised in literature when aiming for pro-environmental and resource-saving benefits (Taiebat and Xu, 2019; Nikitas et al., 2021).

Although numerous studies, the impacts of AVs on mobility and energy remain uncertain (Shaheen and Bouzaghrane, 2019; Miskolczi et al., 2021). The estimated impacts vary according to the model assumptions (Soteropoulos et al., 2019) and the deployment mode, such as privately owned or shared mobility modes and their levels of integration into public transport and Mobility as a Service system (Stocker and Shaheen, 2017; Sochor et al., 2018). In addition, more real-world data is needed in order to support better impact estimates, modelling and simulations (Shaheen and Bouzaghrane, 2019). Else, the level of uncertainties and complexity increase according to the different levels of assessment of AVs: vehicle, transportation system, urban system and society (Taiebat et al., 2018).

The study by Taiebat et al. (2018) evaluated the impacts of connected and automated vehicles (CAV) on the different levels of assessment mentioned. The study points out that at the vehicle level, CAV technology can enhance efficiency via fuel savings (ranging from 2% to 25%) and emission reduction. At the transportation system level, CAV can enable optimisation of fleet operations, improved traffic behaviour, better efficiency in vehicle utilisation, and the provision of shared mobility services. At the urban system level, CAV could help to redesign cities by changing land use, mobility infrastructure (e.g. facilitating the integration of EVs and charging infrastructure), and spatial planning. On the other hand, urban sprawl, induced demand and communications with large-scale data centres, which require energy-intensive, represent the other side of the equation. The society-level impacts comprise mobility behavioural changes and the synergetic effects of vehicle automation, electrification, right-sizing, and shared mobility.

AVs deployed as privately owned, or SAVs without ride-sharing, are mostly found to increase vehicle kilometres travelled and lead to reductions in public transport and soft modes of transport (Soteropoulos et al., 2019). Conversely, shared automated vehicle fleets (with high ride-sharing) could present positive impacts by reducing the number of vehicles and parking spaces and improving the efficiency of the public transport system (Soteropoulos et al., 2019).

Zhang et al. (2020) assessed the impact of automated buses on emissions and energy consumption on the urban expressway. Their results show that CAV technology in buses coupled with managed lane strategy can reduce exhaust emissions and save energy. The study by Shen et al. (2018) simulates the integration of AVs into the public transport system as an alternative for first-mile during morning peak hours. In the context of keeping the high-demand bus routes and repurposing low-demand bus routes, and using shared AVs as an alternative, the results pointed out that AVs in an integrated system have the potential to operate bus services more efficiently, enhancing service quality and occupying fewer road resources. However, the same study warns of the fact that different scenarios for the integration of AVs in public transport could also worsen the system performance, for instance, by increasing passenger car unit kilometres. Therefore, Shen et al. (2018) caution that integrating AVs into the public transport system will not automatically improve the mobility status quo.

AVs are also poised to improve accessibility, safety and lower cost for mobility. Regarding the public acceptance of AVs, the study by Haboucha et al. (2017) indicates that early AV adopters will likely be young, students, educated, and people that spend more time in vehicles. Krueger et al. (2016) investigated the preferences for shared AVs. The main findings point out that travel cost, travel time and waiting time may be critical determinants of the use of SAVs. The study from Krueger et al. (2016) also confirms that young individuals with multimodal travel patterns might be more prone to use shared AVs. The main concerns related to automated driving are found to be software hacking/misuse, legal issues and safety (Kyriakidis et al., 2015).

A questionnaire study among users of automated minibuses in Berlin-Schöneberg pointed out a positive attitude of users towards the automated minibuses and their potential use as feeders to public transport systems (Nordhoff et al., 2018). The study also suggests that speed and effectiveness are features to be improved when aiming the deployment of the AM on wider scales (Nordhoff et al., 2018). Another study by Nordhoff et al. (2019) interviewed users of automated minibuses. The study showed that although the current technology does not meet the users' expectations, respondents presented a positive opinion about the automated minibuses, associating them with flexible, comfortable, fast, and reliable mobility services (Nordhoff et al., 2019).

Another topic of great interest is how AVs can cope with lower mobility costs and cost competitiveness. A total cost of ownership (TCO) study by Ongel et al. (2019) indicates that although the acquisition costs of AVs are high, they could reduce up to 75% and 60% of the TCO per passenger-km compared to their conventional counterparts and buses, respectively.

Litman (2022) argues that AVs are likely to cost more than human-driven vehicles and public transit but less than human-driven taxis and ride-hailing services. Additionally, he argues that AVs can provide large savings for commercial vehicles, such as freight trucks and buses, by reducing labour costs. In this regard, Becker et al. (2020) indicate that high-income countries are more likely to reap economic benefits from vehicle automation in comparison to lower-income countries. This is explained by the different labour costs of current taxi and bus operations among high and low-income countries.

The study by Bösch et al. (2018) provides a cost comparison of different modes with and without autonomous vehicle technology. The study shows that automated driving allows taxi services and buses to be operated at a significantly lower cost, and it alerts to the fact that conventional forms of public transportation may face major competition in the new era.

Another crucial aspect is transport policies; they can influence and determine the impacts of mobility innovations at the city and societal scale. In the case of AVs, transport policies can affect the type and size of the fleet, the mix and integration between public transport, shared vehicles and the acceleration of the adoption of pooling, as well as the congestion and emissions levels in the city (Martinez and Viegas, 2017). In this regard, Audouin and Finger (2019) highlight the importance of more proactive and enabler governance approaches to mobility from public national and local public authorities in order to integrate modes of transport and develop MaaS schemes. Kuss and Nicholas (2022) also suggest 12 effective intervention types combining different pull and push measures and policy instruments targeting the reduction of car use in European cities.

In a nutshell, some of the 'unknowns' or knowledge gaps in the literature refer to the impacts of AVs on the mobility system, society, and environment remain uncertain and unclear (Shaheen and Bouzaghrane, 2019; Miskolczi et al., 2021). Therefore, systemic methods for assessment of AVs, which take into account the new and different dimensions of mobility, is valued (Litman, 2021b). Likewise, the assessment based on empirical data is also needed to improve modelling, estimates and mobility planning (Shaheen and Bouzaghrane, 2019). Moreover, the literature points out that it is necessary to understand better the contributions of AVs and SAEV to sustainable mobility and under which premises and circumstances of deployment (Nikitas et al., 2021; Huber et al., 2022). Such gaps are addressed by this thesis and detailed in the next section, in Chapter 3.

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CHAPTER 3 RESEARCH GAPS, RESEARCH QUESTIONS & METHODS

Through the literature review, it was possible to identify the main research gaps and limitations in the impact assessment of shared automated electric vehicles and automated minibuses in the mobility system. Likewise, the literature pointed out knowledge gaps concerning the transition pathway in mobility with the integration of AVs. Hereinafter, the identified research gaps are presented along with the related research questions and methods that were conceptualised and applied to address the research objective of this thesis.

3.1 RESEARCH GAPS, RESEARCH QUESTIONS & METHODS

In the first place, it is worth noting that throughout the thesis, the terms AV, SAEV and AM are used. Therefore it is important to clarify that 'AV' is used as a more generic term, which refers to vehicles with levels 3, 4 and 5 of driving automation (detailed explanation in section 2.3), and it comprises SAEV and AM. SAEV is a term in literature to designate the combination of AV with shared and battery electric vehicles. In addition, 'shared' can refer to 'goods sharing', such as carsharing, or 'service sharing', such as ridesharing, ridepooling and ridehailing. In this regard, both sharing services could be integrated within Mobility as a Service. Further, the automated minibus is characterised as a mobility gap filler, for instance, providing first and last miles, and by the integration with public transport and in the mobility system in general. In addition, it is worth noting that according to SAE (2018) - "Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles" – the term "autonomous" could be considered misleading when applied to automated driving technology. SAE (2018) argues that the most advanced automated driving system (ADS) are not 'self-governing', but they depend on communication and cooperation with outside entities. Therefore, the terms 'automated driving' and 'automated vehicles' are used throughout the thesis.

Henceforth the identified research gaps are presented, and respective research questions and methods are introduced in an attempt to contribute to filling in the knowledge gaps.

- **Research gap:** lack of frameworks and tools to assess and measure the impacts of Shared Automated Electric Vehicles (SAEV) in mobility systems.

The deployment of SAEV in different forms is a complex and multifaceted topic. The impacts of the deployment of SAEV entail diverse mobility spheres, such as social, environmental, economic, governance and technical performance. Therefore, by targeting sustainable mobility systems with SAEV, comprehensive frameworks and tools for assessing SAEV impacts are required (Dobranskyte-Niskota et al., 2009; Litman, 2021b). For instance, Arsenio et al. (2016) pointed out the absence of specific guidance and gaps in methods to strengthen SUMP's implementation. In addition, SAEV imply the deployment of new technologies and innovations in mobility, and consequently, new indicators and measurements of impacts are needed.

Setting comprehensive criteria and parameters can contribute to filling gaps of knowledge about the performance of SAEV along the time of implementation, towards the targets to be achieved, and to compare SAEV to other means of transport (Castillo et al., 2010; Miranda and Rodrigues da Silva, 2012). By applying the frameworks and tools for assessment, the results could strengthen scientifically based recommendations for transportation policies and provide information for policymakers and decision-makers (Moldan et al., 2012).

Considering these elements, the following research question is formulated:

Research question 1. How to measure the impacts of Shared Automated Electric Vehicles on the mobility of cities?

Method: to answer this research question, the research method consists of an integrative literature review and the conceptualisation of a set of indicators for the sustainability assessment of SAEV. The literature review provided the basis to contextualise the current mobility paradigm and innovations and present concepts and definitions of sustainable mobility, sustainability assessment, and technology assessment. The integrative literature review on methods and frameworks to assess sustainable mobility was also a cornerstone to conceptualise the set of indicators. Furthermore, the conceptualisation and analysis of the study are grounded on real cases of AVENUE project, in which automated minibuses are deployed in pilot trials in four European cities. In a further step, the set of indicators was discussed and validated with experts.

- **Research gap:** the impacts of SAEV remain unclear, and there is a lack of real-world data and impact assessments on the current state of automated vehicles and automated minibuses

As pointed out by the literature review, the impacts of SAEV remain unclear. It could either engender social, environmental and spatial benefits or aggravate even more mobility externalities in cities (e.g. congestion, climate change, accidents, noise pollution) (Taiebat et al., 2018; Jones and Leibowicz, 2019; Soteropoulos et al., 2019).

The impact assessment of SAEV depends on a diversity of variables, and there is a growing number of studies aiming to determine and quantify their impacts. These studies are based on predictions, modelling, estimates and scenarios. However, AVs and SAEV impacts still remain uncertain as their levels of interaction extend the complexity and uncertainty of AVs impacts also augment (Taiebat et al., 2018). In addition, there is a lack of experimental studies and real-world data to underpin more accurate modelling and estimates of AVs and SAEV impacts (Shaheen and Bouzaghrane, 2019; Nikitas et al., 2021).

Considering the mentioned research gaps, the corresponding research questions are:

Research question 2. What are the current performance and impacts of AM integrated into public transport in European cities?

Research question 3. How can AM contribute to SUMP approach?

Research question 4. What are the perspectives for future mobility systems with AM?

Method: to investigate these research questions, the research method builds upon the application of the set of indicators conceptualised in the previous stage of the thesis. The aim is to perform the sustainability assessment of the deployment of automated minibuses in the urban mobility of European cities. The multi-dimensions of mobility assessed comprise five axes: social, environmental, economic, governance and technical system performance. Four case studies from pilot trials of AVENUE project are assessed. The case studies are based in Lyon (France), Luxembourg (Luxembourg) and Copenhagen (Denmark). Primary data and studies related to the impact assessment of the pilot trials are used for the sustainability assessment. In addition, two potential future scenarios for the AM are assessed. The scenarios vary according to the level of integration of the AM into the mobility system. Ultimately, the results from the sustainability assessment are discussed under the SUMP approach, which includes the premises and recommendations for sustainable deployment with AM.

- **Research gap:** lack of in-depth understanding of the transformations in the mobility sector, which entail a new stakeholders constellation and new interactions within the mobility sector.
- **Research gap:** lack of broadening the analysis beyond the technical aspects of AVs, which includes the perspective of different actors, a better understanding of the issues at stake, and the pathway and mechanisms for transition in mobility with AV and AM

The nature of mobility is changing, so the mobility landscape and constellation of stakeholders are also evolving. The rearrangement of all players is currently taking place. And it is characterised by new partnerships and alliances outside the automotive industry, the arrival of newcomers, new business models (e.g. car sharing and carpooling), cooperation and competition, value creation through mobility services, and the embedment of technologies aiming at innovation ecosystems (Attias and Mira-Bonnardel, 2017).

In the face of such changes, there is a need to better understand the new dynamics and relations among stakeholders in the new mobility landscape, especially when it comes to the deployment of SAEV, which encompasses the combination of different technologies and fields of expertise (Marletto, 2019).

Moreover, it is critical broadening the discussion beyond the technical nature of AVs and widen the range of actors involved when addressing the deployment of AVs (Pettigrew and Cronin, 2019). Therefore, a comprehensive approach becomes relevant to expand the analysis to other sectors of society and to better ensure the social benefits of AVs within a long-term vision. By envisioning mobility that would serve the general interest, it also becomes important to take into account the perspective of citizens and their mobility needs (Milakis and Müller, 2021). The perception and attitude of the ensemble of stakeholders are cornerstones to further investigate what AVs represent in terms of socio-technical transition and to identify drivers, barriers and mechanisms to draw a transition pathway aiming for changes in the mobility paradigm and sustainable mobility (Pettigrew and Cronin, 2019).

Hence, the following research questions are formulated:

Research question 5. What are the stakeholders, their roles, interactions and perceptions concerning the integration of automated minibuses in public transport and in the mobility system in general?

Research question 6. What are the drivers and obstacles to the integration of the AM into urban mobility?

Research question 7. How could AM become a game-changer for mobility systems and contribute to sustainable mobility?

Method: The research method builds upon conceptual mapping and semi-structured interviews with the main stakeholder groups (n= 30) and a large-scale survey with citizens in four European cities (n= 1816). The study analyses the integration of automated vehicles and automated minibuses into the urban mobility systems from the perspective of different stakeholder groups and citizens. In addition, it uses the lens of socio-technical transitions and a multi-level perspective (MLP) as a conceptual framework.

The main outcomes and contributions of this thesis encompass:

- The conceptualisation of framework for assessment - the set of indicators for sustainability assessment of SAEV.
- The sustainability assessment of the current deployment of AM and potential future scenarios. The assessment is based on real-world data and empirical cases from pilot trials deployed in European cities.
- The development of premises and recommendations for the sustainable deployment of the AM within mobility systems according to the Sustainable Urban Mobility Planning (SUMP) approach.
- Building a stakeholders map and identifying the stakeholders' goals, interactions and perceptions concerning the automated driving and (public) transport provision.
- Identification of the main drivers and barriers to deploying AV and AM
- Analysing and interpreting the socio-technical transitions in the mobility sector with the integration of AVs and AMs through a multi-level perspective (Landscape, Regime and Niche).
- Identification of mechanisms for a transition in mobility systems with the integration of AM.

Figure 3 summarises the research questions, methods and main outcomes and contributions of the thesis.

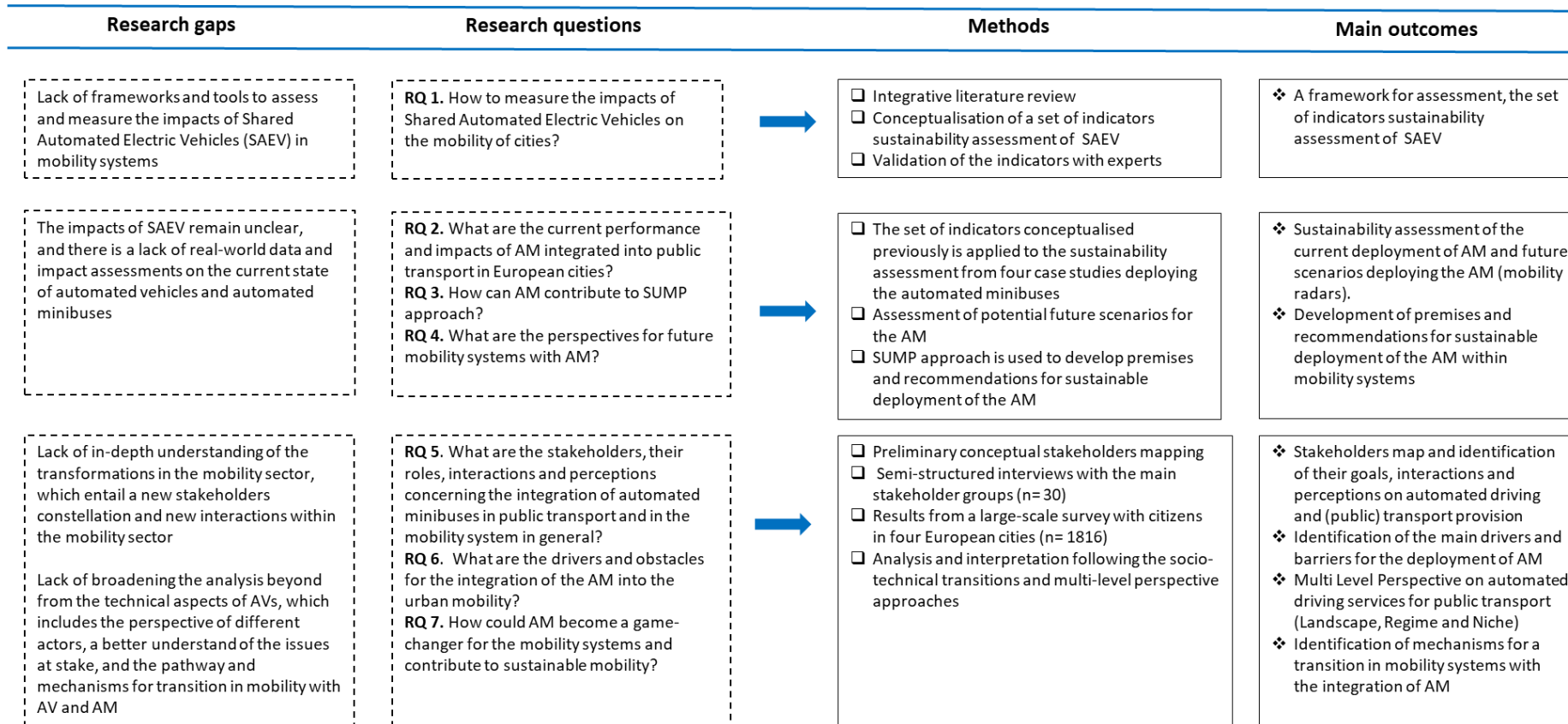


Figure 3. Research gaps, research questions, methods and main outcomes

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CHAPTER 4 HOW TO MEASURE THE IMPACTS OF SHARED AUTOMATED ELECTRIC VEHICLES ON URBAN MOBILITY

Abstract

The arrival of new technologies and innovations in mobility, such as automated vehicles, creates opportunities to tackle urban challenges. The evaluation of the impacts of these innovations on the mobility system requires a comprehensive set of criteria and parameters. This study proposes a method to measure the impacts of Shared Automated Electric Vehicles (SAEV) on mobility through a sustainability assessment. Based on an integrative literature study and in the context of AVENUE, a European project deploying automated minibuses in the public transport of European cities, a set of indicators is defined. These mobility indicators assess the social, environmental, economic, governance, and technical impacts of SAEV. The multiple dimensions of the mobility indicators contribute to filling gaps of knowledge about the performance of SAEV. The proposed method allows an evaluation and comparison of SAEV to other means of transport and thus strengthen scientifically based recommendations for transportation policies.

(adjusted version) Nemoto, E. H., Issaoui, R., Korbee, D., Jaroudi, I., & Fournier, G. (2021). How to measure the impacts of shared automated electric vehicles on urban mobility. *Transportation Research Part D: Transport and Environment*, 93, 102766. <https://doi.org/10.1016/j.trd.2021.102766>

4.1 INTRODUCTION

Mobility of people and goods is at the heart of our society and economic activities (Le Boennec et al., 2019). Globally, in the period from 2000 to 2015, passenger travel activity increased by 74%, freight travel activity by 68%, and the motorisation rate increased by 27% (SLoCaT, 2018). Particularly in cities, the global demand for passenger mobility is estimated to double by 2050 (van Audenhove et al., 2018). Along with the continuously increasing demand for mobility, the negative impacts, such as congestion, air pollution, noise and accidents, tend to be intensified (Bouton et al., 2015; Fournier et al., 2020).

To better tackle the challenges posed by the current mobility paradigm, innovative mobility modes and systems pursue new paths to increase the number of journeys and transport efficiency as well as to pave the way for sustainable mobility (Pribyl et al., 2020). Among several innovations in mobility, Shared Automated Electric Vehicles (SAEV) could provide promising solutions for cities (Willing et al., 2017; Attias, 2017; Sprei, 2017; UITP, 2017). SAEV refers to different types of vehicles, such as robo-taxis and automated minibuses (also called automated shuttles) integrated into public transport, and their business models can vary based on vehicle ownership (public or private) and who controls the network operations (Stocker and Shaheen, 2017). SAEV can provide different services, e.g. on-demand ride services and ridesharing, within a fixed route with fixed stops, a fixed route with on-demand stops, or door-to-door on-demand services, which is a focus of AVENUE. SAEV can further provide a unimodal door-to-door trip or be combined with other means of transport for one trip. And its scale of deployment varies from mobility services within a local area (first and last mile services as mostly deployed nowadays) to city and inter-city mobility services.

Therefore SAEV impacts may also vary according to the deployment modes, means of transport that they will substitute as well as their potential for reducing vehicle ownership, ride-matching capacity, usability and efficiency in response to a potential increase in travel demand and vehicle miles travelled (VMT) (Gurumurthy and Kockelman, 2018; Shaheen and Bouzaghrane, 2019). Although there are estimates and model assumptions, SAEV impacts remain uncertain, and real-world data is valuable for better estimates (Shaheen and Bouzaghrane, 2019).

This study addresses the sustainability assessment of SAEV, of which automated minibuses integrated and complementing the public transport of European cities are an example.

Development and tests of automated vehicles (AVs) have been implemented widely, spanning countries such as the United States, China, Singapore, Germany, Sweden, and South Korea (AIG, 2017). Pilot projects, furthermore, test SAEV in the public transport of cities in an attempt to overcome mobility gaps and improve transport accessibility, flexibility, and sustainability. Examples of these pilot projects are CityMobil2, FABULOS, AVENUE and SHOW in the European Union, 2getthere projects in the Netherlands, SOHJOA in Finland, and Mcity Driverless Shuttle research project in the United States.

Ongoing pilot projects often stress the potential of SAEV in their contribution to a more sustainable mobility system. However, this claim needs to be critically assessed. There is no

full insight into the environmental impacts of SAEV based on real tests and current data. First results of an encompassing life cycle assessment point to the importance of the occupancy of the minibuses, the lifetime of the vehicle, the electricity mix, and the energy efficiency in assessing the environmental sustainability of SAEV (Huber et al., forthcoming). Furthermore, offering personalised mobility by the introduction of SAEV could increase mobility demand, putting additional stress on urban mobility systems (Hymel et al., 2010; Soteropoulos et al., 2019). In addition to environmental sustainability, there are also open questions regarding the social acceptance of the SAEV (Kyriakidis et al., 2015; Krueger et al., 2016; Madigan et al., 2017; Axsena et al., 2019), and economic feasibility (Chen et al., 2016; Chen and Kockelman, 2016). Therefore, SAEV contribution to sustainable mobility in cities is still an open question and it may vary according to the different deployments (Axsena et al., 2019; Litman, 2020). In addition, it has become clear that there is a need for suitable policies, regulations, and incentives for a responsive use of this new mode of transport (Fagnant and Kockelman, 2015; Le Boennec et al., 2019; Nordhoff et al., 2019).

In order to answer these research gaps, this study addresses the following research question: how to measure the impacts of Shared Automated Electric Vehicles on the mobility of cities. To this end, a multi-dimensional set of indicators is conceptualised. The method enables the sustainability assessment of SAEV as a means of transport to be integrated into mobility systems. The definition of a set of criteria and parameters is thus considered a key issue in evaluating the impact of SAEV posed on the mobility system of cities and in formulating policy recommendations (Castillo et al., 2010, 2010; Miranda and Rodrigues da Silva, 2012).

Moldan et al. (2012) point out how measurement indicators could improve the information for policymakers and thus enhance operational policies for sustainable development. The definition of a baseline as a point of reference for assessment helps measure changes; thus indicators help set targets of change to be achieved, and these targets represent policy drivers. The indicators could give quantitative significance to the goals of sustainability, which clarifies the observance and achievement of these goals.

Basis of the research is both a theoretical approach combined with practical experiments based on the European Project AVENUE. This study builds accordingly upon the contextualisation on mobility innovations, AVs and sustainable mobility in the European Union (EU), and the approaches to measure sustainable mobility (section 4.2), description of the methodology (section 4.3), the set of indicators for Sustainability Assessment of SAEV (section 4.4), discussion and conclusion (section 4.6 and 4.7).

4.2 SUSTAINABLE MOBILITY, AUTOMATED VEHICLES, AND THE EU

4.2.1 Current mobility paradigm and mobility innovations

Our current mobility paradigm relies on car ownership, individual mobility, and fossil fuels as the primary source of energy. As mentioned before, such mobility patterns have reached their limits (Fournier, 2017) and aggravated negative external impacts, especially in cities (Bouton et al., 2015; CE Delft, 2019; Fournier et al., 2020). In addressing these negative impacts, there are signs that the nature of mobility is changing, and a new mobility paradigm

is being shaped by new technologies and innovations such as automated, connected, electric, and shared vehicles (Borroni-Bird, 2012; Sprei, 2017; Goehlich et al., 2020). Innovations are followed by new regulations, policies, innovative business models, and mobility solutions that enable car use without owning a car (Schuppan et al., 2014).

Mobility as a Service (MaaS) enables consumers to buy mobility services instead of buying the means of transport, and the services can be provided by the same or different operators (Kamargianni et al., 2015). MaaS is characterised by the integration of various means of transport services into a single mobility service based on individual needs (Sochor et al., 2018; MaaS Alliance, 2020). This way, the dominant status of the privately-owned car, associated with prestige and social recognition, is decreasing, opening up possibilities for inter- and multimodal mobility, sharing means of transport (bicycle, cars, scooters, mobility micro-devices) and ride-sharing (Attias, 2017). Multimodal transportation is defined as “the use of various travel modes within a given period” (Nobis, 2007; Klinger, 2017), while intermodal transport combines several modes of transport (public and private) in one single trip (Eltis, 2019). Such mobility preferences are characterised by convenience, low cost, and flexibility in travel journeys (Lindloff et al., 2014). These new mobility concepts are changing the way we see transport and the way we commute and travel: mobility is not seen as a physical asset to purchase but rather as a “service available on-demand and incorporating all transport services” (Mulley, Nelson, & Wright, 2018).

