Automated Vehicles to Evolve to a New Urban Experience

DELIVERABLE

D8.2 Second Iteration Environmental Impact

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Acronyms

AD	Automated Driving	NF	Near future
APIS	Application Programming Interfaces	NMT	Non-motorised transport
AV	Automated vehicle	$NMVOC_{eq}$	Non-methane volatile organic compound equivalents
AVENUE	Autonomous vehicles to evolve to a new urban experience	NOx	Nitrogen oxides
BEV	Battery electric vehicle	P_{eq}	Phosphorous equivalents
CFC-11eq	Trichlorofluoromethane equivalents	PM	Particular matter
CH	Switzerland	POCP	Photochemical ozone formation
CO_2eq	Carbon dioxide equivalents	PKM