Among those changes, Shared Automated Electric Vehicles have emerged as an innovation that would shape the future of mobility (UITP, 2017). They combine automated driving technology, electromobility, and shared mobility and present potential solutions for urban transport systems (Webb et al., 2019). SAEV has become attractive because they have the potential to customise trips, even for public transport (UITP, 2017). They can also simplify vehicle access, reduce fleet size, avoid parking costs, reduce carbon emissions, air pollution, and contribute to a more efficient transport system (Chen et al., 2017; Sprei, 2017; Loeb et al., 2018; Vosooghi et al., 2019). In addition, SAEV can change travel-behaviour by providing greater mobility to teenagers, the elderly and disabled people and foster a modal shift from private mobility to shared and service-use mobility (Fagnant and Kockelman, 2015; Kamel et al., 2019). Fagnant and Kockelman (2015) estimate benefits of \$2000 per year per AV, considering crash savings, travel time reduction, fuel efficiency, and parking savings. Users seem to be accepting this new technology but require further technological improvements (regarding speed and efficiency) before it can be seen fit to be diffused and deployed on a larger scale (Alessandrini, 2016; Nordhoff et al., 2018). Recent studies indicate that individuality is a key issue for potential users defining willingness to use SAEV as well as to reduce the use of one’s own car (Korbee et al., in prep). However, the real impacts of SAEV on the environment and mobility behaviour remain uncertain (Stocker and Shaheen, 2017). For instance, it is crucial to identify the risk of induced travel demand, as driverless vehicles become more efficient and convenient, more trips should be expected (Hymel et al., 2010). Indeed, Fagnant and Kockelman (2015) anticipate that a market share of 10% of AVs will cause a rise of 20% in total kilometres travelled. This will not support the sustainable cities agenda. Although AVs could reduce the nuisance of congestion and accidents, the increase in total rides will lead to a bigger environmental footprint, not to forget the effects on urban

design (Chase, 2014). A way to counter that is to couple the deployment efforts with Travel Demand Management (TDM). It focuses on altering mobility behaviour to control the growth of transportation demand (Ferguson, 1990). The use of SAEV should be planned in coordination with public transport and public policies to fill mobility gaps, reduce car ownership, and promote walking and biking. As part of a package of a MaaS platform, congestion pricing, and urban planning, the shared rides could provide affordable seamless trips and accessibility in urban areas (Shared mobility principles, 2017).

4.2.2 The EU strategy and goals towards AVs and sustainable mobility

The European Union transport policy aims to ensure an efficient, safe, clean, and connected transport of people and goods (EU, 2019). Future policies are guided by the 'White Paper on transport – Roadmap to a single European transport area' (2011), a strategic document to set a common vision for the future of the EU transport system as well as to define the policy agenda. It sets out 40 actions and lists 131 initiatives. The main goals comprise: reducing the use of oil to achieve CO₂-free city mobility by 2030, developing a multimodal transport information management and payment system, growing transport and supporting mobility while cutting transport carbon emissions by 60 % by 2050, among others (EU, 2015).

In line with the White Paper on transport, the 'European Strategy for Low-Emission Mobility' (2016) states that cities are crucial to achieving the strategy's goals. They include deploying zero-emission vehicles, increasing the efficiency of transport systems, and deploying disruptive trends through digitalisation, new technologies, and innovative mobility modes.

In May 2018, the European Commission launched the report 'On the road to automated mobility: An EU strategy for mobility of the future' (2018). The document addresses connected and automated mobility as an opportunity to present solutions to increasing demand for mobility of people and goods as well as solutions for safer, more accessible, and sustainable transport. It states that such technologies can boost carsharing schemes, 'mobility as a service', and accelerate electromobility. It also notes the importance of properly managing the transition phase, considering the need to strengthen the links between public and privately owned data, vehicles and traffic management, and collective and individual transport. Moreover, it points to new risks of the overreliance and misuse of technology as well as the required level of infrastructure for automated driving. The strategy states the ambition to place Europe as a world leader in the deployment of connected and automated mobility (European Commission, 2018).

And more recently, within the European Green Deal, the European Union will adopt a new strategy for a climate-neutral continent, including sustainable and smart mobility in 2020 (European Commission, 2019). The objective targets the reduction of transport-related greenhouse gas emissions by 90% by 2050 (European Commission, 2020). Digital and green transition will thus be combined with zero-emission solutions, automation and connectivity to address the challenges for future generations (ibid).

In addition to the private investments on technology development and infrastructure, the EU invests in research and innovation through demonstration projects and large-scale

testing taking place in the EU Member States. The programme ‘Horizon 2020’ supported research and innovation in the field of automated vehicles through AVENUE . AVENUE aims to design and implement full-scale demonstrations of automated minibus fleets in urban transportation to demonstrate that automated vehicles can be integrated within the public transport systems as well as to identify the issues, barriers, societal changes, and economic consequences.

The AVENUE project (2018-2022) operates pilot projects in four European demonstrator cities: Geneva, Lyon, Copenhagen, and Luxembourg (AVENUE, 2018). As a first step, automated minibuses are integrated into the public transport system using fixed routes on mixed traffic. In the timespan of the AVENUE project, it is foreseen that these routes will be transformed or complemented by on-demand, door-to-door services. Successful tests in the Belle Idée site (Geneva) in 2020 suggest feasibility hereof. Table 1 presents details of the pilot tests in the four countries. By demonstrating the feasibility of integrating an automated, on-demand, door-to-door minibus service in the existing urban public transport system, AVENUE aims to contribute to the development of a system of widely-available on-demand automated minibuses. The creation of this system is, however, out of the scope of the AVENUE project. In this research, we aim to design an assessment method that can assess both the future system as well as the current state of the art.

Table 1. Overview of the AVENUE pilot tests

City	Pilot	Characteristics of route	Number of minibus	Type of passenger	Start and planned end date	Transport Operators	Frequency
Geneva	Meyrin area	Fixed route with stops 2.1 km	1	Residents of the area	Aug-2017 – April 2022	Transports Publics Genevois (TPG)	every 30 min Monday to Friday: 06h30-08h30 & 16h-18h15
	Belle-Idée	On-demand, door-to-door services	3 or 4	Visitors of the hospital, patients	May-2018 – April 2022		Test phase
Lyon	Groupama Stadium	Fixed route with stops 1.3 km. Will become an on-demand, door-to-station service	2	Different passengers, people with reduced mobility (medical centre nearby)	Nov-2019– April 2022	Keolis	Every 15 min Monday to Saturday: 08h30-19h30
Copenhagen	Nordhavn	Fixed route with stops, will become an on-demand, door-to-door service	2	Residents of the area	August-2020– April 2022	Amobility/ Let's Holo	Monday to Friday: 10h-18h
Luxembourg	Contern	Fixed route with stops, on-demand. 2.2 km	1	Employees working at Campus Contern	Sept 2018 – April 2022	Sales (SLA) Lenz	Monday to Friday: 07h-09h & 16h-19h
	Pfaffenthal	Fixed route with stops, on-demand 1.2 km	2	Workers, tourists, residents, and visitors of Luxembourg city	Sep-18 – April 2022		Every 15 min Tuesday & Thursday: 12h-16h; 16h45-20h Saturdays & Sundays: 10h - 21h

Source: adapted by the authors, based on Nemoto et al. (2020)

4.2.3 Approaches to measure sustainable mobility

To understand the current mobility paradigm and to meet the need for a scientifically based measurement of the impact of SAEV and the requirements of our society, in particular the new strategy of the EU towards sustainable mobility, we will discuss the concepts of sustainability assessment, and technology assessment in the next paragraphs.

4.2.3.1 Sustainability Assessment

Sustainability assessment has its origins in the late 1960s and early 1970s. It has evolved from the fields of environmental impact assessment (EIA), strategic environmental assessment (SEA), policy analysis techniques, and has embraced the sustainable development agenda (Pope et al., 2004). Sustainability assessment is a tool to support decision-makers and policymakers in deciding which plans and actions make an optimal contribution to a sustainable society (Devuyst 2001; Verheem 2002; Pope et al., 2004). A sustainability assessment is more than adding up environmental, social, and economic impacts; it requires the integration of sustainability principles, targets as well as inter- and trans-disciplinary approaches (Sala et al., 2015).

Over the years, a broad range of tools has been developed. Three general areas of application can be discerned (Ness et al. 2007): Indicators and indices to assess sustainability dimensions; Product-related assessment that focuses on resource use, material, and energy flows (e.g., Life-Cycle-Analysis); and integrated assessment (e.g., Multi-criteria analysis).

Sustainability indicators are a powerful tool to simplify, quantify, analyse, and communicate complex information (KEI, 2005; Singh et al., 2009; Innamaa and Salla, 2018). Further, indicators have the ability to embed the multidimensionality of sustainable transport (Castillo et al., 2010). In this study, a set of indicators was chosen as a method to conduct sustainability assessments. This sort of assessment is used to measure sustainable urban mobility, yet considering the role of innovations in the current mobility system, sustainability assessment is boosted in this study by combining concepts of technology assessment.

4.2.3.2 Technology assessment

The term 'Technology Assessment' (TA) aims at developing scientific and research-oriented studies to analyse current and potential societal impacts of technological development and innovations (Jischa, 1998; Bechmann et al., 2007; Banta, 2009; Grunwald, 2009; Nazarko, 2015). Three types of TA have been developed (Jischa), (1998): a participatory assessment with a focus on technological legitimacy, a systematic process based on system theory, and; an instrument for planning and decision making.

Different tools and methods can be applied in a comprehensive TA, such as system analysis, modelling, trend extrapolation, scenario building, interviews, focus groups, discourse analysis, and decision trees. Assessment methods include risk assessment, cost-benefit analysis, life cycle analysis, and eco-balances (Jischa, 1998; Grunwald, 2009; Nazarko, 2015). Indicators as well are cornerstones in TA studies (Boavida and Bösch, 2015; Nayono et al., 2016).

TA is a powerful tool for achieving sustainable development (Ludwig, 1997). TA and sustainability are closely related since both are inter and transdisciplinary approaches that address social, environmental, economic, governance, and technical dimensions. Even more so, Nazarko (2015) states that TA is a suitable framework to achieve sustainability by fostering the synergy between available technologies, strategies of innovation, and the policies of governments. TA sheds light on which technologies can contribute to sustainable development, which is the best use and implementation of the technology, the consequences, and potential unintended consequences of technological innovations to be avoided or mitigated.

Therewith, this section contextualised the mobility innovations, their deployment in the EU to achieve sustainable mobility and climate-neutral cities, and presented the main concepts that steer the next sections and results of this study.

4.3 METHODOLOGY

The methodology builds upon two elements: an integrative literature review and the conceptualisation of a set of indicators.

The literature review was used to contextualise the current mobility paradigm and mobility innovations and to present concepts and definitions of sustainable mobility, sustainability assessment, and technology assessment (as discussed in section 4.2). However, more importantly, we applied an integrative literature review in order to conceptualise the set of indicators.

The integrative literature review is a form of research that reviews and summarises representative literature on a topic and results in new frameworks and perspectives (Torraco, 2005; Snyder, 2019). Four subsequent steps were applied: literature search, selection of studies, in-depth analysis and frequency of indicators, and conceptualisation of a set of indicators for sustainability assessment of SAEV (guided by the concepts and approaches to measure sustainable mobility according to section 4.2).

Step 1. Literature search

The integrative literature review was conducted based on robust existing methods, guidelines, and frameworks addressing indicators for sustainability assessment in the transport and mobility sector.

Academic search engines such as 'Google scholar,' 'ScienceDirect', and 'Research Gate' were used. The results were complemented by reports from international and regional organisations and networks such as Organisation for Economic Co-operation and Development (OECD), European Environment Agency (EEA), United Nations Economic Commission for Europe (UNECE), Local Governments for Sustainability (ICLEI), and World Business Council for Sustainable Development (WBCSD).

The keywords employed for the search were 'sustainable mobility assessment', 'sustainable

urban transport', 'indicators on sustainable mobility', and 'measuring sustainable mobility in cities'. Through these searches, we collected 38 documents.

Limitations in the literature search are associated with the limited features of the search engines for advanced searchers and limitations related to the specific keywords used. Hence, studies on similar topics but containing different keywords could be potentially excluded. In addition, the temporal limitation considered the literature within the period from 1999 to 2019.

Step 2. Selection of studies

From the 38 documents collected in the literature review, 18 sustainability assessment methods were selected for in-depth analysis (a complete overview is listed in table 2) based on the following criteria:

- 1) Broad applicability: the method has already been applied or can be applied to other European cities;
- 2) Comprehensiveness: the method covers at least three classical dimensions of sustainability - environmental, economic, and social;
- 3) Expertise: the methods and indicators are developed by international organisations, experts and networks with expertise in the field of transport and sustainability;
- 4) Complementarity: The methods should cover the dimensions and measurements of sustainable mobility as much as possible.

Table 2. List of methods and references considered for in-depth analysis in the integrated literature review on sustainable mobility/transport assessment, organised by decreasing order according to the publication year

Method and reference	Goal	Type	Scope and application	Sustainability dimensions	N° of Indicators	N° of applied cities
Deloitte Mobility City Index (Deloitte, 2019)	To gauge the health of a city's mobility network and its readiness to embrace the future.	Index	International	Performance and Resilience, Vision and leadership, Service inclusion	15	54
Indicators for Sustainable and Liveable Transport Planning (Litman, 2007)	"To provide guidance on the use of indicators for sustainable and liveable transportation planning."	Indicators set	International	Economic, Social, Environmental	40	-
The Urban Mobility Index (CEBR, 2017)	To assess how cities are approaching sustainable urban mobility and the progress towards achieving zero-emissions transportation solutions.	Index	International	Status Quo, Conditions for change, Preparedness for Future	20	35

Sustainable Cities Mobility Index (Arcadis, 2017)	To compare mobility systems around the world through an indication of sustainable urban mobility that includes measures of the social environmental and economic health of a city.	Index	International	People, Planet, Profit	23	100
Sustainability Measures of Urban Public Transport in Cities (Gruyter et al., 2017)	To assess the sustainability of urban public transport systems in cities by adopting a quantitative measurement framework.	Indicators set	Asia/Middle East	Environment, Social, Economic, System Effectiveness	15	26
Elementary Global Tracking Framework for Transport (Sustainable Mobility for All, 2017)	"To examine the performance of the transport sector globally, and its capacity to support the mobility of goods and people, in a sustainable way."	Indicators set	International	Universal access, System efficiency, Safety, Green mobility	9 (52 Supporting Indicators)	-
Eco-mobility SHIFT (ICLEI – Local Governments for Sustainability, 2017)	"to measure the performance of urban mobility in various areas."	Indicators set	International	Enablers; Transport Systems and Services; Results and Impacts	20	22
TERM 2016: Transport indicators tracking progress towards environmental targets in Europe (European Environment Agency, 2016)	"To track the environmental performance of the transport sector and measuring progress in meeting key transport-related policy targets."	Indicators set	European	No categories	A core set of 12 (Total of 40 indicators)	-
The Sustainable Urban Mobility Indicators (World Business Council for Sustainable Development, 2015)	To evaluate the current mobility system of a city, understand the natural evolution of sustainable mobility and measure the improvements resulting from the implementation of new mobility practices or policies.	Indicators set	International	Global Environment, Quality of life, Economic success, Mobility System	22	-
The Sustrans Index (Dobranyte-Niskota et al., 2007)	The measurement and assessment of transport sustainability performance in the EU Member States.	Index	European	Environment, Social, Economic, Technological and operational, Institutional	55	EU27 (national data)
Transportation Index for Sustainable Places (TISP) (Zheng et al., 2013)	To provide guidance into the issues of selecting an appropriate index for evaluating transportation sustainability	Index	International	Environmental Social and Economic	19	-
Indicators for sustainable urban mobility (Institute of Transport Economics, 2012)	"To develop an indicator set for urban transport and environment illustrating the driving forces behind the development in transport volumes and modal split, the environmental and climate footprint, and the transport and environment policy performance."	Indicators set	National	Drivers, Transport, Environment, Policy	43	-

Transport for Sustainable Development in the ECE Region (United Nations Economic Commission for Europe, 2011)	"To improve competitiveness, safety, energy efficiency and security in the transport sector. At the same time, it focuses on reducing the adverse effects of transport activities on the environment and contributing effectively to sustainable development."	Indicators set	European	Access, Affordability, Safety, Security, Environment	17	-
Sustainable Transportation Indicators (Sustainable Transportation Indicators Subcommittee of the Transportation Research Board (ADD40, 2008)	To identify indicators that can be used for sustainable transportation evaluation	Indicators set	International	Environmental, Economic, Social and Governance	30	-
Indicators for Comprehensive and Sustainable Transport Planning (Litman 2007, 2020)	"To provide guidance on the use of indicators for sustainable and liveable transportation planning."	Indicators set		Economic, Social, Environmental, Good governance and planning	40	-
Defining Sustainable Transportation (The Centre for Sustainable Transportation, 2005)	To define sustainable transportation	Indicators set	National	Environmental Economic and Social	61	-
Towards Sustainable Mobility Indicators: Application to the Lyons Conurbation (Nicolas et al., 2003)	To analyse and compare the different urban transport strategies and sustainability in urban areas.	Indicators set	Municipal	Mobility, Economic, Social, Environmental	21	1
Indicators for the Integration of Environmental Concerns into Transport Policies (OECD, 1999)	To promote the integration of environmental concerns into transport policies and decisions.	Indicators set	International	Environmental dimension with Social, Economic and Policy aspects	33	-

Step 3. In-depth analysis and frequency of indicators

As a next step, the indicators from the 18 studies were analysed and regrouped according to the four pillars of sustainable development: social, environmental, economic, and governance (Shen et al., 2011; Hiremath et al., 2013), subsequently in sub-categories that were frequently present in the analysed methods. The choice to regroup indicators into the four pillars of sustainability is based on their complementarity, balance, and interdisciplinarity; in addition, those are classic, well-recognised, and consolidated pillars of sustainability (Shen et al., 2011; Hiremath et al., 2013; Science for Environment Policy, 2018). Governance is considered the fourth pillar in sustainability assessment in some approaches and methods, referring to planning, strategy and vision, participation, and fairness in mobility (refer to Appendix A); therefore, it was included in this step as well. Subsequently, the frequency of indicators was counted (a complete overview of the frequency of indicators in the studies can be found in Appendix A).

Step 4. The conceptualisation of a set of indicators for sustainability assessment of SAEV

Based on the concepts of chapter 2 and the integrative literature review, the conceptualisation of indicators to assess the sustainability of SAEV can be thus developed. The following elements were considered:

- i) The concepts explored in the theoretical background provided the basis for this part. The sustainable mobility notions integrated the use of renewable energy, mobility diversity, shared mobility, and improvement of accessibility – particularly for the elderly and people with reduced mobility. The technology assessment concepts added elements on technology performance and efficiency and the interaction between society, environment, and technology. In addition, both concepts of sustainability assessment and technology assessment emphasise an inter-and transdisciplinary approach. Ultimately, all these concepts contribute to a robust sustainability assessment deployed to measure the impacts, communicate them, and guide mobility decisions, planning, and policies.
- ii) The frequency of indicators (Appendix A) was considered to propose our indicators. Besides the indicators retained and adapted from the literature, our own indicators and units of measurement were proposed. As a result, five categories are defined for the assessment: social, environmental, economic, governance, and system performance. The system performance category is set as a new axis taking into account that 'technology will form the backbone of mobility in the future' (Mohieldin and Vandycke, 2017). Significant technological transformations encompassing data, connectivity, systems interoperability, automated driving, and intermodality will change how people move (Shaheen and Bouzaghrane, 2019). Therefore, 'system performance' emphasises the assessment of such elements, in addition, some references in Table 2 also address some of those elements in specific categories, e.g. 'mobility system performance' (World Business Council for Sustainable Development, 2015), 'system efficiency', and comprehending connectivity index (Sustainable Mobility for All, 2017).
- iii) The definition of criteria was based on the real case of SAEV's deployment by considering the context of the AVENUE project.

The indicators were selected according to general criteria, the SMART indicators - Specific, Measurable, Achievable, Realistic/Relevant, and Time-limited (EU, 2017; ECA, 2019), and more specific criteria.

SMART criteria comprise:

- Specific: the indicator is clear, unambiguous, and directly relates to the outcome;
- Measurable: the indicator can be counted, observed, and analysed in order to monitor the project progress and the objective achievement;
- Achievable: the indicator and project targets are achievable as a result of the project and as a measure of realism;
- Realistic/Relevant: the indicator is a valid measure of the results/outcomes;

- Time-limited: the indicators are attached to a time frame, and they are achievable in the project time.

More specific criteria comprise:

- Data availability: indicators have to be accessible, frequent, and easy to collect among the target cities;
 - Data quality: indicator data accurate, representative of the selected cities, and suitable for comparison among the target cities;
 - Indicator relevance according to the EU strategy and goals towards AVs and sustainable mobility (presented in section 4.2.2)
 - Indicators reflect the balance among the sustainability dimensions.
- iv) The discussion and validation of the indicators were done with a total of 9 experts and partners from AVENUE project. The process of discussion and consulting occurred via phone or e-mail. The consulted experts and partners were researchers from environmental sciences, social sciences, mobility systems, information science, experts on people with reduced mobility, automated minibuses manufacturers, and public transport operators.

4.4 RESULTS: A SET OF INDICATORS TO ASSESS THE IMPACTS OF SAEV IN THE MOBILITY SYSTEM

The integrated literature review on existing methods and indicators to assess sustainable mobility provided robust building blocks for this part. Nonetheless, the previous studies focus on the assessment of the cities' mobility system as a whole and already consolidated modes of transport. Considering that SAEV is an innovative mode of transport, new benefits and potential rebound effects can be expected. Hence, a set of 20 indicators is presented here to enable the impact assessment stemming from the integration of SAEV in the cities' mobility system. It is meant to be applicable in a broad spectrum of projects implementing automated vehicle technology.

The indicators present a framework to measure the performance and achievement of goals within the pilot projects as well as enable the monitoring and measurement of mobility impacts of this technology for the municipalities, being useful, for instance, for decision-makers, policymakers, and urban designers. The indicators' outcomes might support cities along the implementation process of SAEV in the future.

Table 3 presents the set of indicators. It addresses the four dimensions of sustainability - social, environmental, economic, and governance (Shen et al., 2011; Hiremath et al., 2013) - in addition to the technological dimension.

The social dimension includes aspects of accessibility, affordability, and safety (three of the most frequent sub-categories for social indicators, refer to Appendix A), user acceptance, satisfaction, and security. It is worth noting the distinction between safety, referring "to the absence of unreasonable risk due to hazards", and security, "the protection against

intentional subversion or forced failure” (Aptiv Services US et al., 2019).

The environmental indicators address topics related to energy and resource efficiency, the use of renewable energy, air and noise pollution, climate change, and their related external costs.

Furthermore, the economic dimension assesses investments in mobility, economic incentives, costs, and revenues to calculate the profitability of SAEV. The governance indicators address an incipient environment (Fagnant and Kockelman, 2015; Litman, 2020; Nemoto et al., 2020), in particular the developments of policies, regulations, standards and incentives toward the deployment of shared automated vehicles.

The system performance focuses on the technological and digital integrative dimension in terms of automation, digital services, intermodality (see definition in section 4.2.1), and system interoperability. The latter term refers to the ability of different systems to interoperate by connecting, communicating, and exchanging information to operate automated driving functions such as ‘environment perception, localisation, planning, and control’ (Levinson et al., 2011).

The technology maturity, performance and integration of SAEV may impact all the other dimensions. For instance, its impacts on social acceptance and service usability may affect the environmental and economic metrics by entailing higher or lower energy consumed per passenger per kilometre, and a higher or lower price of the service per passenger.

Table 3 Set of indicators for sustainable mobility assessment of SAEV

Indicators	Unit and methods of measurement	Multidimensions				
		S	En	Ec	G	SP
Accessibility	<ul style="list-style-type: none"> Percentage of the city (area) coverage by the SAEV service Percentage of the population that has convenient access (within 0.5 km) to the SAEV service 					
	<ul style="list-style-type: none"> SAEV digitally accessible (e.g. via apps) 					
Accessibility for people with reduced mobility	<ul style="list-style-type: none"> 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 to wheelchair users 					
	<ul style="list-style-type: none"> Usability of the SAEV by people with reduced mobility (PRM) Rating of users with reduced mobility concerning the SAEV experience 					
	<ul style="list-style-type: none"> Risk factor and number accidents related to the SAEV (mild injuries, serious injuries, fatalities) considering internal risk (related to passengers) and external risk (related to other road users, pedestrians and cyclists) 					
Security	<ul style="list-style-type: none"> Number of criminal occurrences; nr/year 					
	<ul style="list-style-type: none"> Number of cybersecurity threats or attacks; nr/year 					
Passenger's affordability	<ul style="list-style-type: none"> The price of the ride on the SAEV 					

User acceptance	<ul style="list-style-type: none"> • User's perception about the readiness of the technology • User's willingness to pay • Safety feeling • Security feeling 						
User satisfaction	<ul style="list-style-type: none"> • User rating concerning SAEV experience (comfort, speed, punctuality, information, frequency, connection to other means of transport) 						
Energy efficiency	<ul style="list-style-type: none"> • Energy consumed for passenger per km (kWh/pkm) 						
Renewable energy	<ul style="list-style-type: none"> • Use phase: Energy source and percentage of renewable energy sources (%) 						
Air pollution	<ul style="list-style-type: none"> • SAEV emissions of air pollutants: PM levels (ug/m3), NOx, CO emissions 						
Climate change	<ul style="list-style-type: none"> • SAEV GHG emissions: CO₂, N₂O, CH₄ 						
Noise pollution	<ul style="list-style-type: none"> • SAEV traffic noise (dB) 						
Investments on mobility	<ul style="list-style-type: none"> • 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 on the vehicle R&D 						
Economic incentives for SAEV and sustainable mobility	<ul style="list-style-type: none"> • Incentives and subsidies for automated and sustainable mobility, e.g., shared, electric, automated, zero-emission, vehicles (Euro) 						
Economic profitability	<ul style="list-style-type: none"> • TCO (Total Cost of Ownership), TCM (Total Cost of Mobility), Cost/km/passenger, revenues (ticketing from passengers, subsidies from authorities and companies), and payback period 						
External costs related to the SAEV	<ul style="list-style-type: none"> • SAEV 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	<ul style="list-style-type: none"> • Existence of policies and regulations concerning automated vehicles • Regulations for open data and/or APIs for transport 						
Technical performance and reliability	<ul style="list-style-type: none"> • SAEV performance: <ul style="list-style-type: none"> . 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	<ul style="list-style-type: none"> • SAEV 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 SAEV (access, static and/or dynamic real-time data, diffusion format, data quality, and open APIs for transport) • Intermodality: SAEV integration with other public or private means of transport or with a multimodal platform for one intermodal trip (planning, reservation, booking, billing, digital ticketing) 						
Changes in total kilometres travelled in	<ul style="list-style-type: none"> • Changes in per capita vehicle travelled induced by automated vehicles 						

the transportation system	• Transportation demand management measures introduced congestion pricing, biking lanes, zoning measures, land-use policies					
Acronyms 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				

Different colours are used to differentiate the dimensions: yellow for the social dimension, green for the environmental dimension, blue for economic, orange for governance and grey for the system performance dimension.

The first column on the left presents the indicators, the second column specifies the units of measurement, and the columns on the right side assign the correspondent sustainability dimensions assessed. Most of the indicators have multi-dimensions, for example, user acceptance and user satisfaction were assigned in the social dimension and the system performance since the mobility performance directly impacts the user’s experience. Another example is air pollution, which has components on the social and environmental dimension, with impacts on people’s health and entire ecosystems, and the system performance concerning the mobility system efficiency and the use or not of sources of renewable energy, for instance.

Some indicators present diverse units and methods of measurement. Therefore, it is important to point out that the choice of the units of measurement is adaptable to the environment, goals of the project, and context of the test sites and deployments. Thus, some indicators present more than one unit of measurement in order to provide flexibility when applying the indicators.

Furthermore, main indicators like accidents, air pollution, noise, GHG emissions, and affordability could be selected for a matter of comparison with other means of transport as a baseline scenario for mobility impact assessment.

Through the lens of sustainability assessment and technology assessment, the set of indicators gives a step forward in the assessment of SAEV, and it investigates its contributions to sustainable mobility in cities. By monitoring and applying the indicators, the results may provide valuable answers concerning automated driving performance and its contributions to mobility efficiency, safety, accessibility, affordability, and acceptance, among others. Further, by embracing the multi-dimensions of mobility, the set of indicators embeds the mobility complexity, being an enabler to explore the intersections among environment, spatial planning, policies, governance, society, and economy.

4.5 DISCUSSION

The research’s focus on SAEV in the European context takes into account the future usability and selection of the set of indicators. Castillo et al., 2010 define two challenges that are considered while conceptualising a set of indicators; the first challenge is the existence of numerous sustainable transport indicators sets, which makes it difficult to select the appropriate subset. The second is that “Indicators are only abstractions of the system”. Thus, it is challenging to select the right set that aligns with the context of sustainable transport goals to be achieved. The resulting set of conceptualised indicators is easily aligned with similar contexts: they are more targeted to provide appropriate guidance to policymakers seeking to introduce AVs in European cities. The real case

study of the AVENUE pilots addresses the issue of the abstraction of the system. Even more, the conceptualisation is based on a systematic process that adopts transparency and consistency, which results in the selection process being more credible and acceptable to policymakers (Castillo et al., 2010).

As the next steps, the assessment process entails the choice of methods, data collection phase, and analysis. The main methods for data gathering comprehend the use of:

- existing database (city, regional, research institutes, or more generic data, from the ministries, for example)
- empirical data from pilot projects deploying AVs and SAEV
- qualitative methods, such as surveys and interviews
- calculation method, e.g., traffic modelling
- spatial analysis methods, e.g., using geographic information system (GIS)

The use of existing surveys to measure social acceptance, or the application of local surveys, as in the case of the AVENUE project, can provide inputs about the population's awareness of automated driving, openness to use it, and opinions about potential benefits and concerns towards the new mode of transport. In addition, the users' surveys can provide meaningful findings on the users' experience, needs, preferences, and services' usability concerning AVs.

For the economic impact analysis, the Total Cost of Ownership (TCO), Total Cost of Mobility (TCM), costs and revenues analysis, and calculation of mobility externalities are methods that can support estimating the costs and economic attractiveness for users, public transport operators, transport services providers, and municipalities. The TCO approach considers all related costs in the supply chain of a good or service, from the total cost of acquisition, use, and maintenance, to the disposal (Ellram, 2002), from an offering perspective. TCM presents, on the contrary, a more recent and holistic understanding of mobility, which has not been well defined until now. It goes beyond the fact of owning and operating a fleet of vehicles, it is a response to the changes towards current and future service-oriented mobility (PwC, 2019) and has a dedicated emphasis on the demand (passenger/citizen and trip) perspective. For our purposes, the concept of TCM will integrate all the related costs of one door-to-door journey as defined by the European Commission (2005), including all means of transport and mobility services of today and their possible combinations in one (intermodal) trip. This includes trains, buses etc. but also car/bike-sharing, long or short distance ride-sharing, ride-hailing, ride-pooling etc., and transport network-integrated automated vehicles. This change of perspective is closer to the reality of the citizen mobility use case. It allows evaluating customer/citizen-centric business strategies.

In order to estimate the environmental impacts, studies on Life Cycle Assessment (LCA), modelling and simulations, scenarios and sensitivity analysis can be conducted to investigate the variables that influence a more environmentally friendly performance of SAEV. As for the governance perspective for AVs, although the incipient context, it is suggested to follow up on the development of policies and regulations for AVs in a multi-scale approach, to track the incentives for electric and shared mobility, and assess the goals and plans of the cities towards innovative and sustainable mobility.

The empirical data and measurement of the system performance, efficiency and integration of AVs will support future modelling studies and estimates. In this regard, key factors are the level of automation, vehicle speed, on-demand availability, response-speed, travel-matching capacity, and their integration with other means of transport (planning, reservation, booking, billing, and digital ticketing). A key indicator refers to the changes in total kilometres travelled in the transportation

system induced by SAEV. The study from Soteropoulos et al. (2019) reviewed modelling studies about the impacts of AVs on mobility. It reports that Shared Automated Vehicles (SAVs) could lead to an increase in vehicle miles travelled (VMT) due to empty trips, migration effects from other modes of transport, and potential low costs. However, it also mentioned other studies, pointing out that SAVs could decrease VMT in scenarios where a large share of users would be willing to rideshare (Heilig et al., 2017; Martinez and Viegas, 2017). Hence, measuring the changes in per capita vehicle travelled induced by SAEV and related transportation demand management measures are considered key factors in investigating SAEV impacts.

To better communicate the results, the indicators can be represented, for instance, through a mobility radar or spider chart, which can illustrate and highlight the strengths and weaknesses of the mobility dimensions and compare the results in different cities and environments. Furthermore, the correlations among variables can also be explored.

It is also relevant to point out here the current potential limitations in the assessment of SAEV, based on the case of the AVENUE project. The pilot trials are limited to special conditions such as (Nemoto et al., 2020):

- the tests are limited to fixed routes or offering on-demand services in a specific and limited area;
- the vehicles drive at an average speed of 18km/h, with a speed limit of 25km/h;
- the presence of a safety driver on board the automated minibus is required by law, and in some cases, there is the need for human intervention;
- the cities' infrastructure and regulations need to be developed in order to deploy AVs;
- currently, the ride in the automated minibuses is free of charge, and the economic feasibility of deploying SAEV may face challenges in the short term due to the high investments in research and development, continuous improvement, and high costs to purchase and operate SAEV.

Moreover, in the assessment phase, data quality and data availability might vary according to the different cities and transport operators, which might pose challenges in comparing the results and performance in different cities. Limitations also concern asymmetry in data availability from governments, Public institutions' reportings and businesses' reportings (e.g. private mobility providers, transport operators), and therefore, dealing with missing or incomplete data.

The set of indicators is focused on having a deeper understanding and on assessing the performance of SAEV, including a comparison among different European cities and contexts. The study focuses primarily on European cities, as pilot projects testing automated minibuses with a focus on public transport concentrated in Europe (Antoniali, 2019). However, the set of indicators developed in this study is not limited to European cities but can be applied to non-European cities as well.

4.6 CONCLUDING REMARKS

The arrival of new technologies and innovations in mobility, such as SAEV addressed in this study, presents the opportunity to improve accessibility, affordability, environmental friendliness, and efficiency of mobility. New technologies, combined with suitable policies and incentives, can trigger positive changes in mobility as well as entailing rebound effects, such as induced travel demand and aggravating mobility externalities. Therefore, it is important to measure and assess the impacts of the deployment of SAEV as an innovative mode of transport.

In combining concepts of sustainability and technology assessment, this study takes a step forward to measure the impacts of SAEV on urban mobility. Based on an inter and transdisciplinary approach, it conceptualises a set of indicators, with corresponding units and methods of measurement covering the mobility multi-dimensions. Besides indicators on the social, environmental, and economic dimensions, the method comprehends governance aspects such as vision, strategy and development of new policies for AVs. And it includes aspects of system performance that are important in current and future mobility, e.g. intermodality, system interoperability, and services integration.

The indicators are meant to be applicable in a broad spectrum of initiatives implementing automated vehicle technology and pilot tests level. Further steps entail the choice of methods of measurement, data collection, analysis, the choice of scale, weighting, graphic representation of the indicators (e.g., mobility radar), and the options to aggregate indicators to communicate the results better. The application of the indicators may pose some limitations related to data availability, technology maturity, early phases of deployment of SAEV, and gaps in legislation. Besides a tool to measure the impacts of AVs' implementation, the applied set of indicators can enable the production of better impact estimates based on real data as well as the communication and comparison of results with baseline scenarios, thereby providing a sound basis for decision-makers to decide the contexts to deploy SAEV. Furthermore, measuring the impacts may contribute to filling the gaps in scientific and empirical data available concerning the impacts of AVs in our society. Last but not least, the set of indicators can facilitate a comparison of SAEV to other modes of transport, influence the design and planning of transportation systems, and accordingly strengthen sustainable mobility policy responses to the mentioned limits of the current mobility paradigm for cities.

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CHAPTER 5 SUSTAINABILITY ASSESSMENT OF THE DEPLOYMENT OF AUTOMATED MINIBUSES IN URBAN MOBILITY OF EUROPEAN CITIES

Abstract

The deployment of automated vehicles is the object of study as a potential mode of transport to support mobility transitions and sustainable mobility goals. However, the impacts of automated vehicles remain uncertain and more empirical data and assessments are required.

This study performs a sustainability assessment of the deployment of automated minibuses (AM) integrated into the public transport of European cities. The assessment is conducted by applying a set of indicators considering the multi-dimensions of mobility, and it builds upon four case studies from the AVENUE project. A mobility radar illustrates the current performance of the AM and assesses two scenarios considering the AM integrated into or AV competing with the transport system. Further, the study points out the key elements for the deployment of AM to endorse sustainable urban mobility planning and strategies.

Extended version of the conference paper

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5.1 INTRODUCTION

The transport sector is one of the most environmental and social impacting activities in cities. Urban mobility is changing fast, such changes are driven by new concepts and technologies. The new concepts emerging comprise Mobility-as-a-service (MaaS), shared mobility, multi- and intermodal mobility, mobility on-demand, and sustainable urban mobility plan (SUMP). In addition, the combination of new technologies in mobility, such as shared, connected, automated, and electric vehicles, coupled with regulations and policies, is expected to revolutionise the mobility sector (Sperling, 2018).

Along with the mobility innovations, the cities' goals and strategies toward more sustainable mobility systems have become more concrete. Hence, concepts such as sustainable urban mobility plan (SUMP) (European Commission, 2018), smart cities, and the Sustainable Development Goals (SDGs) (United Nations, 2015) have gained momentum. More specifically, the SUMP approach targets sustainable and integrative planning processes to deal with the complexity and dynamicity of urban mobility (Eltis, 2021). The SUMP planning practices are based on integration, participation, and evaluation principles (Rupprecht Consult, 2019).

Considering that the transport sector is one of the most impacting activities, it urges a transition towards lower and carbon-neutral mobility emissions and mitigation of externalities. Worldwide, the transport sector represents 14% of the total anthropogenic greenhouse gas (GHG) emissions (IPCC, 2014). In Europe, transport represents 27% of greenhouse gas emissions, representing the leading cause of air pollution in cities (European Environment Agency, 2019). And road transport is responsible for about 72% of European transport emissions (European Environment Agency, 2019). In addition, mobility is related to other externalities such as particulate matter, noise, traffic jams and accidents (EU and CE Delft, 2019).

The combination of innovations and new technologies in mobility, such as shared, connected, automated, and electric vehicles, coupled with proper regulations and policies, is expected to revolutionise the mobility sector (Sperling, 2018). A step further, Nikitas et al. (2021) add another pillar to the paradigm shift, the multimodality, as means of emphasising a public transport-centred MaaS.

Automated vehicles (AV) and, more specifically, shared automated electric vehicles, are the object of study as a potential mode of transport to reduce mobility costs and greenhouse gas emissions (Jones and Leibowicz, 2019), to impact travel behaviour (Stocker and Shaheen, 2017) and to enhance smart and sustainable urban mobility. On the other hand, AV raise concerns related to their potential to increase energy consumption due to vehicle communication and additional infrastructure (Taiebat et al., 2018), increase vehicle kilometres travelled (Soteropoulos et al., 2019) and require more urban space.

In fact, AV impacts remain uncertain, and as their levels of interaction extend – from vehicle to transportation system and urban system – the complexity and uncertainty of AV impacts also rise (Taiebat et al., 2018). In addition, there is a lack of experimental studies and real-

world data to underpin more accurate modelling and estimates of AV impacts (Shaheen and Bouzagrane, 2019; Nikitas et al., 2021).

In this regard, worldwide pilot tests have been implemented in order to deploy automated minibuses (AM) in urban public transport. AM are perceived as a potential solution to cover mobility gaps, offer first and last-mile solutions and improve transport accessibility, flexibility and sustainability. Furthermore, such pilot tests are important to provide empirical data for impact assessment studies. Likewise, the assessment studies underpin recommendations for policy development, strategic spatial planning, and long-term mobility planning aligned with the cities' mobility goals.

Based on four case studies of pilot tests, this study aims to perform a sustainability assessment to evaluate the impacts of AM integrated into the public transport of European cities. Hence, the study addresses the following research questions: what are the current performance and impacts of AM integrated into public transport in European cities? How can AM contribute to SUMP approach? What are the perspectives for future mobility systems with AM?

The assessment is performed by applying a set of indicators to measure the impacts of AM on the multi-dimensions of mobility (Nemoto et al., 2021). The sustainability assessment builds upon real case studies from the AVENUE project, and it aims to provide real-world data to better substantiate AM estimates, modelling, and future impact calculations. Further, the study assesses two potential future scenarios considering the different levels of integration of the AM into mobility systems: AM integrated into or AV competing with the transport system.

The study is structured as follows: section 5.2 presents the background, section 5.3 describes the methodology, section 5.4 presents the four case studies of the AVENUE pilot tests, results and future perspectives, section 5.5 presents the discussion, 5.6 the limitations and lastly, 5.7 the concluding remarks.

5.2 BACKGROUND

5.2.1 Concepts and definitions of AVs

AVs are equipped with an automated driving system, which consists of the hardware and software capable of performing the dynamic driving task on a sustained basis (SAE, 2018). AV comprise vehicles within SAE levels 3, 4 and 5 of the driving automation system (SAE, 2018).

The combination of new mobility technologies, such as the shared automated electric vehicles, could contribute to more profound transformations in mobility. Mainly, it could contribute to a transition from human to automated driving, combustion engines to the electric powertrain, and private vehicles to shared mobility services (Greenblatt and Shaheen, 2015; Todorovic et al., 2017; Sperling, 2018).

Shared AV, such as robotaxis and AM, could offer a variety of services, ranging in space (line, corridor, and area), time (scheduled or on-demand), and function (first and last-mile, door-to-door, part of the transport network). Their business models vary according to the different forms of shared mobility (car-sharing, ride-sharing and mixed systems), public or private vehicle ownership, and depending on who controls the network operations (Stocker and Shaheen, 2017). Nikitas et al. (2021) argue that automated electric buses and minibuses can be a cornerstone of MaaS systems, playing a role in replacing private mobility with multimodal mass transit.

The object of analysis of this study is the AM, which presents level 3 and level 4 of driving automation, it has been tested as a door-to-door and on-demand mode of transport to fill gaps in urban mobility, offering first and last miles services on a small scale. As technology is expected to evolve along with proper policies and planning, AM services are expected to be offered on the city scale, aiming to improve accessibility, flexibility and sustainability in transport.

5.2.2 The potential impacts of AVs on urban mobility

AVs are likely to add complexity and entail impacts on urban mobility. On the one hand, AVs are related to potential positive environmental impacts such as higher energy efficiency, fewer accidents, less congestion, promotion of shared mobility and vehicle electrification, changes in land use, reduced need for parking spaces and positive externalities in combination with MaaS systems (Fagnant and Kockelman, 2015; Taiebat et al., 2018; Fournier et al., 2020). On the other hand, AV can be associated with potential negative impacts and rebound effects. For instance, some negative aspects foreseen refer to AV additional information and communication technologies (ICT) equipment for navigation and communication; the additional traffic and travel demand, resulting in greater vehicle miles travelled (VMT); AV could trigger increased urban sprawl; and the need for large, energy-intensive data centres (Milakis et al., 2017; Taiebat et al., 2018; Soteropoulos et al., 2019). AV impacts also depend on which mode of transport they will replace.

The environmental benefits of AV depend on how positive impacts for energy savings and reduced emissions will overcome potential rebound effects. For instance, part of the reductions from smoother traffic, shift to electric vehicles and more renewable energy sources within the electricity mix, ride-sharing mobility and shift to smaller vehicles can be offset by increased travel, faster travel and zero-occupant rides (Smith, 2020).

The study by Liu et al. (2019) assessed the effects of AVs deployment on GHG emissions, considering different scenarios of AVs penetration rates and fuel consumption changes. The main findings point out that the introduction of AVs will not lead to significant GHG emission reductions before 2050. It considers that the diffusion of AVs will occur late and that significant results depend on a better future fuel economy, concluding that AVs may deliver better results in the long term. The study also mentions that future studies could evaluate the energy consumption of vehicle manufacturing as an important topic.

Gawron et al. (2018) report on the Life Cycle Assessment (LCA) of Connected and Automated

Vehicles (CAV) Level 4 for internal combustion engine vehicle (ICEV) and battery electric vehicle (BEV). The results reveal that CAV when combined with operational effects – e.g. eco-driving, platooning and intersection connectivity, faster highway speeds – could result in up to 9% reduction in energy and GHG emissions. Still, the study points out that CAVs could increase vehicle energy use and GHG emissions by 3-20%, considering increases in vehicle weight, drag, data transmission, and power consumption. Regarding these last aspects, the authors note that CAVs are at an early stage of development; thus, weight, size, and shape may be optimised and represent fewer impacts in future environmental assessments. Taiebat et al. (2018) conclude that shared automated electric and right-sizing mobility have the potential to deliver significant environmental benefits when coupled with deployment strategies and user behaviour.

Indeed, there is no consensus about the environmental impact of AVs, and the GHG emission balance can be neutral or negative depending on diverse aspects such as the increased use of transportation, empty running vehicles, sharing ride rates, behavioural, and regulatory aspects (van Wee et al.; Nikitas et al.).

In terms of societal changes and AV acceptance, a study by Krueger et al. (2016) suggests that travel time, travel cost, and waiting time are important determinants for the potential users of shared AV. The authors also mention a relation between the individual modality style and the propensity to choose shared AV as a mode of transport. This finding is aligned with the insights from Acheampong et al. (2021); the study states that attitudes and preferences are rooted in the current mobility behaviour of individuals.

In addition, early AV adopters are likely to be young people, more educated, and who spend more time in vehicles (Haboucha et al., 2017). And there is a high preference for AVs with clean engine fuel sources, such as electric and hybrid options (Acheampong et al., 2021).

The studies addressing the user acceptance of AM in public transport systems revealed a positive perception and attitudes towards AM (Nordhoff et al., 2018; Korbee et al., 2022b). Some concerns associated with AV involve software hacking/misuse, safety, security, standards for liability, and data privacy (Fagnant and Kockelman, 2015).

Shared AVs are also the object of studies targeting the decrease in transportation costs. The operational costs to deploy SAV may vary according to the vehicle and battery costs, charging infrastructure, parking and cleaning costs (Shaheen and Bouzaghrane, 2019; Litman, 2022). The study by Bösch et al. (2016) points out that in an urban area, the costs of passenger-kilometre for the automated options - as a bus, individual taxi, and pooled taxi – will be cheaper than for the equivalent conventional modes. As for the automated minibuses, the primary economic barriers are the high initial costs of purchasing the vehicle, which is attributed to the newness of the technology (Henderson et al., 2017). Ongel et al. (2019) suggest that despite the high acquisition costs, shared AVs have the potential to reduce passenger-kilometre costs in the long term.

Considering all the above elements, an integrative approach is crucial in order to combine the synergies among emerging technologies with specific policy instruments to contribute

to achieving the cities' sustainable mobility goals and citizen-centric mobility planning. Next, the concept of sustainable urban mobility planning is presented and considered as part of the solution.

5.2.3 The concept of Sustainable Urban Mobility Plan (SUMP)

Sustainable Urban Mobility Plan aims at a new planning paradigm in mobility and a shift from planning roads and infrastructure for motorised mobility to planning for people (Arsenio et al., 2016). The SUMP approach builds upon existing planning practices and principles such as: the integration of all modes of transport, citizens' participation and broadened stakeholders involvement, long-term vision and implementation plan, assessment of current and future performance, and monitoring and evaluation (Rupprecht Consult, 2019).

Regarding SUMP in practice, numerous cities in Europe and beyond have adopted and implemented SUMP in an attempt to reduce private car dependency and transport externalities (May, 2015; Diez et al., 2018). In addition, the social, environmental, and economic impact assessments predicted in a SUMP support decision-making and actions from policymakers (Sampaio et al., 2020).

Some hurdles to the implementation of SUMP are revealed in the study by May (2015). The authors reviewed the progress in the development of guidance on SUMP and reported the main barriers to effective planning, such as conflicting institutional roles; hesitant political commitment to sustainability; poor integration between the policy sectors; inappropriate financing for preparation and implementation, inexperience in stakeholder involvement; poor data and findings on the performance of specific solutions.

Further, Arsenio et al. (2016) reviewed a sample of forty case studies of SUMP in Portugal, aiming to understand how the first generations of SUMP have addressed climate change goals and equity issues on accessibility. The main findings point out that SUMP guidelines remain very broad and the absence of specific guidance. For instance, the authors point to the lack of guidance on methods to account for GHG emissions and monitoring indicators to measure the progress on different issues. The study mentions, therefore, the importance of the next generation of SUMP to address such gaps in order to strengthen SUMP implementation.

Although the mentioned hurdles, other studies also highlight the role of SUMP in supporting active travel (as walking and cycling) strategies and policies (Maltese et al., 2021), thus supporting the transition to more sustainable modal share and carbon-neutral mobility (Diez et al., 2018). Other benefits related to SUMP are alleviation of air pollution (Pisoni et al., 2019). Furthermore, Mück et al. (2019) describe an innovative approach, the living labs, to foster sustainable mobility planning in Munich. Living labs are perceived as a tool to reduce the gap between long-term planning and the current development of urban mobility. And the user experiences are taken into consideration to build mobility strategies and policies for Munich.

In this study, the SUMP approach is applied in order to develop the premises and recommendations for sustainable deployment and perspectives for the future mobility system with automated minibuses.

5.3 METHODOLOGY

The sustainability assessment of this study is performed by applying a set of indicators to measure the impacts of AM on the multi-dimensions of mobility, which comprise five axes: social, environmental, economic, governance and technical system performance (Nemoto et al., 2021). Indicators were chosen based on data availability from the pilot trials to assess the cases, compare, and provide information for policymakers and decision-makers. Indicators are also a valuable tool to measure changes towards set targets.

In the first step, we selected the AVENUE pilot tests deployed in Groupama Stadium (Lyon), Contern, (Luxembourg), Pfaffenthal (Luxembourg) and Nordhavn (Copenhagen). The assessment is applied at the scale of pilot projects, therefore at a small and local scale. In the second step, we collected primary data from AVENUE demonstrator sites. The assessment comprises: i) data provided by the public transport operator, ii) quantitative data from the large-scale survey and user survey (Korbee et al., 2022a), iii) quantitative data and results from a Life Cycle Assessment (LCA) study on AM (Huber et al., 2022), and iv) data from economic impact assessment (Antonialli et al., 2021). 14 out of 20 indicators proposed by Nemoto et al. (2021) are applied and measured considering the data availability; see Table 4.

Table 4. Indicators for assessment and units of measurement

Indicators	Parameter	Scale of assessment
Social acceptance	average rating for the i) willingness to use the automated minibus; ii) perception about the readiness of the technology; iii) willingness to pay	City
User satisfaction	average rating satisfaction concerning the automated minibuses' speed, comfort, punctuality, information, frequency of service, connection to other means of transport, and satisfaction with the last ride.	Local
Passengers' affordability	costs (Euro)/passenger-km for passengers	City
Climate change	gCO ₂ eq/passenger-km	Local and global
Air pollution	air pollutant emissions, particular matter, PM _{2,5} (g/km), and nitrogen oxides, NO _x (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)/vehicle-km for operators	City
External costs	Costs for climate change, air pollution, congestion €-cent/pkm (CE Delft, 2019; Jaroudi et al., 2021)	City

Institutional development and openness to mobility innovations	ROAD index (Mira-Bonnardel and Couzineau, 2021) sets four variables to measure the level of readiness for the implementation of AV 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 iv) 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

In the third step, we present a definition, a parameter, and a scale for assessment for each indicator (Appendix B). The indicator value varies within a range of one to five, with one for the lowest performance and five for the best performance. The normalisation process is applied to bring all indicators into a common scale. Further, the choice of disaggregated indicators allows for illustrating the strengths and weaknesses of each mobility indicator. The mobility radar enables easy communication and visualisation of the results and comparison among case studies as a graphical representation.

In addition, the following studies were considered as supporting guidelines for the assessment:

- 'Methodology and indicator calculation method for sustainable urban mobility (World Business Council for Sustainable Development, 2015)
- 'Sustainable Urban Mobility Indicators – SUMI' (European Commission, 2020)
- 'Your 10-Step Pocket Guide to Composite Indicators & Scoreboards' (Saisana et al., 2019)

In the fourth step, we assess two potential future scenarios: the AM integrated (AM integrated into Mobility-as-a-Service) or AV competing with the transport system (AV as robotaxis). Ultimately, the results from the sustainability assessment are discussed under the SUMP approach, including the premises and recommendations for sustainable deployment and perspectives for the future mobility system with AM.

5.4 THE CASE STUDIES OF THE AVENUE PILOT SITES AND FUTURE PERSPECTIVES

5.4.1 The AVENUE project and presentation of the pilot sites

The AVENUE project has as its objective to enhance public transport by offering innovative urban mobility, which combines automated, electric, and shared mobility, as well as by offering innovative services such as on-demand and door-to-door trips. The AM services are expected to improve the accessibility, convenience and environmental friendliness of passengers' trips.

AVENUE has deployed automated minibuses into the public transport of four European cities: Lyon, Luxembourg, Copenhagen, and Geneva. From the seven AVENUE pilot sites, four case studies were selected considering data availability for the sustainability assessment: Groupama Stadium (Lyon), Pfaffenthal (Luxembourg), Contern (Luxembourg), Nordhavn (Copenhagen).

Groupama Stadium, also known as Parc Olympique Lyonnais is a football stadium. The area is a high-traffic district, and it attracts visitors to football games, people working in offices, medical centres, leisure centres, hotels, and restaurants. The area is served by a tramway line and a bus every 30 minutes to access the Groupama Stadium by public transport. The route for the automated minibuses is the same as the bus line, and the service is complementary to the bus (Zuttre, 2019). The automated minibuses route comprises crossroads and roundabouts with the vehicle to infrastructure (V2I) intersections (Zuttre, 2019). For the near future, it is envisaged on-demand and door-to-door services with the AM in the Parc Olympique Lyonnais.

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 tourists (Reisch, 2019). The automated minibuses route in Pfaffenthal connects the public elevator, which gives access to the city centre, a multi-modal station and the residential area (Reisch, 2019).

Contern is an industrial zone located about 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 employees mainly use their 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.

Nordhavn is an active industrial port which is expected to become Copenhagen's new international waterfront district (Guldmann et al., 2019). The area hosts residential and commercial buildings and eco-friendly initiatives, such as using renewable energy and recycling resources (Guldmann et al., 2019). Nordhavn area is served by a tramway station about 1km away, and bus stops are 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. Appendix C presents the graphics with the route of the AM in the pilot sites.

Table 5 summarises the main characteristics of the four selected AVENUE case studies.

Table 5. Characteristics of the four selected AVENUE case studies

Demonstrator city	Pilot site	Transport operator	Characteristics of route	Type of passenger	Deployment
Lyon	Groupama Stadium (sportive, medical centre area, offices)	Keolis	Fixed route with stops 1.3 km, it will become an on-demand, door-to-station service	Regular workers, people with reduced mobility (medical centre nearby)	November 2019 - April 2022
Copenhagen	Nordhavn (industrial port area)	Holo	Fixed route with stops, 1,2km, it will become an on-demand, door-to-door service	Residents of the area, tourists	September 2020 - April/2022
Luxembourg	Contern (industrial area)	Sales-Lentz	Fixed route with stops, on-demand. 2.2 km	Employees working at Campus Contern	September 2018 - April 2022
	Pfaffenthal (residential area)	Sales-Lentz	Fixed route with stops, on-demand 1.2 km	Workers, tourists, residents, and visitors to Luxembourg city	September 2018 - April 2022

The next section presents the sustainability assessment results of the deployment of automated minibuses.

5.4.2 Results - the sustainability assessment of the deployment of automated minibuses

Hereinafter, we present the results per pilot site by applying the indicators for sustainability assessment. The results are presented in the form of mobility radars (Figure 4). The radars enable easy visualisation of the results and comparison among case studies.

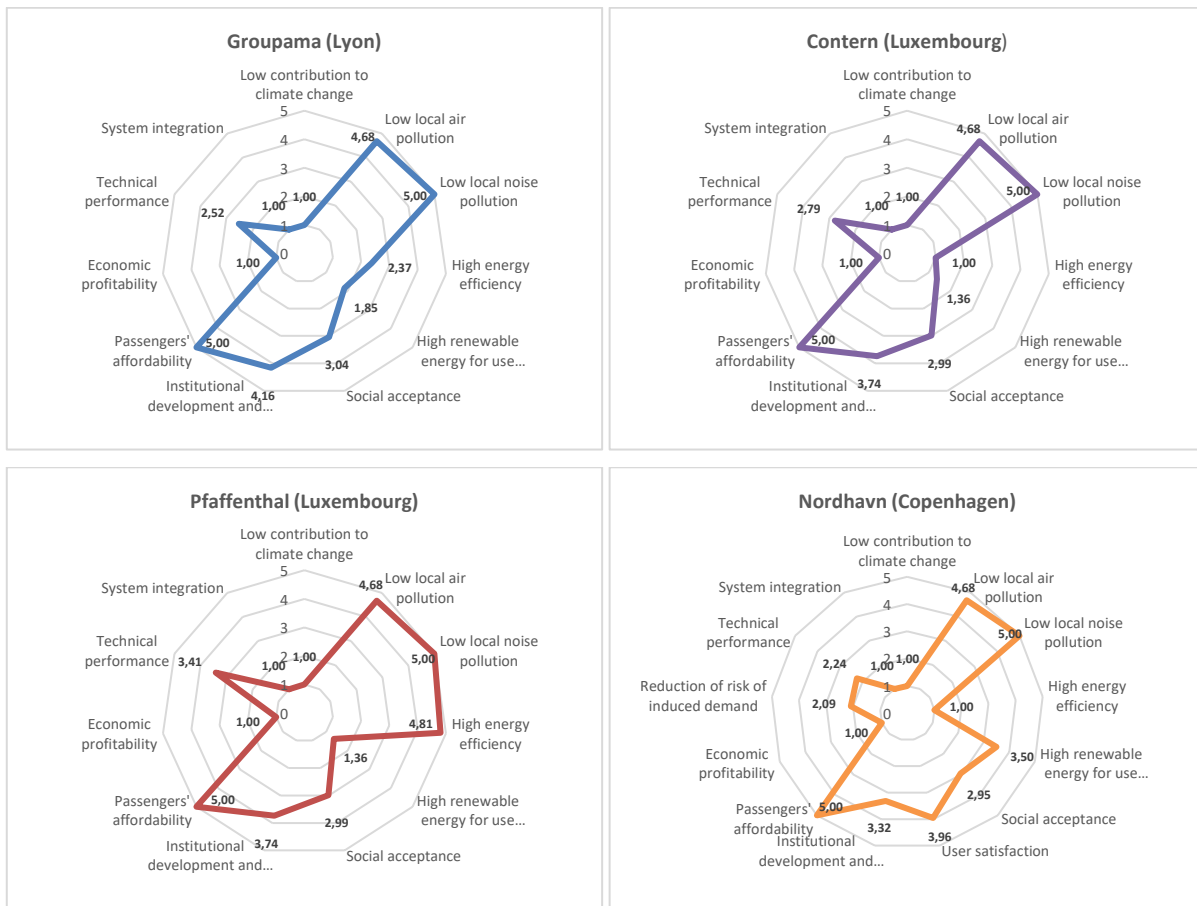


Figure 4 Sustainability mobility radars from the AVENUE pilot sites - with 1 for the worst performance and 5 for the best performance

At the current stage, the deployment of the AM in the pilot sites presents similar performances among the indicators rather than significant differences. The AM score poorly on 'low contribution to climate change' and 'energy efficiency' due to the low vehicle occupancy. The sites presented very low occupancy with the exception of Pfaffenthal (Luxembourg). This could be explained by low demand for the mobility services deployed and certainly by the decrease in the use of public transport due to Covid-19 and subsequent restrictions.

As electric vehicles, the AM are a good alternative to tackle 'local air pollution'. In terms of 'local noise pollution', the AM, at an average speed of 15km/h, emit lower sound than conventional vehicles. However, from 30km/h, the noise pollution from electric and other motorised modes of transport does not differ very much (Marbjerg, 2013). The use of renewable energy for the use phase of the AM varies significantly according to the electricity mix of each region or country. In this case, Nordhavn in Copenhagen has the best score, whereas Luxembourg has the lowest.

Regarding the social acceptance indicator (assessed on a city scale), potential users show goodwill towards using the AM (scoring 3.8 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 indicated good satisfaction (3.96) with the ride and the AM services (comfort, information, punctuality, speed). This finding suggests that acceptance could improve after the first ride. Currently, the ride on the AM is free of charge, therefore, passengers' affordability scores high. In the future, the price of the ride might be integrated into the public transport ticket, with the exception of Luxembourg, where public transport is free of charge nationwide.

Overall, the economic profitability of AM is still low due to the elevated costs of feasibility studies and legal authorisations, infrastructure adaptations, high annual depreciation and salaries for on-board safety drivers. In the near future, the removal of the safety drivers and the development of standards for homologation and authorisations may impact positively on the economic profitability of AM (Antonialli et al., 2021).

Concerning the technical performance factors (speed, frequency, occupancy rate, and automated driven km), all sites face low speed and low occupancy rates as challenges, whereas the percentage of automated driven km is satisfactory, with 80 to 94%. In addition, the manual interventions in AM are mainly due to wrongly parked cars and trucks on the road. Pfaffenthal, a residential site, presents the highest technical performance score, reflecting the highest average speed (17km/h), occupancy rate (an average occupancy of about three passengers), and percentage of automated driven km (94%). In contrast, Nordhavn presents the lowest technical performance score among the four sites, with the lowest speed (8km/h) and occupancy rate (0,23 passengers).

AM present low system integration as temporary pilot trials, and their services can be accessed via a specific application for smartphones. In the near future, it is expected that AM information, booking, and payment to be integrated within the public transport services, considering that in most cases, they are already deployed by public transport operators. Finally, the indicator on 'reduction of risk of induced demand' (available just for Nordhavn) scored low in Nordhavn. This is explained by the users' survey, which shows that AM have been replacing walking and cycling mainly (17% and 45% respectively), instead of motorised modes of transport. In parts, this can be explained due to the vehicles' low speed and/or the type of deployment area. However, this factor warns of the risk of induced demand and increased vehicle kilometres travelled that AM could trigger.

Regarding the level of integration of the AM and the potential impacts on mobility systems, Figure 5 presents the mobility radars for two future scenarios: AM integrated into MaaS and AV deployed as robotaxis. This is an explorative approach, and under certain assumptions for each scenario, the assessment suggests that overall, AM in MaaS tend to present a better performance than AV deployed as robotaxis, especially to reduce external costs on congestion and to provide higher energy efficiency. This can be explained as robotaxis are very attractive for users and compete with public transport. The passenger traffic would thus be displaced from public transport to robotaxis and increase congestion (WEforum, 2020). These future perspectives need further research, and the enclosed developed hypothesis will be broadened on sites in the EU-funded ULTIMO project (2022-2026).

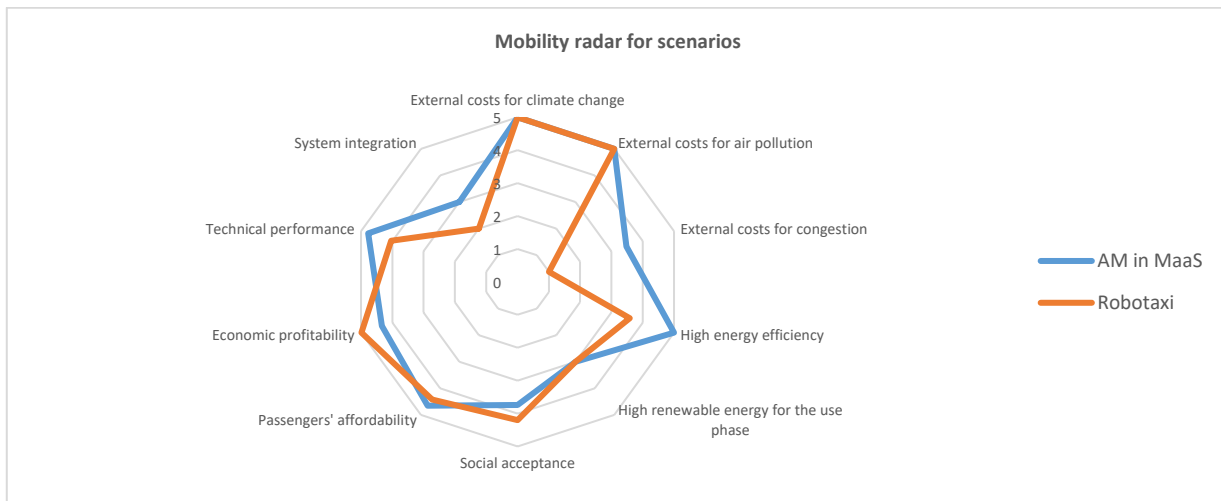


Figure 5. Sustainability mobility radar for the scenarios - with 1 for the worst performance and 5 for the best performance

5.5 DISCUSSION

Given the experimental nature of the pilot sites and Covid-19 restrictions, overall, the results indicate that AM have yet limited performance concerning the different indicators assessed. However, they prove to be feasible as new alternative mobility by offering new services, improving the transport network and supporting cities to achieve sustainable mobility under certain premises. The assessment results provide valuable findings to discuss the integration of the AM into public transport, MaaS system and under SUMP premises. According to MaaS and SUMP approaches, mobility system integration is crucial to fostering intermodality and sustainable mobility, as shown in figure 5. This vision is in line with Nikitas et al. (2021) and Fournier et al. (2022), who argue that AM can be a cornerstone of MaaS systems, playing a role in replacing private mobility with multimodal mass transit. Hereinafter, we ponder certain premises in the form of recommendations for the deployment of AM in order to be aligned with SUMP and the Green Deal goals for sustainable mobility:

- i) The AM 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 consequently a better performance in climate change and energy efficiency, reduction of the risks of induced demand and of increase in vehicle kilometres travelled.
- ii) The development of policy instruments and push and pull measures as levers for a mobility shift towards public transport-centred MaaS. For instance, transportation demand management (TDM), incentives towards shared mobility (e.g. high occupancy vehicle lanes), reduction of costs for public transport and improving the network, road pricing, congestion pricing, and parking policies.
- iii) To develop tools to enhance citizens' participation in mobility planning, as living labs and citizen forums.

- iv) The assessment of the current and future performance, assessment of scenarios and setting goals for the deployment of AM aiming at sustainable mobility.
- v) Institutional cooperation is a key factor. Cooperation among transport operators, companies (as the vehicle manufacturer and software providers), and the municipality is crucial to achieving a beneficial deployment for the city. In addition, the cooperation allows city planners and decision-makers to better prepare for long-term vision and mobility planning.
- vi) To keep an integrated vision of the mobility system. Thus, AM are enablers within the mobility ecosystem, supporting intermodality, MaaS, mobility hubs and the use of soft modes of transport.

Contrasting our results with the literature presents some constraints since many studies have as assumptions the use of fully automated vehicles and high diffusion of the technology. Yet, our results confirm that the automated minibuses can contribute to low CO₂ emissions and better energy efficiency from an average occupancy rate of 3 people or more. They can also contribute to reducing local air pollution. In terms of acceptance, the survey pointed out openness and goodwill from potential users and high users' acceptance once they experience a ride. The economic attractiveness presents many bottlenecks inherent in innovation and deployment of new technologies that can be overcome in the medium and long term. As long as technical performance improves and the services become permanent, the integration of the automated minibuses into the mobility system integration is expected to improve.

5.6 LIMITATIONS

It is important to note that this study has some limitations. For instance, the assessment of the pilot sites consists of local and small-scale deployment, the AM are not yet integrated into the transport system, and the pilots face technological limitations due to the ongoing development of the technology. Other limitations concern the data availability and data asymmetry among pilot sites, trial interruptions and limitations in the number of passengers due to the Covid-19 pandemic. In addition, weighting the different indicators to account for the heterogeneity of contexts is envisaged for future research. With regard to the scenarios' assessment, some assumptions are subjects for future research. For instance, the AM deployed as robotaxis could be cheaper and faster and offer a more individual and not an intermodal service, therefore ensuring higher social acceptance. Nonetheless, this deployment would be less sustainable. In addition, the indicators assessing the external costs were applied only to the scenarios assessment; this is due to the lack of data on local traffic for the pilot sites. Furthermore, in the near future, it is foreseen the deployment of the AM on a larger scale and more significant changes in the modal shift with the AM.

5.7 CONCLUSION

The present study applied a set of indicators for sustainability assessment aiming to measure the current performance of the automated minibuses in four case studies. Our study points that the current performance of the automated minibuses does not fulfil all the premises for sustainable mobility. In addition, the small scale of deployment, the newness of the technology and Covid-19 pandemic restrictions posed some limitations to the performance of the automated minibuses. However, the AM prove to be a feasible new mobility option, with the potential to support cities to achieve sustainable mobility under certain premises. The premises comprise, for instance, higher average occupancy, technological improvements, better integration of the mobility system, as well as policy instruments, pull and push measures aiming at a system innovation and a shift from private mobility to a mobility that serves the general interest.

Our results confirm the potential of the automated minibuses to contribute to lower emissions, energy efficiency and tackle local air pollution. Social acceptance revealed openness and goodwill. The bottlenecks for economic attractiveness for operators might be overcome in the medium and long term. And the technical performance of the automated minibuses, as well as the system integration, might evolve hand in hand.

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 the occupancy rate will be; how fast the technology and policies development will occur; to which extent AM will be integrated into the mobility system, and under which policies and incentives. The scenario for the AM integrated into the mobility system provided evidence of being more beneficial than AV competing with the transport system. An in-depth assessment of the different levels of integration of the AM into the mobility system is the subject of future research.

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

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CHAPTER 6 THE INTEGRATION OF AUTOMATED MINIBUSES INTO THE MOBILITY SYSTEMS – AN ANALYSIS BY THE LENS OF SOCIO-TECHNICAL TRANSITIONS AND MULTI-LEVEL PERSPECTIVES

Abstract

Automated driving, along with other mobility innovations, is expected to entail socio-technical changes in mobility systems. Automated vehicles, and more specifically automated minibuses integrated into the transport system, are analysed in this study as a breakthrough technology through the perspective of different stakeholder groups and citizens. Our research approach builds upon conceptual mapping and semi-structured interviews with the main stakeholder groups (n= 30) and a large-scale survey with citizens in four European cities (n= 1816). This study brings forward insights into the interaction between technology and society as a dialectical process through the prism of socio-technical transitions and multi-level perspectives. The study addresses the main drivers and barriers to steering the deployment of automated minibuses to meet the mobility needs of citizens and the aims of cities towards sustainable mobility. Further, it points out five main mechanisms to pave the way to a mobility transition with the automated minibuses integrated into the mobility system.

Our findings support the prospect that the automated minibuses - integrated into public transport and MaaS systems and coupled with other niche innovations and policy instruments – can be part of the solution to pave the way towards a socio-technical transition to a new mobility paradigm.

Nemoto, E.H.; Korbee, D; Jaroudi, I.; Viere, T; Naderer, G.; Fournier, G. (2022). Integrating automated minibuses into the mobility systems – socio-technical transitions analysis and multi-level perspectives. *Technological Forecasting and Social Change*.

6.1 INTRODUCTION

Urban mobility systems are changing, such changes are engendered by social and technical innovations on mobility aiming to tackle global issues such as urbanisation processes, increasing demand for mobility, climate change and sustainability goals (Kaan, 2017; Janasz, 2018b; Moradi and Vagnoni, 2018)

Automated vehicles (AVs) represent one of the breakthrough innovations within a socio-technical transition of the mobility system (Milakis and Müller, 2021). The currently emerging social and technical innovations in mobility comprise automated driving, electric vehicles, shared mobility, mobility on-demand, intermodal journeys and Mobility as a Service (MaaS) (Stocker and Shaheen, 2017; Janasz, 2018b; Sochor et al., 2018; Litman, 2022). It also includes sustainable urban mobility planning and changes in mobility patterns, for instance, the hybridisation of individual and public transport by deploying automated mobility on-demand (Fagnant and Kockelman, 2015; Fraedrich et al., 2015).

AVs can be deployed in different manners, such as a private car for individual mobility, robotaxis in competition with public transport or automated minibuses integrated into public transport and MaaS (UITP, 2017). This study discusses AVs and, more specifically, automated minibuses (AM). AM deployed as a public microtransit, provide a combination of on-demand ridesharing and car-sharing in public transport and can be integrated into MaaS and Intelligent Transport Systems (ITS).

The objects of study are the automated minibuses (AM) integrated into mobility systems. The automated minibuses present levels 3 and 4 of automation, they are electric and have a maximum capacity of 15 passengers. The AM is envisaged to complement other modes of transport and provide greater flexibility to mobility systems (Nemoto et al., 2021b). Pilot trials deploying the automated minibuses are booming (Ainsalu et al., 2018; Haque and Brakewood, 2020; Antonialli, 2021) in an attempt to deploy the AM as a mobility gap filler, which provides first and last miles, convenient and flexible services within public transport, and a new mode of transport that could support intermodality and a MaaS approach (Nemoto et al., 2021).

Such innovations can be studied through the lens of socio-technical transitions since they entail changes in multiple dimensions, such as infrastructure, industrial networks, business models, policy and mobility behaviour (Fagnant and Kockelman, 2015; Geels, 2019). Further, socio-technical transitions are frequently analysed through the prism of a multi-level perspective (MLP) (Lachman, 2013). The MLP approach interprets transitions throughout the interplay and interacting processes and developments within three analytical levels: niches, regime and landscape (Geels, 2010, 2011).

A MLP approach is applied in sustainable urban mobility studies by considering 'multi-dimensional, multi-actor and multi-level transition' (Geels et al., 2017; Canitez, 2019) and providing an integrated and systemic perspective on socio-technical change (Whitmarsh, 2012). In addition, the MLP proved to be a valuable tool for stakeholder analysis by differentiating levels, actors, groups and domains of involvement (Whitmarsh, 2012;

Fraedrich et al., 2015).

Therefore, this study aims to analyse the integration of automated minibuses into the urban mobility systems through the perspective of different stakeholder groups and citizens and using the lens of socio-technical transitions and a multi-level perspective (MLP) as a conceptual framework. The study is guided by the following research questions: what are the stakeholders, their roles, interactions and perceptions concerning the integration of automated minibuses in public transport and in the mobility system in general? What are the drivers and obstacles for the integration of the AM into urban mobility? How could AM become a game-changer for mobility systems and contribute to sustainable mobility?

A conceptual stakeholder mapping was made to answer these questions. Based on this preliminary assessment, important stakeholder groups and themes were identified and selected for in-depth interviews. Semi-structured interviews were conducted with the main stakeholder groups, as identified in the conceptual analysis (n= 30). To account for the perceptions and attitudes towards automated vehicles and automated minibuses by citizens, we included results from a large-scale survey with citizens in four European cities (n= 1816). The research, both the qualitative interviews with key stakeholders and the large-scale survey, was conducted within the AVENUE project, a project deploying automated minibuses in the public transport of European cities (AVENUE, 2021).

The added value of this research lies in a comprehensive approach that brings together the different perspectives from diverse stakeholder groups to analyse the role of AM within mobility systems. The analysis considers the interactions and complexities at stake by integrating this new mode of transport while attempting to draw main mechanisms for a suitable pathway for the deployment of breakthrough innovations to meet the mobility needs of citizens and sustainable mobility.

We present the conceptual background on socio-technical transition, multi-level perspectives and automated driving according to these approaches (section 6.2) in the following sections. Thereafter the methodology is presented (section 6.3), followed by the results (section 6.4), discussion (section 6.5) and conclusion (section 6.6).

6.2 CONCEPTUAL BACKGROUND

6.2.1 Socio-technical transitions

Transition can be described as flowing changes towards a new future and new systems, which are considered an improved version of the existing ones (Moradi and Vagnoni, 2018). Geels et al. (2017) argue that transitions are disruptive, contested and non-linear. They are disruptive as they threaten the dominant business models and economic positions, contested because actors present different opinions and disagree about the desirability of the novelties and non-linear because the changes and shifts can experience accelerations and setbacks. Moreover, transitions are characterised by i) multi-actor processes and dynamics, ii) long-term processes, iii) macroscopic scale, iv) multiple changes in societal systems, and v) radical shifts (Geels and Schot, 2010).

The socio-technical transitions address the systems changes and transformations to fulfil specific societal functions and needs (Fraedrich et al., 2015; Geels, 2019). Those changes and transformations involve the interaction and co-evolution of new technologies with organisations, institutions, actors, and structures (Fraedrich et al., 2015). The socio-technical transitions address complex interactions among societal groups, resulting in new public policies, business models, markets, infrastructure, and new attitudes, norms and values (Fraedrich et al., 2015; Geels, 2019).

Furthermore, Patterson et al. (2017) describe four conceptual approaches related to transformations and transitions applied in sustainability studies: socio-technical transitions, social-ecological transformations, sustainability pathways, and transformative adaptation. These approaches present overlaps, as well as different focuses of analysis and views. Socio-technical transitions address long-term societal changes 'involving technological, social, institutional, and economic systems', and frequently they are analysed by the prism of multi-level perspectives (MLP), which are detailed in the next section. Social-ecological transformations focus on systems resilience and adaptability, sustainability pathways shed light on transformations through governance, bottom-up initiatives, multiple narratives, equity and justice, and transformative adaptation focuses on the relation between local problems and global conditions and dynamics, and it claims new alternatives and paths for the problems Patterson et al. (2017).

Studies on socio-technical transition emerged in the early 2000s in the field of economics, science & technology and innovation studies, and it has grown exponentially (Whitmarsh, 2012; Geels, 2019). Socio-technical transitions approach has been applied in diverse sectors, such as agriculture, mobility, energy and water (Whitmarsh, 2012; Geels, 2019). And due to its integrated and systemic view, socio-technical transitions have also been applied in sustainability studies (Geels et al., 2017; Canitez, 2019; Wells et al., 2020) and sustainable urban mobility (Fraedrich et al., 2015; Canitez, 2019; Marletto, 2019; Milakis and Müller, 2021).

The socio-technical transition perspective provides a useful approach to studying the social and technical dynamics and complexities encompassing sustainability transitions (Canitez, 2019). Moreover, sustainability transitions involve fundamental changes in systems and structures (Geels, 2019). Socio-technical transitions are envisaged considering the principles and hurdles of our current mobility paradigm. Conventional mobility planning, as explained by Banister (2008), revolves around two main principles: travel as a derived demand (not a standalone activity) and reducing travel time and cost. The two principles explain the shift from active modes and public transport to cars as well as the inflexibility of the current mobility paradigm. In addition, mobility transitions are addressed by recognising the limits of the current mobility system, characterized by individual mobility, fossil fuels, significant power of the automotive industry, infrastructure and urban planning designed for cars (Fournier, 2017). As a consequence, the current mobility system is responsible for high CO₂ emissions and mobility externalities costs borne by societies. Thus, changes in urban planning, policies and technological innovations are foreseen in order to foster the reduction of car use, reduction of travel as derived demand, as well as a modal shift towards more

sustainable and public means of transit (Banister, 2008; Kuss and Nicholas, 2022).

The multi-level perspective is described in the next section, as it is a common approach to analysing and conceptualising socio-technical transitions.

6.2.2 Multi-Level Perspective (MLP)

The multi-level perspective (MLP) approach is commonly applied within socio-technical transition studies due to its multi-dimensional, integrated and systemic concept (Whitmarsh, 2012). According to Moradi and Vagnoni (2018), "multi-level perspective considers the transition as a non-linear process of change resulting from the interactions of social and technological factors at different levels".

MLP is a middle-range theory structured into three analytical levels and the interplay of developments at these analytical levels: the regime, the landscape, and the niches (Geels, 2010, 2011). The socio-technical regime is the 'locus of established practices and associated rules that stabilise existing systems' (Geels, 2011). It comprises institutions, regulations, standards, infrastructures, routines, and behavioural norms (Geels and Schot, 2007). The niches concern the locus where novelties and innovations emerge, characterised by experimentations, unstable environment, and low performance (Geels and Schot, 2007). And the landscape refers to the exogenous environment in which slow-changing developments usually take place (Geels and Schot, 2007). The landscape embraces demographics, geopolitics, macro-economic trends, and external shocks (e.g. wars, financial crises, pandemics, and oil prices (Geels, 2019).

Geels (2010) argues that socio-technical transitions to sustainability do not occur easily due to lock-in mechanisms in diverse fields (energy, transport, agri-food system), the lock-in mechanisms concern, for instance, behavioural patterns, sunk investments, infrastructure, and dominant regulations. The MLP provides a framework to understand sustainability transitions taking into account 'the multi-dimensional complexity of changes in socio-technical systems' (Geels, 2010). In addition, MLP is also a tool for stakeholder analysis, useful to differentiate levels, actors, groups and domains involved in the changes (Whitmarsh, 2012; Fraedrich et al., 2015).

The MLP perceives transitions as regime shifts, which occur through the interacting processes within and between the three levels (Geels, 2010). Geels (2019) explains the multi-level dynamic of transitions, influenced by: "(a) niche-innovations gradually build up internal momentum, (b) niche-innovations and landscape changes create pressure on the system and regime, and (c) destabilisation of the regime creates windows of opportunity for niche-innovations, which then diffuse and disrupt the existing system".

Furthermore, besides the three analytical levels, Geels (2019) proposes four temporal phases of analysis:

- i) Experimentation: characterised by experiments, deployment and trials of new technologies and innovations. This phase is also marked by uncertainty, instability,

failures, and challenges, such as expensive technologies, uncertainties about the users' preferences and acceptance, and liability of newness.

- ii) **Stabilisation:** in this phase, innovation stabilises and entails learning processes, standardisation, guidelines, and best practices. Resistance and opposition by social groups may also occur due to negative side effects, lack of communication and awareness, and/or insufficient participation during the decision-making process.
- iii) **Diffusion and disruption:** the innovation diffuses into mainstream markets, they are boosted by better performance, economies of scale, and windows of opportunity created by the landscape and pressures on the regime. This phase is characterised by struggles between niche innovations and the existing regime, for instance, economic competition, business struggles, political conflicts, and cultural conflicts.
- iv) **Institutionalisation and anchoring:** in this fourth phase, the new socio-technical system is recognised, institutionalised and anchored through regulations and standards, user habits and societal norms. This new system then replaces part of the old system.

In addition, Geels and Schot (2007) present four transition pathways based on the timing and nature of the multi-level interactions. They are described briefly:

- i) **Transformation path** occurs at moderate landscape pressure at a moment when niche-innovations are not yet completely developed or mature. In response, the regime actors may react by reorienting the direction of development paths and innovations. Although regime actors survive, a new regime may arise or be rebuilt.
- ii) **De-alignment and re-alignment path** is described by large and sudden landscape change, and consequently, the loss of credibility in regime actors and de-alignment from the current regime. In this path, if niche-innovations are not yet mature, multiple niche-innovations will emerge and co-exist, and eventually, one niche-innovation will become dominant and re-align with a new regime.
- iii) **Technological substitution** is characterised by a 'specific shock', which causes high landscape pressure, and consequently, it creates windows of opportunity for niche-innovations. In combination, the niche innovations are sufficiently mature to break through and replace the existing regime. This way, this path is characterised by a technology-push.
- iv) **Reconfiguration pathway** is described by the combination of symbiotic technologies and innovations developed in niches at first adopted to solve local problems. Over time, the symbiotic innovations may entail reconfigurations in the regime, and the breakthrough is caused by 'multiple component innovations.

One step further, Hargreaves et al. (2012) explore the points of intersection and complementarity of two 'middle-range' approaches, the MLP and Social Practice Theory (SPT). The SPT sheds light on the transitions in practices in everyday life (Shove; Hargreaves et al., 2012). According to Shove and Pantzar (2005) the practices are built upon images (meanings and symbols), skills (know-how), and material (artefacts and technologies). The complementarity of both approaches is explained by the fact that the MLP analyses the transition through new regime innovations, stemming from vertical relations between the levels (niche, regime, landscape), whilst the SPT analyses the changes and transition in practices from the horizontal nature of relations (Hargreaves et al., 2012).

We recognise the points of intersection between the MLP and SPT for this study. However, the focus of our analysis and interpretation remains based on the MLP approach, given the nature of the data used in this study in combination with the heuristic lens provided by the MLP approach.

6.2.3 Automated driving and socio-technical transition

Automated driving and automated vehicles represent a socio-technical transition of the mobility system, considering that they entail changes in infrastructure, industrial networks, policies, market and mobility behaviour and habits (Fagnant and Kockelman, 2015; Hopkins and Schwanen, 2018; Milakis and Müller, 2021).

Hirschhorn et al. (2019) describe current trends influencing the landscape when considering the land passenger mobility system, such as global warming and climate awareness, digitalisation, Information and Communications Technology (ICT), sharing economy, growing income, and the increase in speed and convenience of travel. The car regime holds a dominant position among other regimes as the public transport regime or the non-motorized regime, given a series of stabilising factors and lock-in mechanisms as sunk investments in road infrastructure, cultural values and the car status (Parkhurst et al.; Hirschhorn et al., 2019). Some examples of niches are the biofuels, electric vehicles (EV) and MaaS niches arising in a land passenger mobility system (Hirschhorn et al., 2019).

Milakis and Müller (2021) argue that AVs, in combination with other emerging technologies and concepts gaining momentum on mobility, could be inserted into the 'reconfiguration pathway' conceptualised by Geels and Schot (2007). Hence, the AVs, along with electromobility, shared mobility, intermodality and MaaS (Janasz, 2018b, 2018a; Taiebat et al., 2018; Shaheen and Bouzaghrane, 2019), could result in symbiotic innovations and entail reconfigurations in the regime and mobility breakthroughs.

Alternatively, a 'sequence of transition pathways' could occur as described by Geels and Schot (2007), "beginning with transformation, then leading to reconfiguration, and possibly followed by substitution or de-alignment and re-alignment". Applied to the mobility context, the transformation path could correspond to our current situation, in which there is a certain level of landscape pressure (e.g. climate change, urbanisation processes, climate agreements and sustainable development goals). However, some niche-innovations are not yet completely mature, e.g. AVs level 3 or 4 of automation, infrastructure challenges for electric

vehicles, and regulation for e-scooters. Subsequently, the reconfiguration path, in which the combination of symbiotic technologies starts triggering significant changes and then the de-alignment and re-alignment path, in which a niche-innovation becomes dominant (e.g. shared automated electric vehicle) and re-aligns with a new mobility regime.

Fraedrich et al. (2015) present three potential transition scenarios of fully automated driving and their socio-technical contexts and consequences for the future mobility system:

- The 'evolution' scenario concerns the evolution of the personal automobile from driver assistance systems to fully automated driving; such improvements in individual mobility aim at safety, convenience and comfort. The main actors are the vehicle manufacturers and component suppliers, following the typical approach of the automotive industry.
- The revolution of personal mobility describes a scenario in which non-automotive technology companies lead the mobility transition. For instance, information technology companies with a focus on mobility data and services and artificial intelligence applied to mobility could start laying the ground through living labs and pilot trials testing automated driving. Besides cooperations, the information and communication companies could posteriorly replace established original equipment manufacturers.
- The transformation of personal mobility foresees significant changes in mobility patterns through the hybridisation of individual and public transport by deploying automated mobility on-demand. In this way, shared, intermodal and automated convenient public transportation systems are seen as technological and social innovations in an attempt to integrate personal mobility with public transportation and parallelly tackle safety, pollution, and congestion problems. The leading actors in this context are startups and service companies in cooperation with public transport authorities and public and private mobility providers.

Marletto (2019) argues that the transition pathways to an automated driving future and their respective impacts depend considerably on the configuration and relations among the network of innovators. Hence, the study conceptualises socio-technical maps of urban mobility in 2040 to illustrate three potential transition pathways towards automated driving according to different networks of innovators. The 'individual transition pathway' is led by automotive companies in cooperation with suppliers of technologies and components for automated driving, but no relevant changes are expected in urban mobility. The 'shared transition pathway' is characterised by the cooperation between leaders of the internet system, artificial intelligence and managers of shared and collective transport systems. Positive impacts on mobility are foreseen within this path by reducing the impacts of individual mobility. And urban mobility is taken over by energy agents, who integrate AVs and smart grids on the 'smart transition pathway'. These actors are driven by the discourse of energy efficiency and sustainability; however, pervasive rebound effects are foreseen.

6.3 METHODOLOGY

6.3.1 Setting the stage

As a first step, we defined the approaches to socio-technical transitions and the multi-level perspective (MLP), and we explored the nexus between automated driving. These concepts are the theoretical foundation and guidance to structure the study.

In the second step, based on a conceptual stakeholders mapping, we identified and selected different sectors and groups of stakeholders involved directly or indirectly with automated driving and mobility for in-depth interviews.

6.3.2 Data collection

In the third step, representatives of the key stakeholder groups that were identified by the conceptual stakeholder mapping were invited for interviews, either in person (or face-to-face), per phone or Skype. The interviews were semi-structured (see appendix D and E), lasting about 60 to 90 minutes, and they occurred between 2018 and 2020. The sample comprises a total of 30 interviews. Table 6 presents the group of stakeholders interviewed and their roles.

Table 6. *Semi-structured interviews with stakeholder groups*

Interviewee ID	Sector	Interviewee role	Country
1	Public Transport Operator	Expert in automated vehicles	Switzerland
2	Public Transport Operator	Project Manager - Automated vehicles	France
3	Public Transport Operator	Project Manager - Automated & E-Mobility	Luxembourg
4	Public Transport Operator	Project Manager – Automated vehicles	Denmark
5	Original Equipment Manufacturer	General Manager	USA
6	Original Equipment Manufacturer /Software provider	Global Head of Technical Sales	Germany
7	Original Equipment Manufacturer	Head of Marketing	France
8	Software provider	Founder - fleet platform company	Switzerland
9	Technology/software provider	Vice President Product Innovation Management	Germany
10	Component supplier	Project Manager Purchasing	Germany
11	Government	Urban planner	Germany
12	Government	Mobility Strategist	Netherlands
13	Government	Transport planner	Denmark
14	NGO	Head of Transport Policy	Germany
15	NGO	Head of Transport and Air Pollution Control	Germany
16	NGO	Expert in clean vehicles and new mobility	Belgium
17	Driven Union	Head of Transport	Denmark
18	Driver Union	Bus driver	Austria

19	Driver Union	Founder of a Public Transport Union	Germany
20	Citizens Association	Researcher at the transportation field	Germany
21	Citizens Association	Professor and Researcher in the transportation field	Belgium
22	Citizen/Consumer association	Communications Officer for product safety, sustainable mobility and trade	Belgium
23	Citizens/passenger association	Consultant for mobility policy	Netherlands
24	Safety driver	Safety driver of the automated minibus	France
25	Safety driver	Safety driver of the automated minibus	France
26	Safety driver	Safety driver of the automated minibus	Switzerland
27	Safety driver	Safety driver of the automated minibus	Norway
28	Safety driver	Safety driver of the automated minibus	Norway
29	Safety driver	Safety driver of the automated minibus	Norway
30	Safety driver	Safety driver of the automated minibus	Luxembourg
31	Cluster of citizens: Unreserved goodwill (19%)	Citizens, as potential users	Copenhagen, Geneva, Luxembourg, Lyon
32	Cluster of citizens: Skeptical goodwill (34%)	Citizens, as potential users	Copenhagen, Geneva, Luxembourg, Lyon
33	Cluster of citizens: Undecided (29%)	Citizens, as potential users	Copenhagen, Geneva, Luxembourg, Lyon
34	Cluster of citizens: Critical reserved (12%)	Citizens, as potential users	Copenhagen, Geneva, Luxembourg, Lyon
35	Cluster of citizens: Unconvinced refusers (6%)	Citizens, as potential users	Copenhagen, Geneva, Luxembourg, Lyon

In order to include perceptions and attitudes of citizens in our analysis, results from a large-scale study were included. The survey was conducted within the AVENUE social impact assessment (Korbee et al., 2022a). Citizens of four European cities (n=1816) took part in this study: Lyon (n=501), Geneva (n=284), Copenhagen (n=491) and Luxembourg (n=540). The survey is based on a fully structured questionnaire of 28 questions. The questions addressed the mobility behaviour and perceptions of AVs and AMs. The survey ran from 28th June up to 23th July 2021.

We included a selection of questions from the quantitative study for this research, the detailed information on the methodology can be found in appendix F. The quantitative survey resulted in the construction of five clusters of citizens. These clusters differ in their perception of risks and benefits associated with the deployment of automated minibuses. A major advantage of including citizens (potential users) through clustering them is that a differentiated view on the acceptance of automated minibuses can be included in the stakeholder analysis. We address five clusters of citizens as stakeholders in the remainder of this study, which are numbered in Table 6. Figure 6 illustrates the research approach of this study.

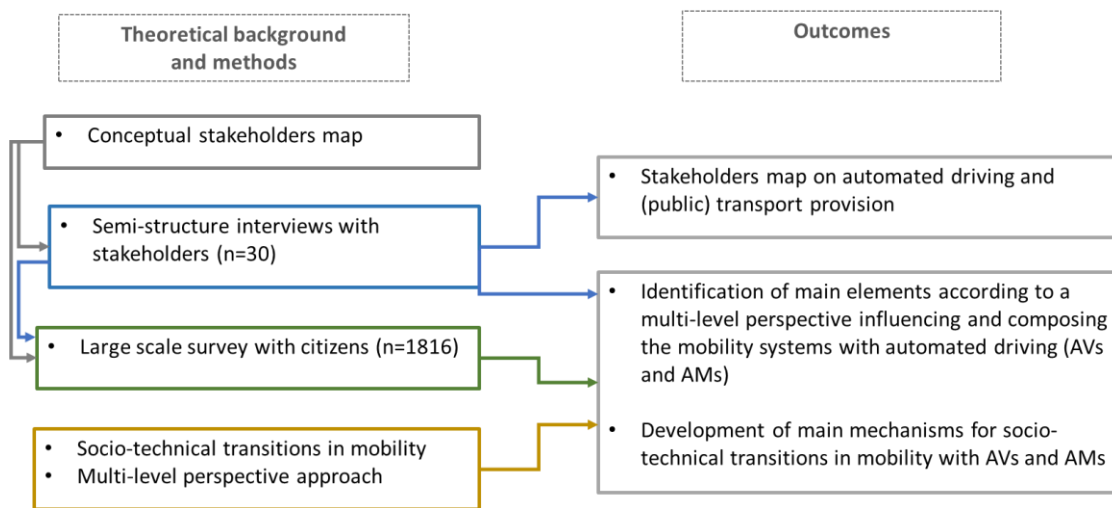


Figure 6. Research approach and outcomes

6.3.3 Data analysis

The interviews were recorded, and we proceeded with the summary report of each, assigned ID numbers, and coding using the program Atlas.ti. We used a mix of deductive codes for the coding based on the interview guideline and inductive codes based on data from the interviews (Appendix G).

Data analysis, interpretation and results were guided by the three analytical levels of the MLP: niches, regime and landscape MLP. In addition, a graphical representation illustrates the stakeholder groups' interactions, and we describe their roles and positionings regarding the integration of AVs and AMs into the mobility system.

6.4 RESULTS

6.4.1 Stakeholder map and interactions on automated driving and (public) transport provision

Figure 7 introduces an overview of the main stakeholders involved in automated driving initiatives and transport provision. Likewise, the main interactions among the stakeholder groups are illustrated. Hereinafter, the role and aims of the main group of stakeholders are described based on the interviews.

It became clear through the analysis that not all actors have an equal influence on the development of AVs/AMs in public transportation systems. Therefore, we defined three types of actors based on the interviews: primary actors, secondary actors and tertiary actors.

Actors that are able to influence this development and deployment directly, and have a large stake in the direction of the development, are labelled primary actors. These include the city governments, the public transport operators, the manufacturers, the software developers, the European Union, and citizens/end-users.

The secondary actors influence the development, but in a more indirect manner, by influencing the prime actors. This category of actors includes civil society organisations, such as driver unions, environmental NGOs and citizen associations, research institutes and the media.

The third group, the tertiary actors, are important for the technical development of the system (suppliers), as well as for the operation of the system (safety drivers and insurance companies). They provide constraining and enabling conditions but are not actively involved in shaping the system.

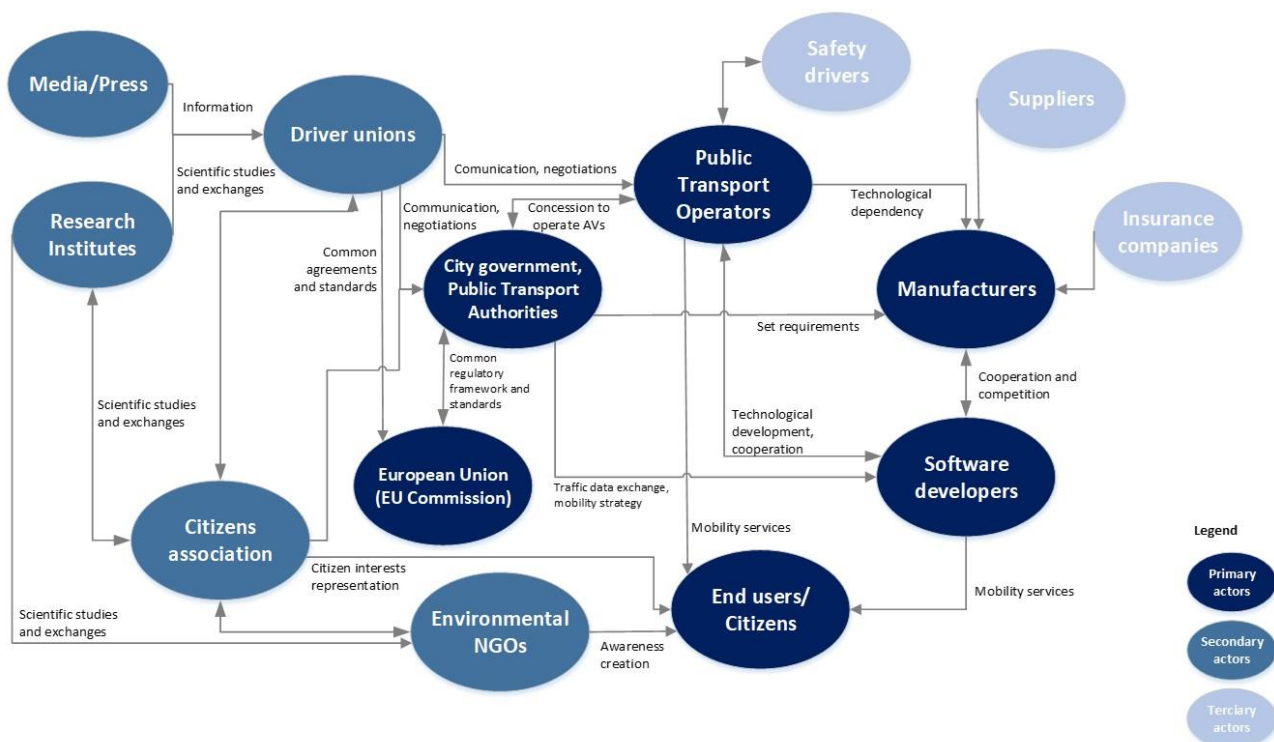


Figure 7 Graphical representation of the stakeholders and their interactions

The **manufacturers** of the AMs have the following goals: i) provide new mobility solutions; ii) improve safety and support the cities to re-think their mobility; iii) deploy and improve their vehicles according to different environments, as stated:

“Our interest is to be able to understand all the driving scenarios and to provide fully or high automated systems to drive in all traffic complexities” (ID6).

“the more we run, the more we learn, the more use cases we will discover and the fewer issues we will have at the end of the day” (ID7).

Manufacturers want to meet the needs of their customers and citizens, improve transportation services, play an active role in shaping the future of mobility, and drive this new technology with their vehicles. The stakeholders, such as the PTOs and the local

government, are key partners for the manufacturers. Their cooperation helps the manufacturers improve their products to provide better deployment (traffic regulations, concessions).

The **software providers** offer platforms that enable intelligent operation and optimisation of automated mobility services. Their goal is to enable the integration and connection of AVs into the mobility network, to enable shared mobility, and move beyond technology demonstration to services demonstration (ID8). They also focus on safety, efficiency and on providing fleet management and singular solutions for the cities (ID6).

Another stakeholder group, the **public transport operators** (PTOs), are responsible for providing public transport services in cities. PTOs perceive automated driving as a “key topic for the future” (ID2) and as a decisive element of competition, considering that “newcomers are arising” (ID2).

PTOs expect automated public transportation to contribute to societal benefits such as better quality of life and improved health and environmental conditions due to reduced pollution (ID4) and enhanced comfort in public transport (ID3). In addition, PTOs currently deploying AVs see themselves as pioneers (ID3) and mention their role in intervention with public transport authorities (PTA) to deploy AVs (ID2).

Policymakers and urban planners perceive their centric role to adopt a proactive role towards new forms of mobility such as the AVs/AMs and to shape the city and the traffic for the future (ID11). Hence, it is their role to project ahead the spatial planning, including green areas and low emissions zones, as well as to identify infrastructure needs (ID11). This stakeholder group also relies on insights from pilot projects to further base their actions (ID12).

The **driver unions** address topics like the drivers’ re-education and training for work, better road conditions, safety assurance, and agreements with employers’ organisations and governments. One of the primary actions of the driver unions is to be part of the dialogues in the transport sector and to negotiate collective agreements for their members. As stated: “We have a lot of willingness to negotiate, bargain, make agreements and compromises and bring the work organisations together” (ID17). The interviewed driver unions highlighted the strategic importance and their focus on professional education, information and training; as quoted, “for us it is more about re-educating people ... there will be a big need for skilled workers” (ID17).

Further, the **civil society organisations** address issues concerning urban mobility and citizens and the representation of end-users from different sectors. The interviewed civil society organisations focus on promoting public transportation. They expressed the urgency of developing and innovating public transport (ID20, ID21) in a way that it should become the first choice and individual private transport should be reduced (ID20). Their emphasis also comprises active modes of transportation.

And the **environmental NGOs** aim to promote a new mobility system that is more efficient

and environmentally friendlier than the current system (ID14). The interviewees state that they strive for future mobility systems that are more flexible and should focus on shared and electric mobility solutions that are convenient for users (ID16). The NGOs perceive the need to become active and support this development, as industry alone will not necessarily advance towards these new future mobility systems by itself. NGOs also play a role in giving recommendations for policy building (ID15). In general, environmental NGOs need more solid science and knowledge concerning the effects when scaling up AVs in our mobility system.

Some of the common goals among the diverse stakeholder groups when addressing AVs and AMs comprise safety, efficiency, and shared and environmentally-friendly mobility. Stakeholders such as manufacturers, software providers, and PTO address their market-oriented objectives to improve the product or solution, place themselves in the market and keep competitive, in addition to offering solutions for societal benefits, such as health and environmental improvements, by improving mobility systems. Other groups such as policymakers and urban planners, driver unions, NGOs and citizen associations address better people-centred planning, citizens' participation, promotion of public transport, active modes, and environmentally friendly solutions as primary goals.

6.4.2 A Multi-Level Perspective on automated driving services for public transport

This section presents the main findings from the stakeholders' interviews and the large-scale survey addressing the deployment of AVs into the mobility system. The findings are structured following the MLP, first the landscape level, second the regime level with a focus on the AV and AM regime, and third, the niche level. Figure 8 illustrates the main elements influencing and composing mobility systems from a multi-level perspective.

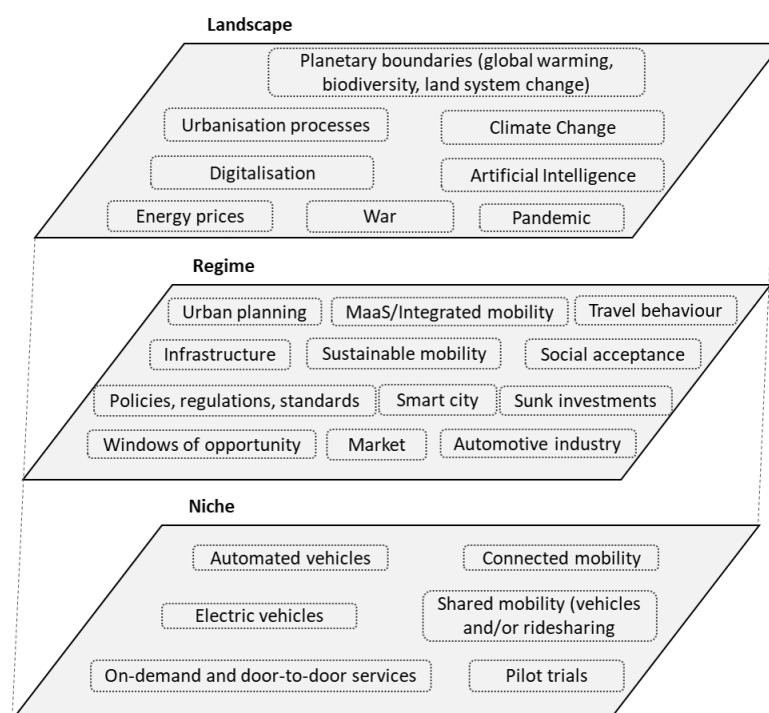


Figure 8. Multi-level perspective from mobility system adapted from Geels (2019) and Fraedrich (2015)

6.4.2.1 *The landscape*

The analysis shows that the landscape is subject to societal, environmental and technological changes. The interviewees pointed main changes and trends pressuring the landscape, such as the urbanisation processes (ID14), climate change (ID21), hence the pursuit of green development strategies and goals (ID12), transformations entailed by artificial intelligence (ID9), and digitalisation (ID14), as digital platforms and platform-based economies that may disrupt local businesses (ID17).

The driving forces on the landscape also comprehend changes in perspectives on how we plan the cities and urban mobility. These changes aim, therefore, for more space for green areas, pedestrians and cyclists (ID12), a shift in mobility behaviour from individual cars to public transport and soft modes of transport (ID3, ID20, ID21), and a citizen-centric approach (ID11, ID12, ID16, ID19).

Main trends and innovations driving changes in the field of mobility concern sustainable mobility, automated mobility, electric (ID3, ID22, ID16), on-demand (ID3, ID8, ID19), shared (ID16, ID21, ID 9), multi-modal (ID12, ID21), connected and integrated mobility networks and services (ID8, ID21). It is also foreseen that the combination between automated, electrified, and shared mobility could transform the transport sector (ID5, ID14, ID16).

6.4.2.2 *The regime for AVs*

As mentioned previously, the regime is the 'locus of established practices and associated rules that stabilise existing systems' (Geels, 2011). Hence, the analysis is structured following pillars of the regime level in this section. Such pillars are analysed along with the main elements that are triggering regime shifts in mobility.

This section, therefore, discusses: the role of AVs and AMs on mobility; urban planning and infrastructure with AVs/AMs; policies and regulations for AVs/AMs; AVs/AMs market, investments and windows of opportunity; potential impacts of AVs/AMs and uncertainties for institutions; and the social acceptance of AVs/AMs.

- ***The role of AVs and AMs on mobility***

Stakeholders from different sectors share the vision that AVs should be deployed as integrated mobility, offering bundling services and not used as individual private cars (ID7, ID8, ID11, ID12, ID21). AVs are integrated into public transport in order to improve comfort (ID3, ID23), provide on-demand, higher service frequency and late-night services (ID3), better mobility connections (ID12, ID21), reliability and safety (ID23). More specifically for the AMs, interviewees mentioned that they could be deployed as a gap filler solution, as first and last-mile solutions, to develop better connections to the metro, airport, and mobility hubs (ID5, ID7, ID11, ID12). In the case of Dutch cities, interviewees see the AMs as part of the highway network outside the inner city (ID12), considering that The Netherlands is a cycling country, and for first and last miles, the bicycle is used very often (ID23).

The AM pilot trials have a focus on public and not on private transport, plus automated driving is seen as the “next higher level in public transport”(ID11). The deployment of AM is seen within a small system, on a specific lane and in a secure way to interact with different road users (ID12). Hence, the deployment of AMs directly in the urban area is seen as a challenge due to other road users (ID11, ID12). The potential areas for deployment are hospitals, universities, residential areas, airports and industrial areas (ID9).

In contrast, one interviewee stresses that the role of the AMs cannot be reduced to filling first and last miles, but more than that, the AMs with software can provide smart solutions adapted to the context of different cities and different needs (ID6). In the interviewee's words: *“I basically don't like to talk just about first and last mile, because this is only adding to an already existing set of transport... We don't see our buses just as a small little bus in a fleet, but the software behind them can enable so many different uses and business cases that we should not stick to the old type of technology and add a new one. We should think in terms of ecology, resources...”* (ID6).

In addition, the different deployment of AMs and robotaxis is described as the robotaxis offering service between private and public transport, running a longer distance, for example, from the city to the airport, with speed between 70 and 90km/h (ID7). Whereas the AM are expected to be deployed for short distances in the urban and suburban areas as shared mobility, running up to 50km/h (ID7).

- **Urban planning and infrastructure with AVs/AMs**

Interviewees from the government sector (urban planners) advocate that AVs can be an attractive mode of transport by allowing the planning of better cities, meaning fewer parking spaces, fewer roads and bridges, more efficiency in public transport and more space for green areas (ID11, ID12). AVs are also related to sustainable mobility notions of reducing emissions and congestion (ID4, ID15, ID16) and economic development of the cities (ID12). Further, AV can play a part in the cities' transformations, and they present a potential to re-design our cities based on a future that we envision (ID16).

Infrastructure poses a challenge for automated driving (ID5, ID14, ID17), considering that good infrastructure is required (ID17), which comprises the expansion of 5G network nationwide, artificial intelligence and Internet of Things (IoT) connectivity (ID 9, ID10, ID14), and exchange of massive amounts of data (ID10). In addition, investments in lane changes, reference points, intersections, and accurate maps are foreseen (ID3, ID11).

Yet, urban planners approach the topic of automated driving with extremely high interest. Roads and bridges are already being planned for the next 25 years; thus, urban planners acknowledge their role in planning and preparing future mobility with AVs (ID11). Safety and lowering the number of accidents are seen as a priority for urban mobility and citizens' needs (ID 6). Some uncertainties raised by one interviewee addressed the challenge of AVs circulating in dense areas and how their interaction with pedestrians and cyclists might be, for instance (ID12).

- **Policies and regulations for AVs/AMs**

The development of policies and regulations for the use of new technology such as AVs is challenging (ID12); as a consequence, the legal development lags behind the technology (ID11). Yet, some countries will be faster than others (ID8). In the EU, for instance, it is a challenge to transpose the European Commission's directives to the multi-levels of governance, hence, to the national and regional policies and regulations (ID6).

The fact of not having regulations for automated driving poses difficulties (ID2, ID5, ID7) for the public transport authorities to issue approvals and permissions for the pilot trials (ID2). The bottlenecks are related to regulating aspects of responsibility, safety, and liability for AVs (ID2), in addition to the different processes in different cities and countries across the EU (ID2). A transport planner raised the point that developing regulations for technical safety – not based on safety perception – is a challenge because the topic is unclear (ID13). Furthermore, there are ambiguities and no consensus about legal and ethical issues (ID10, ID14).

Further, data protection (ID11, ID14, ID19) and data privacy (ID9) were commonly mentioned concerns for the AVs' regime; the questions raised addressed who owns the data and how it is used (ID14, 19). In addition to data security and cybersecurity against hackers, the perception of attacks on systems was seen as a major danger (ID10, ID19), and how to regulate the use of the data.

Additionally, the development of technical standards for automated driving and vehicle communication is seen as a barrier (ID11, ID16). On the one hand, it is understood that common standards for interoperability and safety are necessary (ID6, ID11, ID13). On the other hand, *"a lot of investment could be wasted if there is one standard that prevails over another"* (ID16).

One interviewee highlights the challenges of an unregulated market, stating that *"automated driving is not a playground for different companies having different softwares that are not aligned"* (ID6). Hence, the interviewee exposes the need for a common understanding of safety and setting standards for software certification (ID6). As a consequence, the approval process for AVs is long because the approval authorities need to understand the new technologies, in addition to *"a very heterogeneous scenario in terms of approval systems"* (ID6).

Another key aspect addressed by one interviewee emphasises the role of regulators and policymakers in order to orient AV deployment towards public goals of safety, reduction of congestion, greenhouse gas emissions and better mobility for the cities (ID16). The interviewee stated the need for a holistic approach across policies for mobility as a whole, which encompasses, for instance, road pricing, low emission zones, and infrastructure for cycling and walking (ID6). Otherwise, the interviewee states, *"we run the risk of ending up with more problems than solutions"*. In addition, policies and regulations play an important role in steering AVs towards public, shared and electric mobility and in avoiding higher mileage than an average car (ID6, ID8, ID14).

It is worth noting some contrasting points of view regarding the nexus between policies and new technologies. One interviewee stated that mobility policies should be guided by our vision of *“what do we want the future to look like”* (ID6), whereas another interviewee said that technologies might emerge *“and then regulations will follow”* (ID8).

In addition, there is common thinking among manufacturers and software providers, who opined about the role of the cities to decide on how to use new technologies, hence some statements that illustrate this positioning: *“the cities need to think about how they want to use the shuttles to prepare policies, they can’t just wait and see and react”* (ID 8), *“The city itself will identify what is the best for them”* and will purchase and implement it (ID 6), *“The cities and the citizens will have to make a trade-off between how many AM and how many robotaxis to offer, and how much to spend on public transport, also to provide access to non-users”* (ID 7).

- **AVs/AMs market, investments and windows of opportunity**

Automated driving brings new players and new competitors onto the scene. For example, software and ICT companies (e.g. Waymo, Google) could become a competitor to traditional car manufacturers, and car manufacturers (e.g. Renault) envision becoming mobility operators as well (ID2). Hence, technology is seen as a competition strategy (ID1), positioning the company as a pioneer (ID4), and a *“way to keep a company when newcomers are arising”* (ID2) for some transport operators investing in automated driving.

Likewise, automated driving technology opens windows of opportunity for companies to position themselves in the market as well. A software provider stated that, on the one hand, the technology inside vehicles is evolving very fast; on the other hand, fleet management and embedding AVs into other mobility services is also a large field to advance (ID8). Therefore, shared mobility, matching rides, multi-modal, on-demand and door-to-door services open windows of opportunity (ID8). Another software provider sees opportunities by understanding and adapting the products and software to become attractive for the city and citizens. In the interviewee's words:

“when talking about strategic goals for 2030 and 2050 and reducing emissions to the zero level in comparison to 1999 values, then you need to identify what kind of solution is the best for a city. The city itself will identify what is the best for them and will purchase it, so we need to be able to understand those needs and to make our products attractive for them” (ID 6).

Yet AVs face technical challenges (ID14, ID8), such as the high prices of the new technologies for AVs (ID5), technology maturity, and for instance, the AMs presenting a low speed and having to be operated with a safety driver on-board (ID2), being considered not mature enough for larger market adoption (ID5, ID6).

- **Potential impacts of AVs/AMs and uncertainties for institutions**

Some interviewees from NGO organisations expressed concerns about the potential environmental impact of AVs. The uncertainties raised consider the amount of servers, data

transmission and storage required for AVs, the effects on energy consumption and the consequences of scaling up the technology (ID16) if AVs were deployed or not as a shared, electric mobility (ID16, ID19) and rather for public transport than as privately owned vehicles (ID20).

What the effects and impacts of AVs will be are unclear (ID14), there is a lack of data and what the scientific findings beyond the estimates are, *“it would be important to know what the actual consequences for a transport system are”* (ID14). *“If the systemic approach is cleverly made and autonomous vehicles play a role in it that expresses a clear efficiency gain compared to the current system, then we would also politically advocate that we shape the framework conditions in such a way that this technology can also be used”* (ID14).

Other uncertainties concern how a mobility system with machines and human driving would work (ID17), how the insurance for AVs would be regulated (ID15), liability questions in case of accidents (ID19), data protection regulations (ID16), and what the impact of AVs will be on mobility behaviour and for users (ID7).

Regarding the potential AV effects on jobs, some interviewees from driver union organisations reported the current and future lack of bus drivers (ID17, ID18). They stated that instead of losing their jobs, automated driving technologies could bring new opportunities and better jobs once qualified employees are required (ID17, ID18), for instance, in the maintenance and supervision of vehicles; hence other *“jobs are created elsewhere”* (ID20). However, according to an interviewee from a drivers' union, the experience a bus driver gets over the years is very difficult to replicate via automated driving (ID18). For instance, driving on icy or snowy highways with low visibility can be a challenge for automated driving (ID18).

AVs are not yet a topic of importance or priority (ID15, ID18, ID21) for some interviewed organisations, such as NGOs and driver unions.

- **The social acceptance of AVs/AMs**

The stakeholders depict a very positive mood, which is considered very positive towards automated driving (ID 4). The window of interest is wide open on a political level, authorities' level, and for private users (ID 4). On the other hand, the users' high expectations that the AVs work (ID 4, ID11) are expected from day one. Concerning social acceptance, one interviewee stated that *“if the automated minibus work how they (the end-users) need it, it's fine for society”* (ID8).

Citizens, as potential users, show a more differentiated picture. About half of the citizens show a positive, goodwill attitude toward automated minibuses (ID31, ID32). However, this group can be divided into two groups, whereby the larger group (ID32) also recognises risks associated with automated minibuses and is therefore characterised as 'sceptical goodwill' (ID32). The most positive citizens (unreserved goodwill) see the automated minibuses as a means to fulfil their mobility needs, not because they are driverless, but because they could increase the spatial and temporal flexibility of transportation (ID31). The group of

unconvinced refusers, hence, those citizens that do not recognise any benefits but primarily see risks associated with automated minibuses, is small with only 6% (ID35). A large group of 29% is undecided, which means that they do not have a stable attitude yet (ID33).

Some interviewees do not exclude the deployment of combustion engine AVs; however, they state that electric AVs would have better social acceptance due to ecological reasons (ID9, ID2). In addition, it is expected that manual cars with an internal combustion engine will co-exist with AVs (ID4).

One of the criticisms addressed by one interviewee is that the discussion about AVs has been framed mainly by the industry, and it lacks the involvement and participation of citizens on this topic (ID 6). Concerning the ethics discussion on automated driving, one interviewee stated that it might become obsolete as new technology proves to be safe and there will be no more car accidents on the road. (ID 11)

It is agreed among different stakeholders that the customer perspective and needs must be a priority. Hence, such statements exemplify this positioning: *"If you want to have regular service with this one day, you have to think about the real requirements of the customers"* (ID2); *"The software developer should develop the services from the perspective of the customer"* (ID1).

6.4.2.3 *The niche for AVs*

The automated minibuses are currently deployed at the niche-level. Most operations have the character of pilot- or demonstration projects. Lessons learned in these projects are of crucial importance for the future feasibility of the AM and for beneficial deployment for the cities and citizens., This section portrays the state of the art of the AM and describes aspects of the current deployment, the AM and interactions with other road users, as well as the user profiles and behaviour on-board based on the experimentations.

- ***State of the art of the AM and current deployment***

The AM are defined as the combination of automated, electric and connected technologies (ID5, ID11, ID20). They are deployed in pilot projects (ID11, ID16, ID20, ID21), offering short rides (ID23), free of charge (ID3), at low speed (ID5, ID20, ID23) and with a focus on public transport (ID11) by complementing bus line services or serving areas with no public transport options (ID26, ID27).

The vehicle has a level 4 of automation (ID1), and the top speed ranges from 25km/h to 40km/h (ID5, ID7). The price of the acquisition of AMs is very high (ID1, ID2, ID8), the technology is under development, and the components are expensive. However, the goal is to develop long-term projects with larger fleets to serve on-demand traffic and to provide business case orientation (ID6), and in the future, the AM could be chargeable within the traditional public transport ticketing system (ID2). As a next step, removing the safety driver is a key aspect of reducing the costs of deployment (ID7).

Some experiments are deployed in isolated areas (ID21), while others are better integrated

into urban traffic (ID7). As mentioned by one AM manufacturer, *“the more we run, the more we learn, the more use cases we will discover and the fewer issues we will have at the end of the day”* (ID7). Likewise, the trials can provide more empirical data to ground studies on the evaluation of this new technology (ID16). Further, a software developer stated that the pilot projects need to advance beyond technology demonstrations to service demonstrations (ID8).

- ***The AM and other road users***

Interruptions during the ride in the AM occur, for example, due to inappropriately parked cars and growing plants along the route, and braking occurs when other vehicles get too close to the AM (ID26, ID27). Another problem frequently reported by the safety drivers is the lack of patience from other road users, who often overtake the AM (ID1, ID26, ID30). However, the safety drivers also reported that there is a period of adaptation for other road users in order to understand the technology and better accept it and respect the traffic flow with the AM (ID24, ID26). In addition, reducing the difference in speed between the AM and other vehicles is important to avoid dangerous situations (ID2).

The unknown effects of automated minibuses on other road users is an important factor in the more sceptical attitude of citizens (ID32; ID34; ID35). Over 50% of these groups state that they are worried about the deployment of automated minibuses because it is unclear how AM react in unforeseen situations, accidents, and motorised and non-motorised road users.

- ***AM user profiles and user behaviour on-board***

The user profiles vary according to the pilot trial areas. In general, users are tourists, students, employees, residents, commuters, medical patients, families, children, and elderly people (ID5, ID24, ID25, ID26, ID27, ID28, ID29, ID30). Knowledge of automated minibuses has not (yet) spread through society as a whole, as only 55% of the citizens were aware of the existence of automated minibuses prior to participating in the AVENUE survey (ID31, ID32, ID33, ID34, ID35). Only a small proportion of citizens (8%) have experience with automated minibuses.

In general, the users have a positive attitude towards the AM (ID27, ID28, ID30, ID31, ID32; ID33); they are interested and curious about how the technology works (ID24, ID26, ID27, ID29, ID30). However, a small group of citizens is not convinced about the positive implications that automated minibuses could bring. This group recognises risks associated with automated minibus deployment and does not recognise the added value that automated minibuses could bring (ID34; ID35).

They are also more communicative than in a normal bus, considering that the safety driver stands in the middle of the AM, and the seats are placed face to face, it creates more social interaction and discussion, so the passengers greet and talk to each other (ID25, ID26, ID27, ID28). In addition, the presence of the safety driver makes people feel more comfortable and safer in case of an emergency, plus the safety drivers explain how the technology works to

the passengers (ID25, ID26). Surprisingly, citizens are supportive of the automated minibus deployment and still perceive that it is important that a safety driver is on board. This accounts for 38% within the group of unreserved goodwill and 70% of the group of sceptical goodwill. Hence, supportive attitudes toward automated minibuses are not based on the fact that the minibuses drive without a driver but because they perceive them as a solution that could increase flexibility (ID31, ID32).

The willingness to use them is generally high. More than 50% „would be willing“ or even be “very willing” to use AM, even two-thirds (63%) if an on-demand service is offered. When asked about the willingness to pay for the AM in comparison with the price of regular public transport, most of the respondents (51%) stated the willingness to pay the equivalent. In addition, the AM is considered an alternative to the use of their private car, with 45% of car drivers ‘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 (Korbee et al., 2022b).

6.5 DISCUSSION

Our findings support the main elements depicted in the literature. Automated driving, along with other mobility innovations, marks a transition in the mobility paradigm, which is characterised by multi-actor processes and dynamics and long-term processes (Geels and Schot, 2010). The results of the stakeholder interviews and large-scale citizen survey point out that the combination of new mobility technologies, such as the automated minibuses, are marked by complex interactions among institutions and societal groups, as well as the need to develop new policies, regulations, business models, infrastructure and changes in mobility behaviour. Such findings are in line with the studies from Fraedrich et al. (2015) and Geels (2019).

The study corroborates the fact that automated driving coupled with other niche innovations, such as shared, electric, on-demand mobility, and MaaS have been paving the way and building pressure on the mobility system towards a socio-technical transition marked by a disruptive, contested, and non-linear process (Geels et al.):

- Disruptive: the AM integrated into public transport and MaaS systems, along with other mobility innovations, represent game-changers in mobility. The rise of such innovations challenges the dominant business models of the traditional automotive industry and exposes the limitations of individual and impactful current mobility patterns.
- Contested: actors present different positioning, opinions and concerns towards the AVs and AMs. Those are not necessarily conflicting, but the focus of analysis and interest of different stakeholder groups towards the deployment of the AM are different.
- Non-linear: the transition process faces advances and setbacks impacted by the pace of technical development, user acceptance, political willingness, and the development of procedures and authorisations for the deployment of AVs and AMs. These processes may also vary from country, region and city.

The study identified that the main drivers boosting the development and deployment of AM address the pursuit of improving public transport, innovation strategy and competition, the window of opportunities established in the market, as well as the pursuit of sustainable mobility and re-design of the cities. The main obstacles concern the uncertainties about the environmental and energy impacts of automated driving and connectivity, the need for specific policies and regulations to steer the novelty to shared, electric and sustainable mobility, the need for standards and to assure safety, for instance, data protection, security, technical obstacles and technology maturity.

Based on these findings, we define five main mechanisms of transformation supporting the integration of AM in the mobility system and aiming to pave the way to a mobility transition with AM: technology maturity; social acceptance; changes in the governance approach; cooperation and new arrangements among stakeholders; policy instruments.

- ***Technology maturity and business models' feasibility, from niche to the regime***

Seen through the MLP perspective, the AM is featured at the niche level and at the first temporal phase, experimentation (Geels, 2019). As described as state of the art, the experimentation and current deployment of the AM is characterised by challenges in line with the ones described by Geels (2019): low speed, medium performance, small scale trials, technical challenges, elevated costs, the liability of the novelty, uncertainties concerning social acceptance, and the impacts on the mobility systems. The deployment of automated driving and AMs rely on long-term planning and investments in infrastructure, preparation of the institutions, urban planning, development of policies, regulations and standards, viable business models and larger social acceptance at the regime level. Thereupon, as pointed out by the stakeholders' interviews, the learning processes, cooperation and exchange among stakeholder groups are crucial.

- ***Social acceptance, from niche to the regime***

The acceptance of automated vehicles is a precondition for the deployment and diffusion of this innovation. With regard to the societal dimension of the AVs' transition, Milakis and Müller (2021) suggest the extension of the research from consumers' adoption to citizens' acceptance and from short-term to long-term societal implications of AVs.

The results of the large-scale survey show that about half of the citizens present positive goodwill toward the AM by acknowledging the increased flexibility of transportation as the main benefit. Conversely, the unknown effects of AM on other road users and the case of unforeseen situations are significant factors for a sceptical attitude. What is also important is the fact that citizens consider the AM offering on-demand and door-to-door services a potential alternative to reduce the use of private cars. The AM could foster the shift to shared and integrated public transport options in this perspective. The positive attitude and experience towards the AM are also reported in other studies, as by Nordhoff et al. (2018), Bernhard et al. (2020), Feys et al. (2020).

- ***Governance approach at the regime level***

The importance of new governance structures and new governing approaches from public authorities to improve mode integration and to develop MaaS schemes is considered one of the pillars targeting mobility transitions and sustainability.

Hirschhorn et al. (2019) address different governance approaches to develop the MaaS system, from hands-on strong intervention to hands-off soft scoping. In addition, Audouin and Finger (2019) point to the importance of having national and local governments' participation in order to have a shift from a 'governing by doing' and 'laissez-faire approach', in which public authorities are limited, have limited or non-interactions with private actors to a 'governing by enabling' approach. Public authorities facilitate and encourage actions with non-public actors in the latter approach.

Governing by enabling and hands-on approaches from public authorities play a crucial role in better system integration and intermodality, system innovation with AM and MaaS, infrastructure adaptation and sustainable urban planning. The new governance approaches could foster a 'purpose-driven governance' (based on the purpose economy concept by Hurst, 2016), which targets decision-making and planning to create purpose and value for society, serving wellbeing and the general interest.

- ***Cooperation and new arrangements among stakeholders at the niche-regime space***

The interplay among manufacturers, software developers, public transport authorities and urban planners can entail learning processes, standardisation and guidelines. Such aspects contribute to shifts and mitigate resistance at the regime level, which is frequently portrayed as the locus that reproduces institutionalised practices and resists the development of niches (Smith et al., 2010; Geels, 2014; Hirschhorn et al., 2019). In this regard, pilot projects deploying the AM contribute to paving the way for this second temporal phase, the stabilisation of the innovation (Geels, (2019).

The study points out that the main and active stakeholders currently developing and shaping the implementation of the AM are the PTO, manufacturers, software developers, city government, public transport authorities, policymakers and citizens. The current arrangement is in line with the 'shared transition pathway' described by Marletto (2019), characterised by the cooperation between leaders of the internet system, artificial intelligence and managers of shared and collective transport systems. In addition, this arrangement could mitigate the 'winner-take-all' effect. Moreover, the different stakeholder sectors present different discourses and perspectives towards the AM. For instance, members of the city government tend to analyse the deployment of the AM, focusing on the citizens' needs, safety and well-being, spatial planning and green areas. The PTO see the AM as part of their innovation strategy and competition and the offer of a sustainable solution as a secondary purpose. The NGO actors constantly raised questions about the role of technology on society, the environment and the energy system, as well as the need to go beyond the technology point of view to apply policies that can steer the use of technology to better and greener mobility. In general, the discourse of manufacturers and software developers is also aligned to the cities' goals towards more efficient and sustainable mobility

and the use of technology to optimize and improve mobility services, which follows a customer-centric approach.

Considering the interaction between technology and society as a dialectical process (Milakis and Müller, 2021), besides the main and active stakeholders previously mentioned, this study pinpoints the importance of strengthening the interactions and cooperation with policymakers, urban planners and public transport authorities in order to:

- i) better prepare these professionals and consequently the mobility transitions
- ii) steer the use of the AM to desired changes in the urban mobility and spatial planning of the cities, e.g. fewer congestions, more green areas, less pollution and emissions
- iii) develop the policy instruments aiming at a transition to sustainable mobility.

Likewise, it is also important to broaden the participation of civil society associations, NGOs, and driver unions by creating spaces for debate and means of participation. For instance, the citizens' forums and consultations are instruments to foster a citizen-centric approach to mobility.

- ***Policy instruments at the niche-regime space***

It is also worth endorsing that beyond the deployment of new mobility technologies, a balanced combination of diverse policy instruments is required to address sustainable transport (Kuss and Nicholas, 2022). It is normally crucial to implement both push and pull measures: i) push measures: such as restricting and/or discouraging private motorised transport, parking policies, road pricing, and congestion management, ii) pull measures: promoting the use of public transport, cycle lanes and pedestrian zones, and mode integration. As described by Thaller et al. (2021), the policy instruments embrace:

- Planning instruments: policies to support long-term planning and development of infrastructure provision and spatial planning, for instance.
- Command-and-control instruments: rely on regulation and monitoring actions, such as transport restrictions or standards.
- Incentives: such as subsidies and financial offers, and inducements aiming to support specific behaviours, and they include attractive infrastructure.

We argue that the AM in MaaS is a pull measure that could be sufficient to enhance mode integration, attractive public transport and technology improvements. Such pull measures present high public acceptance (see above) and high policy effectiveness, according to Thaller et al. (2021); therefore, it could possibly prevent unpopular push measures. This should of course be deepened in further research. In addition, considering the Avoid-Shift-Improve (A-S-I) concept (GIZ, 2019), the AM in MaaS could support a shift towards more environmentally friendly and integrated modes as well as improvements in energy efficiency and optimisation of mobility systems. Last but not least, AM in MaaS could enable value creation depending on the contribution of each stakeholder, thus avoiding a market-dominant position and "the winner takes it all" phenomenon and contributing to sustainable

societal transformations to answer to societal challenges (the so-called “purpose”) (Fournier et al., 2022).

Finally, it is important to note that this study presents some limitations. For instance, the topic of investigation focuses mainly on automated minibuses and public and private transport, and not necessarily on AVs deployed as robotaxis or individual transport. The integration of AM in MaaS must further be deepened and will be the aim of ULTIMO, a new Horizon Europe project (2022-2024) where a customer-centric approach and the integration of logistics will be analysed. Most of the stakeholders interviewed were based in the European Union; therefore, a European perspective is overrepresented. Although main stakeholder groups were interviewed for this study, there is room to enlarge the analysis and include other stakeholder groups and sectors concerning the future of automated driving in urban mobility. Such topics are the object of future research.

6.6 CONCLUSION

Our findings support the vision that the AM integrated into public transport and MaaS systems, and combined with other niche innovations - such as shared, connected, electric, on-demand mobility, and Intelligent Transportation Systems (ITS) - gain momentum to provoke regime shifts from the conventional individual combustion engine car to intermodal and individualised public transport. Therefore, the AM as product innovation integrated into a MaaS can be seen as a game-changer in the transport system and as part of the solution for a socio-technical transition towards a system innovation and a new mobility paradigm. This vision is in line with the study by Fournier et al. (2022), in which the authors present a pathway for the integration of AM into a citizen-centric MaaS system coupled with Intelligent Transport Systems (ITS).

Primary stakeholders involved in the development and deployment of AVs and AMs are public transport operators, manufacturers, software developers, public authorities, citizens and end-users. Secondary and tertiary actors are, for instance, suppliers, driver unions, environmental NGOs, citizens’ associations, and research institutes. The common goals among the diverse stakeholder groups when addressing AVs and AMs comprise safety, security, efficiency, shared and environmental friendly mobility. Stakeholders such as manufacturers, software providers and PTO addressed their market-oriented objectives to improve their products and solutions, place themselves in the market and keep competitive, in addition to offering solutions for societal and environmental benefits. Other groups such as policymakers and urban planners, driver unions, NGOs and citizen associations addressed as primary goals people-centred planning, citizens’ participation, promotion of public transport and active modes, and environmentally friendly modes of transport.

Additionally, the main drivers leading the development and deployment of AM concern the improvement of public transport, innovation strategy and competition, the window of opportunities in the market, sustainable mobility and the perspective to reshape the urban spaces. The main obstacles to the deployment of AM concern the uncertainties about the environmental and energy impacts of automated driving and connectivity and the need for

specific policies and regulations to steer the novelty to shared, electric and sustainable mobility. Further obstacles for AV/AM concern technology maturity and the need for standards to assure interoperability, safety, data protection and security.

Regarding the social acceptance of citizens, on the one hand, the unknown effects of automated minibuses on road users and unforeseen situations raise concerns. On the other hand, the increased flexibility of transportation is a factor that may increase social acceptance. Acceptance of citizens is mostly dependent on the (perceived) added values of the AM deployment, such as increased spatial and temporal flexibility and a reduction in travel time. The AM on-demand, offering door-to-door services and integrated into the public transport options is considered by citizens as a potential alternative to reduce the use of private cars. The complementarity of the different means of transport could lower negative externalities and enable positive externalities, for instance, through network effects and innovative uses of existing data targeting social welfare (Coyle and Diepeveen, 2021). Further, the AM can provide greater flexibility and better mobility connections, in addition to environmentally-friendly mobility. As pointed out by the environmental life cycle assessment study by Huber et al. (2022), future use cases of automated minibuses can present great advantages over individual vehicles depending on their average utilisation, lifetime and total mileage, the electricity mix used, and the substituted means of transport.

Additionally, the study pointed out five main mechanisms to pave the way to a mobility transition with AM through the lens of the multilevel perspective of socio-technical transition, namely: i) technology maturity and business models' feasibility, from niche to the regime; ii) social acceptance, from niche to the regime; iii) changes in the governance approach and purpose-driven governance at the regime level - towards governing by enabling and hands-on approach iv) cooperation and new arrangement among stakeholders at the niche-regime space; v) a combination of policy instruments and pull and push measures aiming at sustainable mobility transition at the niche-regime levels.

The outcome of this study is valuable for decision-makers at different levels and for the different stakeholder groups addressed in this research. It also helps policymakers decipher the long-term dynamics needed to transition towards the deployment of AV and AM in a sustainable mobility paradigm. Based on our findings, AVs and the AMs integrated into public transport and, in a later step in a MaaS can be framed on the reconfiguration pathway described by Geels and Schot (2007) and supported by Milakis and Müller (2021). In this path, the AVs, in combination with other symbiotic innovations adopted to solve local problems at the niche level, may trigger further adjustments and reconfigurations at the regime level. Furthermore, our findings are also in line with the transition scenario of transformation by Fraedrich et al. (2015). This scenario describes the hybridisation of individual and public transport by deploying automated mobility on-demand, in an attempt to tackle mobility externalities, and it is marked by the cooperation among actors to set a new mobility system.

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CHAPTER 7 GENERAL DISCUSSION AND CONCLUSIONS

This thesis investigated the role and impacts of shared automated vehicles, with a focus on automated minibuses, in the transition to sustainable mobility and a new mobility paradigm.

The conceptual foundations for the studies comprise the mobility paradigm, automated driving, sustainability assessment, technology assessment, sustainable mobility, socio-technical transitions, and the multi-level perspective approach. The methods applied build upon theoretical background, concepts, literature review, and empirical data from the pilot trials, the use of case studies, interviews and surveys.

This chapter summarizes and discusses the knowledge obtained in the context of this PhD, outlines the limitations, provides recommendations for future research and presents the final conclusions.

7.1 MEASURING THE IMPACTS OF SHARED AUTOMATED ELECTRIC VEHICLES ON URBAN MOBILITY

The evaluation of the impacts of SAEV on the mobility system requires a comprehensive set of criteria and parameters. In this regard, indicators are a powerful tool to quantify, analyse, and communicate complex information. In addition, indicators can embed the multidimensionality of sustainable mobility and are, therefore, a valuable tool for performing sustainability assessment and technology assessment.

The main outcome and contribution is the conceptualisation of a framework for assessment - the set of indicators for sustainability assessment of SAEV.

The study pointed out that the arrival of new technologies and innovations in mobility, such as SAEV, presents the opportunity to improve accessibility, affordability, environmental friendliness, and efficiency of mobility. However, new technologies and innovations have to be combined with suitable policies, viable business models, incentives, and new governance approaches to trigger positive changes in mobility and reduce mobility externalities.

Taking into account the need for a systemic approach for the assessment of SAEV, the sustainability assessment of the mobility sector requires inter and transdisciplinary approaches, which comprise different dimensions, such as social, environmental, economic, governance, technological and system performance. In this regard, the use of indicators for assessment could provide a quantitative significance to the goals of sustainability, which clarifies the observance and achievement of these goals.

The application of the set of indicators to assess SAEV can enable better impact estimates based on real data as well as the communication and comparison of results with baseline scenarios, thereby providing a sound basis for decision-makers to decide the contexts to

deploy SAEV, and to design and plan transportation policies.

7.2 THE CURRENT PERFORMANCE AND IMPACTS OF AM, THEIR CONTRIBUTIONS AND RECOMMENDATIONS TO SUMP AND FUTURE PERSPECTIVES

The study performed the sustainability assessment of the deployment of automated minibuses from pilot trials in European cities. The assessment builds upon the set of indicators conceptualised in this thesis and case studies grounded on empirical data. A selection of indicators was made according to data availability from the pilot sites.

The main outcomes and contributions of the study comprise the sustainability assessment of the current deployment of AM and potential future scenarios. The assessment is based on real-world data and empirical cases from pilot trials deployed in European cities. In addition, it developed the premises and recommendations for the sustainable deployment of the AM within mobility systems according to Sustainable Urban Mobility Planning (SUMP) approach.

The key takeaways point out that at the current stage, the performance and deployment of the AM in the pilot sites present similar performances among the measured indicators rather than significant differences.

The results from the sustainability assessment of AM indicate that they have yet limited performance concerning the different indicators assessed. For instance, the AM score poorly on 'low contribution to climate change' and 'energy efficiency', mainly due to the low vehicle occupancy. The economic profitability of AM is still low due to the elevated costs of feasibility studies and legal authorisations, infrastructure adaptations, high annual depreciation and salaries for on-board safety drivers. The performance is limited to low speed, and low system integration since the AM are temporary pilot trials. However, the social acceptance indicator pointed out goodwill from potential users towards using the AM.

The limited performance of the AM is also explained by the experimental nature of the pilot sites and the Covid-19 restrictions. Our study indicates that the current performance of the AM does not fulfil all the premises for sustainable mobility. Yet, overall the AM prove to be feasible as new alternative mobility by offering new services, improving the transport network and supporting cities to achieve sustainable mobility under certain premisses that are aligned with SUMP, such as:

- The AM 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 consequently a better performance in climate change and energy efficiency, reduction of the risks of induced demand and of increase in vehicle kilometres travelled.
- The development of policy instruments and push and pull measures as levers for a

mobility shift towards public transport-centred MaaS.

- To develop tools to enhance citizens' participation in mobility planning, as living labs and citizen forums.
- The assessment of the current and future performance, assessment of scenarios and setting goals for the deployment of AM aiming at sustainable mobility.
- Institutional cooperation is a key factor. Cooperation among transport operators, companies (as the vehicle manufacturer, and software providers), and the municipality and public transport authorities is crucial to achieving a beneficial deployment for the city.
- To keep an integrated vision of the mobility system. Thus, AM are enablers within the mobility ecosystem, supporting intermodality, MaaS, mobility hubs and the use of soft modes of transport.

The perspective is that AM could be integrated into urban mobility to improve the transport network, cover mobility gaps, foster intermodality by substituting motorised vehicles and offering on-demand and door-to-door services. Indeed, AM could support the MaaS approach, electrification, and shared mobility, and according to the recommendations in our study, they can foster SUMP and the sustainable agenda of cities.

7.3 THE STAKEHOLDERS, THEIR PERCEPTIONS AND INTERACTIONS CONCERNING THE INTEGRATION OF AVs AND AM IN THE MOBILITY SYSTEM. THE ISSUES AT STAKE AND MECHANISMS FOR A TRANSITION

Automated vehicles, and more specifically automated minibuses integrated into the transport system, are analysed in this study as a breakthrough technology through the perspective of different stakeholder groups and citizens. Our research approach builds upon conceptual mapping and semi-structured interviews with main stakeholder groups (n= 30) and a large-scale survey with citizens in four European cities (n= 1816). The stakeholder groups interviewed comprise: transport operators, Original Equipment Manufacturers (OEM), software providers, component supplier, government, NGO, driver union, citizens association, safety driver of the AM.

The main outcomes and contributions comprise a stakeholders map and identifying their interactions, goals and perceptions concerning the automated driving and (public) transport provision. The study also identifies the main drivers and barriers to the deployment of AM. It analyses and interprets further the socio-technical transitions in the mobility sector with the integration of AVs and AMs through a multi-level perspective (Landscape, Regime and Niche). Lastly, the study develops the mechanisms for a transition in the mobility systems with the integration of AM.

The key findings support the vision that the AM integrated into public transport and MaaS systems and combined with other niche innovations - such as shared, connected, electric, on-demand mobility, and Intelligent Transportation Systems (ITS) - gain momentum to provoke regime shifts from the conventional individual combustion engine car to intermodal and individualised public transport.

The primary stakeholders involved in the development and deployment of AVs and AMs are public transport operators, manufacturers, software developers, public authorities, citizens and end-users. Secondary and tertiary actors are, for instance, suppliers, driver unions, environmental NGOs, citizens' associations, and research institutes. The common goals among the diverse stakeholder groups when addressing AVs and AMs comprise safety, security, efficiency, shared and environmental friendly mobility. Stakeholders such as manufacturers, software providers and PTO addressed their market-oriented objectives to improve their products and solutions, place themselves in the market and keep competitive, in addition to offering solutions for societal and environmental benefits. Other groups such as policymakers and urban planners, driver unions, NGOs and citizen associations addressed as primary goals a people-centred planning, citizens' participation, promotion of public transport and active modes, and environmentally friendly modes of transport.

Furthermore, the main drivers leading the development and deployment of AM concern the improvement of public transport, innovation strategy and competition, the window of opportunities in the market, sustainable mobility and the perspective to reshape the urban spaces. The main obstacles to the deployment of AM concern the uncertainties about the environmental and energy impacts of automated driving and connectivity and the need for specific policies and regulations to steer the novelty to shared, electric and sustainable mobility. Further obstacles for AV/AM concern technology maturity and the need for standards to assure interoperability, safety, data protection and security.

Regarding the social acceptance of citizens, on the one hand, the unknown effects of automated minibuses on road users and unforeseen situations raise concerns. On the other hand, the increased flexibility of transportation is a factor that may increase social acceptance. Acceptance of citizens is mostly dependent on the (perceived) added values of the AM deployment, such as increased spatial and temporal flexibility and a reduction in travel time. The AM on-demand, offering door-to-door services and integrated into the public transport options, is considered by citizens as a potential alternative to reduce the use of private cars.

Finally, the study pointed out five main mechanisms to pave the way to a mobility transition with AM through the lens of the multilevel perspective of socio-technical transition, namely: i) technology maturity and business models' feasibility, from niche to the regime; ii) social acceptance, from niche to the regime; iii) changes in the governance approach and purpose-driven governance at the regime level - towards governing by enabling and hands-on approach iv) cooperation and new arrangement among stakeholders at the niche-regime space; v) a combination of policy instruments and pull and push measures aiming at sustainable mobility transition at the niche-regime levels.

To summarise the findings and discussion figure 9 illustrates the potential contributions and added value of the automated minibuses to the different levels: from vehicle, to mobility system, urban system and society. In addition, figure 10 presents socio-technical system for road transportation from the current to the new mobility paradigm, in which the automated minibuses should be a game-changer and a support for sustainable mobility and the new mobility paradigm.

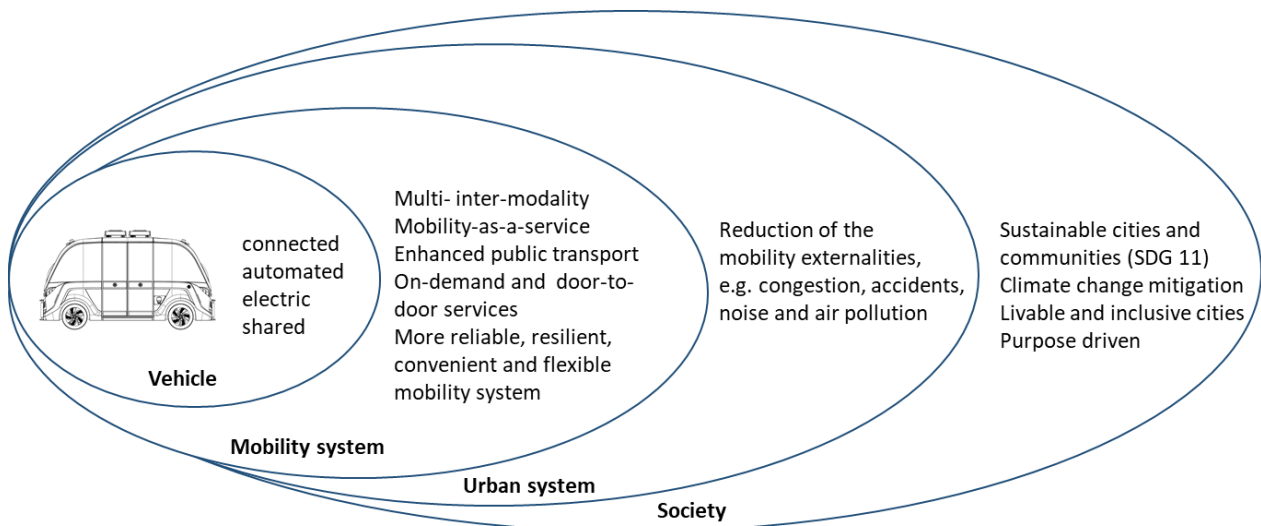


Figure 9. Added value of the AM to different levels – from vehicle, to mobility system, urban system and society

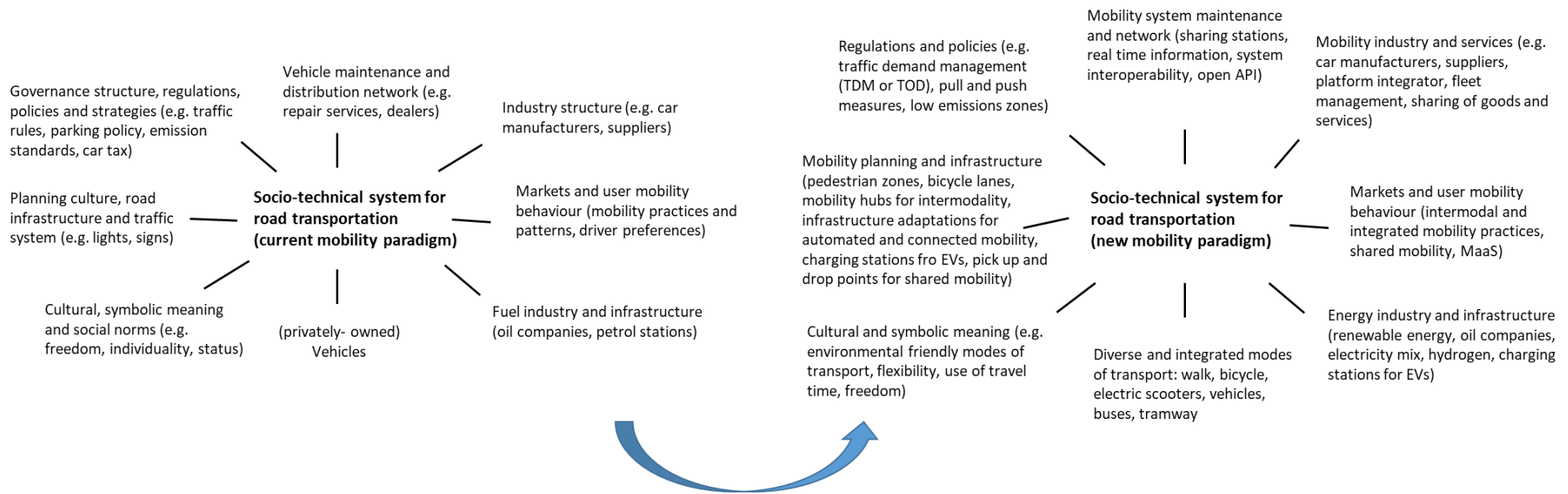


Figure 10. Transition in the socio-technical system for road/passenger transportation, left figure adapted by the author by Geels (2017) and Catinez (2019), right figure developed by the author.

7.4 APPLICATIONS OF FINDINGS

The knowledge obtained by the present thesis could be used by academics and practitioners who envision the deployment of AVs and AM to contribute to the attractiveness and sustainability of public transport and the mobility system in general. The findings contribute to theoretical and experimental approaches in sustainable mobility, automated driving, transitions in mobility, and changes in the mobility paradigm.

The set of indicators for sustainability assessment of SAEV is a useful framework for researchers and decisionmakers to measure the impacts of SAEV, compare the performance of SAEV in different contexts, and compare SAEV to other modes of transport. The framework is also valuable for communicating the results, setting targets and goals, and producing more accurate impact estimates based on real data. The results of the assessment can guide academics and practitioners in the design and planning of transportation systems and strengthen sustainable mobility policy responses.

The insights resulting from the analysis of the AM integrated into the mobility system through the lens of socio-technical transitions and multi-level perspective are valuable for different stakeholders involved directly or indirectly in the deployment of AVs, since the deployment of AVs may bring changes that concern the cities and citizens. The outcomes of the stakeholder analysis, the identification of drivers, barriers and mechanisms for a transition pathway for the deployment of AV and AM are valuable for decisionmakers, policymakers, urban planners, mobility providers and operators.

The outcomes can help such stakeholders at different levels to decipher the long-term dynamics – the perspectives, drivers, barriers, levers and mechanisms at stake - needed to transition towards the deployment of AV and AM towards a sustainable mobility paradigm.

7.5 LIMITATIONS

Part of the research work developed in this thesis was developed under the H2020 AVENUE project. On the one hand, this fact facilitated access to empirical data and primary data for the studies, as well as the constant and direct dialogue and exchanges with different actors involved in the deployment of automated vehicles and automated minibuses. These elements supported the richness and quality of the studies. On the other hand, it is worth acknowledging that within the frame of AVENUE, the setting up of the research topics presented a focus on the automated minibuses and on the demonstrator cities of the project.

In addition, the main limitations of the ensemble of studies that constitute this thesis are addressed in detail in chapters 4, 5, and 6. These chapters contain the main contributions of the thesis. Therefore, it is provided hereinafter a summary of the studies' limitations.

First, the conceptualised set of indicators to measure the impacts of SAEV on the mobility system was, so far, applied to pilot trials. Such trials are characterised by small-scale tests and are not yet completely integrated into the urban mobility systems. However, the framework developed can be applied to assess and benchmark wider deployments and

larger projects testing SAEV, considering that the scale of the trials will evolve.

Second, the sustainability assessment of the automated minibuses deployed in the pilot sites of the AVENUE project was impacted by:

- i) technological limitations, such as levels 3 and 4 of driving automation and low speed
- ii) limitations in infrastructure and gaps in regulations to deploy AVs
- iii) the application of the indicators was limited to data availability and data asymmetry from the pilot sites
- iv) also significant, all the pilot trials 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.

Third, the study addressing the socio-technical transitions in mobility with AV and AM included interviews with different groups of stakeholders. Most of the stakeholders interviewed were based in the European Union; therefore, a European perspective is overrepresented. In addition, there is room to enlarge the analysis by either conducting more interviews or including other stakeholder groups, also from other locations, to discuss the future of automated driving in urban mobility.

Finally, the topic of investigation in this thesis focuses mainly on automated vehicles and automated minibuses to be integrated into public transport and in MaaS – which would provide integration with public and private mobility alternatives. The main investigation does not embrace AVs deployed as robotaxis for individual rides or AVs as individual-owned vehicles.

7.6 PERSPECTIVES ON FUTURE RESEARCH

The research on automated driving has been evolving over the past few years, and there is a large room for future research. With regards to the topics addressed in this thesis, future research could apply the set of indicators to measure the impacts of SAEV integrated into the mobility system, considering different forms of deployment, contexts and in larger-scale projects deploying a fleet of AVs. The next endeavours in trial projects aim to deploy AV and AM in larger fleets, improve fleet management and efficiency (e.g. right-sizing vehicles and matching shared rides), better integrate mobility services - including private and public, non-motorized and motorized - for passengers, and include on-demand and door-to-door services.

Furthermore, the set of indicators for the sustainability assessment of SAEV is a valuable framework for planners and decision-makers to set the targets to be achieved and measure and monitor the progress. Therefore, collecting data and measuring the performance of the

deployment of SAEV over time is crucial to investigate how the innovation evolves and how and if it contributes to the sustainable mobility of cities.

In addition, assigning weight to the indicators could account for the different contexts and priorities of the cities. Weighting the indicators would involve the consultation of different stakeholders in each city, such as public transport operators and authorities, urban planners, decision-makers, etc. Moreover, weighting the indicators will be helpful when aiming to aggregate indicators into a composite measure.

Future research could also investigate AV and AM integrated into MaaS and ITS. In this regard, a diversity of aspects could be explored, such as the governance models and structures, energy and environmental impacts, changes in land use and spatial planning, business models, social acceptance and changes in mobility behaviour, interoperability and technical performance, among others. Furthermore, besides the transport of passengers, AV and AM could serve the transport of goods, for instance, in off-peak hours. Synergies between MaaS and LaaS (Logistics-as-a-service) should be explored.

As technology and trial projects advance, future research will rely upon more empirical data to better assess and estimate the impacts of AVs and develop scenario planning. Future research could further develop the pathways for transition to the new mobility paradigm using different lenses for analysis and interpretation, such as socio-technical transitions, transition management, multi-level perspective, nested governance, socio practice theory, responsible innovation and others. Future research on AV and AM may address new governance approaches and structures, participatory approaches, and the combination of policy instruments and measures to provoke shifts in the mobility paradigm and enhance sustainable mobility.

7.7 FINAL CONCLUSIONS

The present thesis investigated the role and impacts of shared automated vehicles - with a focus particularly on automated minibuses - in the transition to a new sustainable mobility paradigm. The ensemble of studies used both theoretical and empirical approaches, and the knowledge obtained could be used by academics and practitioners who envision the deployment of SAEV and AM to contribute to the attractiveness and sustainability of public transport and the mobility system in general.

The studies carried out corroborate that SAEV coupled with other innovations and approaches (governance, policies, changes in mobility preferences and behaviour) can bring significant changes in the mobility landscape. Depending on the mode of deployment and level of integration of SAEV within the mobility system, the technology could either mitigate or aggravate mobility externalities. Therefore, the assessment of the deployment and performance of SAEV within the mobility system is a key element to plan, monitor, put in practice and achieve sustainable mobility. For this purpose, frameworks for assessment, as the multi-dimensional set of indicators conceptualised, can support the assessment over time, the comparison among deployment cases, communication and decision making to deploy technologies in mobility to serve common goals and the general interest for

sustainable and liveable cities. The assessments are based on sustained data collection from empirical deployments and can support better model assumptions and impact estimates. In addition, the impact assessment is one of the pillars of SUMP.

Further, the sustainability assessment of the pilot trials revealed that at the current stage, the automated minibuses have yet limited performance concerning the different indicators assessed. The technology is under development, and the pilot trials are characterised by the experimental nature. Some premises for more sustainable deployment of the automated minibuses refer to higher average occupancy, technological improvements, cooperation among stakeholders, participatory approaches, better integration of the mobility system, as well as policy instruments, pull and push measures aiming at a system innovation and a shift from a car based and private mobility to public transit and intermodal mobility.

The main findings in this thesis pointed out five mechanisms to pave the way to a mobility transition with AM interpreted through the lens of multi-level perspective and socio-technical transition. The mechanisms are: i) technology maturity and business models' feasibility, from niche to the regime; ii) social acceptance, from niche to the regime; iii) changes in the governance approach and purpose-driven governance at the regime level - towards governing by enabling and hands-on approach iv) cooperation and new arrangement among stakeholders at the niche-regime space; v) a combination of policy instruments and pull and push measures aiming at sustainable mobility transition at the niche-regime levels. Such mechanisms help decision-makers, and policymakers decipher the long-term dynamics needed to transition towards the deployment of AV and AM in a sustainable mobility paradigm.

The thesis emphasises that it is crucial to keep an integrated vision of the mobility system. Thus, the automated minibuses can be seen as a game-changer and enabler within the mobility ecosystem to support intermodality, MaaS, mobility hubs and the use of soft modes of transport. 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. Indeed, the automated minibuses could support the MaaS approach, electrification, and shared mobility, and according to the recommendations in our study, they can foster SUMP and the sustainable agenda of cities.

The automated minibuses integrated into public transport and MaaS systems and combined with other niche innovations gain momentum to provoke regime shifts from the conventional individual combustion engine car to intermodal and individualised public transport. Therefore, the AM as product innovation integrated into a MaaS can be seen as a game-changer in the transport system and as part of the solution for a socio-technical transition towards a system innovation and a new mobility paradigm.

APPENDICES

APPENDIX A. ANALYSIS OF THE FREQUENCY OF INDICATORS

Table A1. Analysis of the frequency of indicators according to 18 studies of methods considered for in depth analysis in the integrated literature review.

Category	Sub-category	Indicators	Frequency	Data source
Social : 16 studies out of 18	Safety	Traffic fatalities (injuries and death) Number of fatalities and injuries in each mode of transport Road fatalities Active level crossings Transit safety Working condition: accident, precarious employment conditions	14 out of 16	(Litman, 2007) (GMR, 2017) (UNECE, 2011) (Ecomobility, 2017) (Deloitte, 2018) (WBCSD,2015) (Arcadis, 2017) (Dobranskyte et al, 2009) (Gruyter et al., 2016) (Zheng et al,2013) (Litman, 2018) (OCDE,1999) (SCTRB,2008) (Gilbert,2005)
	Affordability	Household spending on transport The price of transport Affordability of public transport Transit affordability	12 out of 16	(Litman, 2007) (UNECE, 2011) (Lyon Regional's Indicator Mobility, 2003) (Deloitte, 2018) (WBCSD,2015) (Arcadis, 2017) (Dobranskyte et al, 2009) (Gruyter et al., 2016) (Zheng et al,2013) (Litman, 2018) (Gilbert,2005) (SCTRB,2008)
	Accessibility	Proportion of population that has convenient access to public transport, by age, sex and persons with disabilities (SDG 11.2.1) Access to public transport Accessibility commute costs time and money Accessibility quality of transit, taxi availability, cycling, walkability Internet accessibility and delivery service quality Access to basic services Car independence	10 out of 16	(GMR, 2017) (Deloitte, 2018) (WBCSD,2015) (Arcadis, 2017) (Dobranskyte et al, 2009) (Gruyter et al., 2016) (Zheng et al,2013) (Gilbert,2005) (SCTRB,2008) OCDE, 1999
	Accessibility for impaired	Quality of transport for disadvantaged people (disabled, low incomes, children, etc.) Accessibility for impaired Wheelchair access Universal design (consideration of disabled people's needs in transport planning)	6 out of 16	(Litman, 2007) (WBCSD,2015) (Arcadis, 2017) (Litman, 2018) (Gilbert,2005) (SCTRB,2008)
	User satisfaction	Overall satisfaction rating of transport system (based on objective user surveys) Customer satisfaction User rating User satisfaction	4 out of 16	(Litman, 2007) (Deloitte, 2018) (Litman, 2018) (SCTRB,2008)
	Security	Terror threats indicator Criminal activities Vehicle thefts and other crimes Security in public transportation	3 out of 16	(Unece 2011) (WBCSD,2015) (Gilbert,2005)

	Health	Fitness Walking or biking sufficiently for health	3 out of 16	(Litman 2007) (Litman 2018) (Gilbert,2005)
	Cultural and social values	Community cohesion (quality of interactions among neighbours) Degree cultural resources are considered in transport planning Social interaction Cultural preservation Cultural degradation by transport facilities	4 out of 16	(SCTRB,2008) (Litman 2018) (Zheng et al 2013) (Litman 2007)
	Social equity: no discrimination based on sex, religion, colour livability	Social equity Community livability Children's travel Livability: walkability Equity: fairness horizontal equity Equity: income vertical equity	3 out of 16	(Zheng et al 2013) (Litman,2018) (Gilbert,2005)
Environmental: 18 studies out of 18	Energy consumption	Transport final energy consumption by mode Energy efficiency and specific CO ₂ emissions Energy consumption in transport Structure of road energy consumption by type of fuel	9 out of 18	(Litman,2007) (TERM) (UNECE,2011) (Nicolas,et al. 2003) (Cebr) (Gruyter et al 2016) (Zheng et al 2013) (OCDE,1999) (Gilbert,2005) (Chen et al., 2017)
	Air pollution	Per capita air pollution emissions (various types), disaggregated by mode Annual premature deaths due to air pollution and physical inactivity from transport-related sources Population exposed to air pollution from transport Transport emissions of air pollutants Exceedances of air quality objectives due to traffic Levels of CO, NO _x , hydrocarbons and particles (in g/m ² , total and per resident) NO _x from road traffic (Kg) NO _x per capita (kg/cap) PM ₁₀ (particulate matter) from road traffic (Kg) PM (particulate matter) per capita (kg/cap)	15 out of 18	(Litman,2007) (GMR,2017) (TERM) (Nicolas,et al. 2003) (Eco mobility SHIFT)(TOI) (Deloitte) (WBCSD) (Cebr) (Arcadis) (Zheng et al 2013) (Gruyter et al 2016) (Litman, 2018) (OCDE,1999) (SCTRB,2008)
	Climate change and GHGs emission	Global GHG emissions from the transport sector (GT CO ₂ e) CO ₂ -emissions from road traffic (Ton) CO ₂ -emissions from road per capita (kg/cap) Amount change CO ₂ -emissions (mobile sources), 1991-2009 Ton	14 out of 18	(GMR, 2017) (TERM) (UNECE,2011) (Eco mobility SHIFT) (TOI) (WBCSD,2015) (Cebr) (ARCADIS) (Dobranskyte et al, 2009) (Zheng et al 2013) (Litman,2018) (OCDE,1999) (SCTRB,2008) (Gilbert,2005)

	% change CO ₂ -emissions (mobile sources) 1991-2009		
Noise pollution	Percentage of urban dwellers exposed to Lden/Lnight noise levels from transport above 55dB/40dB (percent of total inhabitants) Population exposed to transport noise greater than 65dB Traffic noise: people exposed to traffic noise above 55 LAeq,T	10 out of 18	(Litman, 2007) (GMR,2017) (TERM) (UNECE,2011) (Nicolas,et al. 2003) (WBCSD,2015) (Litman,2018) (OCDE,1999) (SCTRB,2008) (Gilbert,2005)
Land use	Per capita land devoted to transport facilities Daily individual consumption of public space involved in travelling and parking (in m2.h) Space taken up by transport infrastructures Transport infrastructure/ urban dense area (%) Fragmentation of land Land area consumed by public transport facilities	9 out of 18	(Litman,2007) (Nicolas,et al. 2003) (TOI) (Gruyter et al 2016) (Zheng et al 2013) (Litman,2018) (OCDE,1999) (SCTRB,2008) (Gilbert,2005)
Water pollution	Water pollution emissions	3 out of 18	(Litman,2007) (Litman,2018) (Gilbert,2005)
Habitat and ecological impact	Habitat preservation Impacts on special habitats and environmental resources Functional diversity Habitat fragmentation Ecological habitat degradation Collision with wildlife Introduction of alien species	7 out of 18	(Litman,2007) (WBCSD,2015) (Zheng et al 2013) (Litman,2018) (SCTRB,2008) (Gilbert,2005) (Dobranskyte et al, 2009)
Resilience to natural disaster	Impervious surface coverage and stormwater management practices Number of countries that have taken intentional action to build resilience against climate-related hazards and national disasters within the transport sector Resilience for disaster and ecologic/social disruption	4 out of 18	(Litman,2007) (GMR,2011) (WBCSD,2015) (Dobranskyte et al, 2009)
Alternative, renewable and clean energy	Use of renewable fuels Share of renewable energy in the transport sector Proportion of vehicle fleet by alternative fuel type	4 out of 18	(Litman,2007) (TERM) (Eco mobility SHIFT) (Dobranskyte et al, 2009)

		Low emission vehicles Renewables energy sources		
	Resource efficiency	Transport facility resource efficiency (such as use of renewable materials and energy-efficient lighting) Waste production Infrastructure materials consumption Vehicle materials consumption Generation of non recycle waste	4 out of 18	(Litman,2007) (Zheng et al 2013) (Litman,2018) (Gilbert,2005)
Economic 16 studies out of 18	Expenditure on mobility	Per capita mobility Total per capita transport expenditures (vehicles, parking, roads and transit services) Annual costs chargeable to residents of the conurbation Annual expenditures for investments and operates (total and per resident) Investement on mobility: transport budget Net public finance Public finance Economic subsidies Annual operating cost Infrastructure expediture Transport investments by mode	11 out 16	(Litman 2007) (Nicolas,et al. 2003) (Deloitte, 2018) (WBCSD,2015) (Arcadis,2017) (Gruyter et al 2016) (Litman 2018) (OCDE, 1999) (SCTRB,2008) (Gilbert,2005) Bongardt 2011
	External costs related to the transport system	Congestion costs	4 out of 16	(Litman 2007) (SCTRB,2008) (Litman 2018) (Gilbert,2005)
		Crash costs		
		External transport costs		
	External costs related to environment	Environmental damage cost relating to transport	3 out of 16	(Litman 2018) (CST,2003) (OCDE, 1999)
		Final energy consumption		
		Land use mix		
	Economic incentive related to energy consumption	Finance for ecomobility	4 out of 16	(OCDE, 1999) (Bongardt 2011) (Arcadis,2017) (Cebr,2017)
		Price of fuel to price of electricity ratio		
		Financial incentives for zero-emission vehicles		

		Minimum taxation on fuel		
		Relative taxation of vehicles and vehicle use		
		Structure of road fuel prices and taxation		
		Electric vehicles incentives		
	System efficiency	Mode split for personal travel	6 out of 16	(Gilbert,2005) (SCTRB,2008) (Litman 2018) (Gruyter et al 2016) (Deloitte,2018) (Litman 2007)
		Average commute travel time and reliability		
		Integration and shared mobility		
		Average time per trip		
		Passenger km travelled per unit GDP		
		Cost efficiency		
		Planning quality		
		Land use planning		
		Transport pricing efficiency and reforms		
	Economic profitability	Public revenues from taxes and traffic system charging	7 out of 16	(Litman 2007) (WBCSD,2015) (Arcadis,2017) (Dobranskyte et al 2009) (Gruyter et al 2016) (Litman 2018) (Gilbert,2005)
		Gross value added		
	Employment accessibility			
	Cost recovery (proportion of costs recovered)			
	Economic opportunity			
	Number of public services within 10-min walk and job opportunities within 30-min commute of residents			
Governance: 10 studies out of 18	Participation and consensus	Inclusive (substantial involvement of affected people, with special efforts to ensure that disadvantaged and vulnerable groups are involved)	3 out of 10	(Zheng 2013) (ICLEI, www.ecomobility.org) (Litman 2007)
		Public participation		
		Community involvement		
	Strategic vision and innovation	Vision, strategy and leadership	3 out of 10	(OCDE,1999) (Deloitte,2018) (ICLEI, www.ecomobility.org)
		Vision and innovation		
		Environmental sustainable initiative		
		R&D expenditure on clean transport fuels		

Planning and performance	Planning efficiency	6 out of 10	SCTRB,2008 (UNECE,2011) (Dobranskyte et al, 2009) (Cebr,2017) (ICLEI, www.ecomobility.org) (Litman 2007)
	Public investment on transport		
	Institutional development		
	Commitment to low emission agenda		
	Personnel and resources		
	Based on accessibility rather than mobility		
	Application of smart growth land use policies		
Accountability	Measures to improve transport sustainability	2 out of 10	(ICLEI, www.ecomobility.org)
	Monitoring, evaluation and review		
Transparency	Government interoperability	2 out of 10	(Zheng 2013) (Deloitte,2018)
	Regulatory environment		
Fairness and equity	Neutrality (public policies do not arbitrarily favor a particular mode or group) in transport pricing, taxes, planning, investment, etc.; applies least-cost planning	1 out of 10	(Litman 2007)

APPENDIX B. METHODOLOGY FOR THE INDICATORS

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. (2022), D8.9 Social impact assessment

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 rate.

Scale:

1 = very poorly rated/very dissatisfied

5 = very good rated/very satisfied

Calculation:

User satisfaction	
User rating concerning the ride experience	
Parameter value:	3,96
Indicator value	3,96

User rating concerning the ride experience		1	5
min scale	max scale		
1	5		

Obs: Example of Nordhavn (Copenhagen)

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

Passenger's affordability

Definition: Transportation affordability refers to 'household's ability to purchase basic mobility within its limited financial budget' (Litman 2021). 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).

Climate Change

Definition: greenhouse gases emitted by the AM per passenger-km

Parameter: gCO₂ 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.

gCO₂eq = grammes of CO₂ equivalent.

Methodology: the LCA study of the AM provided the GHG emissions (gCO₂ 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 (gCO₂eq/pkm) for two/three-wheelers, buses and minibuses, small/medium and large vehicles as individual transportation or public transport.

Scale:

1 ≥ 273 gCO₂eq/pkm (average operation of large ICECAV - internal combustion engine connected and automated vehicle)

5 ≤ 48 gCO₂eq/pkm (average operation of a battery electric bus - BEB)

Calculation:

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

gCO₂/pkm

Obs: Example of Pfaffenthal (Luxembourg)

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

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 minibus 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).

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 from Jochem et al. (2016) pointed 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 for 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 minibus 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 were 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 for a BEV, as 50 decibels in constant speed at 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. (2016), Cai (2012), Dudenhöffer, Hause (2012), Lelong and Michelet (2001).

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 (SO_x). 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 NO_x emissions (ibid).

The automated minibus is a BEV, and during the use phase, BEVs have zero exhaust emissions, e.g. NO_x 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 provokes 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 present 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:

PM2,5

1 ≥ 0.005 PM2,5 g/km

5 = 0 PM2,5 g/km

NOx

1 ≥ 0.08 NOx g/km

5 = 0 NOx g/km

PM2,5 Non exhaust

1 ≥ 0.0474 PM2,5 g/km

5 = 0 PM2,5 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 the table below.

Table 1. 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 × 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

Parameter value: 0,00

Indicator value 5,00

1	5
min scale	max scale
0,005	0

 PM 2,5 g/km

NOx

Parameter value: 0,00

Indicator value 5,00

1	5
min scale	max scale
0,08	0

 NOx g/km

Non exhaust

Parameter value: 0,01

Indicator value 4,03

1	5
min scale	max scale
0,0474	0

 Non exhaust PM2,5 g/km

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

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 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
Parameter value:	0,18	min scale	max scale
Indicator value	4,81	0,97	0,14

KWh/pkm

Obs: Example of Pfaffenthal (Luxembourg)

Sources: WBCSD (2015).

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 minibuses 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 from 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).

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 monetise 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)

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
- 2. Local territories autonomy
- 3. National sustainable development policy and declination
- 4. Governance and integration at local level”

The assessment is performed for the fours 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 2. The Road index

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 are 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.

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.

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 complement 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

i) Average occupancy

1 ≤ 1

5 ≥ 6 passengers

ii) Km driven autonomously

1 ≤ 60%

5 = 100%

Calculation:

Technical performance

Parameter value:	3,1
Indicator value	3,14

Speed

Parameter value:	17
Indicator value	2,89

1	5
min scale	max scale
6	25

 km/h

Frequency or response speed for on-demand

Parameter value:	15
Indicator value	3,57

1	5
min scale	max scale
40	5

 minutes

Average occupancy rate

Parameter value:	2,84
Indicator value	1,84

1	5
min scale	max scale
1	6

 passengers on board

Km driven autonomously

Parameter value:	94
Indicator value	4,25

1	5
min scale	max scale
60	100

 % km drive autonomously

Obs: Example of Pfaffenthal (Luxembourg)

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

Parameter value:	1
Indicator value	1,00

1	5
min scale	max scale
1	5

Obs: Example of Contern (Luxembourg)

Source: Sochor et al. (2018)

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 not 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		1	5
Parameter value:	27	min scale	max scale
Indicator value	1,36	0	100

Obs: Example of Nordhavn (Copenhagen)

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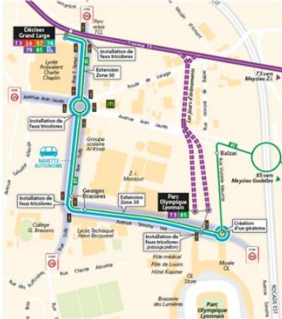
APPENDIX C. THE AVENUE PILOT SITES



The four case studies within AVENUE project

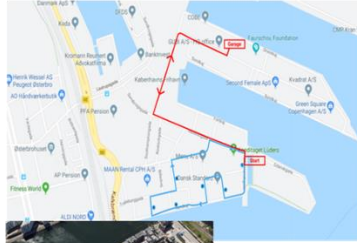
Fixed route, fixed stops, mixed traffic, aiming to extend the routes and provide on-demand services, full integration on public transport

Groupama Stadium, Lyon



Sportive and medical centre area, it contains also and offices
 Fixed route, 1,3km trip
 Passengers: regular workers, visitors, people with reduced mobility (medical centre nearby)

Nordhavn, Copenhagen



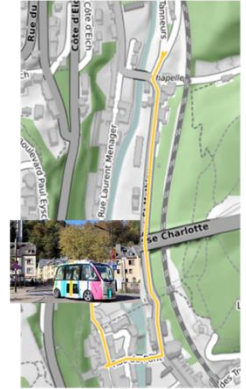
Industrial port area
 Fixed route, 1,2km trip
 Passengers: residents of the area, tourists

Pfaffenthal, Luxembourg



Residential area
 Fixed route 1,2 km
 Passengers: Workers, tourists, residents, and visitors of Luxembourg city

Contern, Luxembourg



Industrial area
 Fixed route, 2,2km
 Passengers: Employees working at Campus Contern

APPENDIX D. GUIDELINES FOR SEMI-STRUCTURE INTERVIEWS WITH STAKEHOLDER GROUPS

Key topics:

- Role of interviewee in organisation
- Introduction of organisation
- Perception on automated mobility
- Perception on automated minibuses integrated in public transport
- Barriers, risks, obstacles and solutions
- Resources
- Information behaviour
- Relation to other stakeholders

Guideline:

- To provide respondents a maximum level of openness the guideline determines the topics in detail but does not determine accurate direct questions.
- At the start of the interview, we ask for personal introduction & attitudes, in the remainder of the interview, we are interested in the perceptions, goals, resources etc. of the organisation.

General Introduction

about 5 min.

- Introduction to AVENUE (EU project, aim to demonstrate the usefulness of integrating automated minibuses in public transport, role of HS-PF, goal of stakeholder analysis, methodology of qualitative interviews)
- Data protection declarations
- Request for audio recording
- Use of citations for reporting
- Introduction of the interviewer

I. Warm-Up

about 5 min.

Aim: Introduction of the interviewee

- Professional background, professional career such as technical, economic, political, social, psychological background
- Current areas of responsibilities

II. Involvement, Attitudes, Expected Trends regarding mobility and automated mobility

about 10 to 20 min.

Aim: Identifying the interviewee's role within his/her organisation with regard to automated vehicles. Understanding the role and interests of the organisation.

How would you describe the role, the specific interests, strategic goals or even responsibilities of your organisation with regard to introducing and establishing automated public vehicles (minibuses in the first place) in your community/city? With regard to your own person but as well with regard to your professional tasks, what do you think about mobility in general, public transport and finally automated vehicles in particular?

CHECKLIST

- Description of organisation (public, private, civil society)
- automated mobility involvement concerning e-mobility, automated vehicles (core objective of organisation; are they open-minded, neutral, enthusiastic or skeptical)
- Future trends, developments concerning mobility in general: multimodal integrated mobility on demand and ticketing
- Expectations towards different target groups, attractive market segments, application fields
- Customers of organisation? Value they are proposing to add.
- End Users of automated vehicles (e.g. general public, scholars/commuters, tourists, shoppers, weekenders & 'night owls')

III. Perception on automated minibuses/pilot

about 10 to 20 min.

Aim: Involvement and perception on integration of automated minibuses in public transport

Now I'd like to go into more details concerning automated vehicles especially automated minibuses. You may know there will be a pilot in your city. What do you know about this pilot so far?

(If respondents are not yet involved, some prepared background information is given).

IV. Perceived barriers, risks, obstacles and solutions

about 10 to 15 min.

Aim: Identifying the barriers and obstacles that the interviewee's organisation perceives, and the solutions proposed to overcome these barriers

Which upcoming barriers and obstacles regarding automated public transport does your organisation foresee?

Checklist:

- Formal regulations (policies, rules, etc.)
- Cooperation with other actors
- Social acceptance
- improvement of technology
- Desired automation
- control and monitoring levels
- Level of acceptance of different service and business models
- Reduction in environmental impact
- Public vs. private mobility
- Security

V. Resources of interviewee's organisation

about 10 to 15 min.

Aim: Identify the resources that the interviewee's organisation possess to resources

What resources does your organisation possess that help to achieve the solutions proposed, what resources are missing?

Checklist:

- Financial resources
- Institutional resources
- Technical resources
- Social resources

VI. Identification of other Stakeholders, information behaviour

about 10 to 15 min.

Aim: Identifying important stakeholders

What other stakeholders/organisations does your organisation cooperate with, depend on, or have regular interaction with?

Which of these stakeholders are most crucial for enabling automated public transportation and why?

Checklist:

- Customers
- Partners for cooperation
- Stakeholders that they depend on for their success
- Public organisations, private companies, civil society organisations
- Opponents and supporters of AVENUE goals
- New competitors (Google, Apple, Uber, etc.)

VII. Information behaviour

about 5 to 10 min.

Aim: Identifying relevant sources for information

What sources of formal and informal information does your organisation rely upon?

Checklist:

- Formal and informal information
- Social networking
- Interaction with other stakeholders
- Important influencers
- Working groups, personal network

VIII. Wrap Up - Final Self-Reflection

about 5 to 10 min.

Aim: Invite interviewee to address topics that we have not yet touched upon

Thanks for your time and the information provided. Are there any themes/issues regarding automated public transport that you would like to discuss with us?

APPENDIX E. GUIDELINES FOR SEMI-STRUCTURED INTERVIEWS WITH THE SAFETY DRIVERS

Key topics:

- Description of the interviewee responsibilities and tasks
- Perception on automated minibuses and test sites
- The roles of the safety driver
- Description of the automated minibuses in practice
- Identifying the operational main challenges
- Description of the users' profile, behaviours and interactions

Guideline:

- To provide respondents a maximum level of openness the guideline determines the topics in detail but does not determine accurate direct questions.
- At the start of the interview, we ask for personal introduction & attitudes, in the remainder of the interview, we are interested in the perceptions, daily operations, challenges in practice, user's profile and behaviours.

General Introduction

about 5 min.

- Introduction to AVENUE (EU project, aim to demonstrate the usefulness of integrating automated minibuses into public transport, role of HS-PF, goal of stakeholder analysis, methodology of qualitative interviews)
- Data protection declarations
- Request for audio recording
- Use of citations for reporting
- Introduction of the interviewer

I. Warm-Up

about 5 min.

Aim: Introduction of the interviewee.

- Professional background, professional career
- Description of his/her responsibilities and tasks
- What your experiences are in transport/supervising the automated minibus?

II. Perception on automated minibuses

about 5 min.

Aim : Identifying the interviewee's perception on automated minibuses.

I'd like to know, personally, what do you think about mobility in general, public transport and what is your perception regarding automated minibuses?

CHECKLIST

- Safety drivers' personal perception
- Automated mobility involvement concerning e-mobility, automated vehicles (core objective of organisation; are they open-minded, neutral, enthusiastic or sceptical)

III. Integration into public transport and pilot projects

about 5 min.

Aim: Involvement and perception on integration of automated minibuses into public transport

What do you personally think about the integration of automated vehicles into the city transport system?

What do you personally think about the pilot tests in the city so far? From a more professional view, what do what think?

CHECKLIST

- Identification of main problems, solutions
- Personal opinion
- Professional opinion
- Are the buses already well integrated?

IV. The roles of the safety driver

about 5 min.

Aim : Understanding the role and importance of having a safety driver on board of the automated minibus.

From your perspective, how do you see yourself in the role of a safety driver? What is your self-perception as a safety driver?

CHECKLIST

- How important is it to have a safety driver on board?
- Reasons of having a safety driver on board
- Having a safety driver on board make people feel trust/safer?
- During the ride, is there a lot of interaction between you and the users?
- What requirements does a safety driver need to have?
- Importance of safety driver out of technical or more psychological reasons
- Privacy: Do the users feel disturbed by the safety driver or is it an advantage?

V. Description of the automated minibuses in practice

about 10 min.

Aim: Understanding how the daily operations of the automated minibus take place in the test sites.

Please, could you describe how the daily operations with the automated minibus take place?

CHECKLIST

- Description of a normal working day / bus service
- Responsibilities of the safety driver
- Description of the test sites
- Automated minibus performance (hours of work, occupancy, possible interruptions, causes of interruptions)
- Depth of customer contact (e.g. only small talk or are the operators answering a lot of questions)

VI. Description of the users' profile, behaviours and interactions

about 10 min

Aim: Identifying the users' profiles and understanding the interaction between human and the automated driving technology.

How would you describe the users' public? Do you perceive the predominance of a certain users' profile?

Please, could you describe the users' behaviours during the ride?

CHECKLIST

- User public/profile: aged people, young people, PRM, businessman, tourists, family, locals, etc.
- Users' behaviours: main questions, comments, reactions, perceptions on trust feeling
- On what day/time is the bus mostly used?
- Do users need help to get on the bus?
- Are they carrying special luggage with them (e.g. baby carriage etc.)
- Do they give personal feedback when they are about to leave the minibus?
- Are people getting on the minibus easily or do they hesitate?
- What are users doing during the ride? (look out of the window, talk to other passengers, reading, smart phone)
- Differences in the behaviour to a normal bus situation?
- Is the low speed a reason to not get on the bus?/ Are there complaints (e.g. that the minibus is too slow)?
- What users most like or dislike considering the ride experience
- Critical situations observed

VII. Focusing on people with special requirements /people with reduced mobility (PRM) about 5 min.

Aim: Analysing the use and needs of PRMs in the automated minibus.

Have you also experienced that people with reduced mobility (PRMs) use the automated minibus?

CHECKLIST

- Do PRM use the bus?
- Did they have problems, e.g. finding SOS buttons, driving and exit indicators, announcements etc.
- Are they in need of special requirements / help?
- Which aids did the PRMs carry with them (wheelchair, walking stick, guide dog, magnification glasses, talking smartphone)

- Is there a change in the situation compared to standard public transport?
- Did they give personal feedback?

VIII. Identifying the operational main challenges**about 5 min.**

Aim: Identifying the challenges on the daily operations of automated minibuses.

Could you tell us about the main challenges in the daily operations of the automated minibuses?

CHECKLIST

- Maturity of the technology, necessary improvements
- Frequent errors (do they lead to delays or are they just not convenient?)
- Necessary human interventions, frequency of interventions
- Risks of accidents/incidents, critical situations involving users
- Possible solutions

IX. Wrap Up – Final Self-Reflection**about 5 min.**

Aim: Invite interviewee to address the topics that we have not yet touched upon

Thanks for your time and the information provided. Are there any themes/issues regarding automated public transport that you would like to discuss with us?

APPENDIX F QUESTIONS AND METHODOLOGY FOR THE SURVEYS

Finally, the fourth concerns the representative survey with citizens in four European cities: Lyon, Geneva Copenhagen and Luxembourg. The representative survey is based on a fully structured questionnaire of 28 questions, questions comprised mobility behaviour and perceptions on AVs and AMs.

We applied a 5-point Likert scale for the majority of the questions. To not overburden respondents, an additional answer option (6) "I can't judge" or "I don't know" was added in specific questions. All questions were set as mandatory. The questionnaire was programmed using Questback/Unipark. The data was collected through online surveys, in the period from June – July 2021. The invitation to the survey was distributed through a sample bought from a specialised agency. Great care was taken that the sample was representative; based on gender and age distribution.

Concerning the data cleaning and sample structure, a total of 3,995 respondents were invited to participate in the survey. The geographic limit eliminated 1925 respondents from the sample. We checked the validity of the remaining responses via postcode areas. The data cleaning procedure consisted of three steps:

1. Deleting of records that took too long to respond.
2. Deleting of records that answered the survey too quickly
3. Deleting records that provided inconsistent answers.

Finally, 1816 records remained. The structure of the sample is diverse; we reached all age groups, female and male potential users, employees as well as students, households with or without children (Table 3). Our parent population consists of about 2 million residents with our geographical limit set at a radius of 30 kilometres from the city centre. Recognised calculators for sample sizes in this case recommend sample sizes of about n=1000.

The statistical program SPSS was used for data analysis.

Table 3. Sample structure

2021	
<i>Total respondents</i>	1816
<i>City</i>	Lyon: 501 Copenhagen: 491 Geneva: 284 Luxembourg: 540
<i>Age</i>	25% younger than 36 years 75% older than 36 years
<i>Sex</i>	53% Female 47% Male <1% Other/unknown
<i>Occupation</i>	55% Employee 24% Retired 6% Student 6% Self-employed 1% On maternity or paternity leave 1% On sick leave 7% Other
<i>Household composition</i>	62% do not have children in household 37% have children in household 1% refused to answer
<i>Own private car</i>	16% none 45% one car 39% more than one car
<i>Most frequently used</i>	59% own car

transport system

7% bus
4% train
13% bike
13% walking
10% other means of transport

The survey questions

What is your preferred mode of transport:

What is your preferred transport system

One answer only, please.

- Own car
- Motor bike
- Bus
- Train
- Metro
- Tram
- Taxi
- Shared taxi
- Taxi on demand (uber, Grab, etc)
- Car-sharing
- Bike
- E-bike/E-scooter
- Walking

Could you indicate what aspects are important in selecting your preferred means of transport?

Please rank the following items, with rank 1 as most important and rank 9 as least important (drag&drop).

- Comfort
- Accessibility, meaning can be used by all people
- Pleasure and joy
- Safety and trust feeling
- Environmental friendliness
- Punctuality
- Private atmosphere
- Price performance
- Speed and travel time

Have you ever heard of automated e-minibuses before participating in this survey?

- Yes, I have heard of automated e-minibuses before
- No, I have not heard of automated e-minibuses before

How important are the following services for you in using the automated minibus?

Please tell us on a scale from 1 to 5, where 1 means not important at all and 5 means very important. You can grade your answer with the other points on the scale.

- In-vehicle entertainment e.g. screens displaying the news
- In-vehicle information, e.g. information about the area where the automated minibus operates
- In-vehicle information about the performance, e.g. speed of the vehicle
- A safety operator on board
- An app that helps me to organize my journey
- Access to Wifi in the automated minibus
- Giving my feedback about the minibus service via QR codes in the vehicle
- Other

How much do you agree with the following statements?

Automated e-minibuses will...

Please tell us on a scale from 1 to 5, where 1 means fully disagree and 5 means fully agree. You can grade your answer with the other points on the scale.

- ... Provide enhanced freedom for people with reduced mobility issues
- ... Reduce the negative impact on the environment
- ... Increase flexibility by an increase in locations to get on public transport
- ... Be used for routes that are less popular
- ... Increase flexibility by an increase in frequency of public transport
- ... Guarantee security due to installed video cameras inside the bus
- ... Be successfully integrated into the public transport system
- ... Be booked on-demand in the future
- ... Reduce congestion
- ... Be pleasant and comfortable
- ... Be more efficient, as you would be able to use your time better than in a car, walking or cycling
- ... Cause fewer accidents, as they avoid human errors

To what extent do you agree with the following statements?

The idea that automated e-minibuses will be introduced everywhere worries me, because...

Please tell us on a scale from 1 to 5, where 1 means fully disagree and 5 means fully agree. You can grade your answer with the other points on the scale.

- ... It is not clear how automated e-minibuses interact with motorized road users
- ... It is not clear how automated e-minibuses interact with non-motorized road users
- ... I would not feel secure in an automated e-minibus in case of harassment and assault
- ... It is not clear who is liable in the event of an accident
- ... The technology is not yet ready to drive on public roads
- ... The systems are not reliable
- ... The software may be hacked or otherwise misused
- ... I have to learn how to use an automated e-minibus
- ... The pleasure of driving gets lost
- ... It is not clear how automated minibuses react in unforeseen situations
- ... It will be difficult to integrate automated minibus services into the public transport system
- ... The systems are not secure
- ... Privacy is not protected
- ... Jobs get lost

The automated minibuses can provide a service that is not based on a fixed timetable. The automated minibus comes at a time requested by you, to a location specified by you. This location can be the nearest bus stop, or even your doorstep.

This is called an on-demand, door-to-door service.

The automated minibuses can be integrated into the public transport system to bridge the distance between your place of departure or destination to a public transport station.

This is called a service that bridges the first and last mile.

The automated minibuses service can be integrated into a system together with other means of transportation. This means that you can easily combine a trip with the automated minibus with a trip on the train, bus or taxi. As the automated minibuses will operate on-demand, the system will allow you to plan your trip seamlessly.

This is called a seamless, intermodal trip.

How willing would you be, to use the automated minibus, if the automated minibus...

Please tell us on a scale from 1 to 5, where 1 means not willing at all and 5 means very willing. You can grade your answer with the other points on the scale.

- offers an on-demand, door-to-door service
- offers a service that bridges first and last mile
- is part of a seamless, intermodal trip

How willing would you be, to reduce the use of your own car, if the automated minibus...

Please tell us on a scale from 1 to 5, where 1 means not willing at all and 5 means very willing. You can grade your answer with the other points on the scale.

- offers an on-demand, door-to-door service
- the automated minibus offers a service that bridges first and last mile
- the automated minibus is part of a seamless, intermodal trip

How willing would you be, to give up the use of your own car, if the automated minibus...

Please tell us on a scale from 1 to 5, where 1 means not willing at all and 5 means very willing. You can grade your answer with the other points on the scale.

- offers an on-demand, door-to-door service
- offers a service that bridges first and last mile
- is part of a seamless, intermodal trip

How willing would you be, to increase the use of public transport systems in general (including current offers), if...

Please tell us on a scale from 1 to 5, where 1 means not willing at all and 5 means very willing. You can grade your answer with the other points on the scale.

- the automated minibus offers an on-demand, door-to-door service
- the automated minibus offers a service that bridges first and last mile
- the automated minibus is part of a seamless, intermodal trip

What would you be willing to pay to use the automated minibus, compared to current, classic public transport ?

A lot more A lot less ... Nothing

- In general
- If the automated minibus offers an on-demand, door-to-door service
- the automated minibus offers a service that bridges first and last mile
- If the automated minibus is part of a seamless, intermodal trip

APPENDIX G. CODING LIST FOR THE INTERVIEWS

Multi-level perspective	Codes
Landscape	AVs as mobility innovation AVs as a societal change Changes in the mobility system and paradigm Citizen centric approach Electric mobility Mobility services Shared mobility Shift in mobility behaviour Vision of mobility/future mobility
Regime	AVs acceptance AVs and other road users AVs and safety AVs and sustainability AVs and urban/city planning AVs are a new topic, not priority AVs as economic development AVs challenges/barriers AVs for public transport AVs investments and competition AVs investments and infrastructure AVs negative effects AVs policies and regulations AVs positive effects AVs uncertainties Concerns about AVs e-AVs and sustainability Economic feasibility and challenges Ethical questions about AVs Potential resistance towards AVs Role of AVs/AM Window of opportunity
Niche	AM current deployment AM itinerary/performance according to safety drivers AM users types/profile AM and other road users Users behaviour inside the AM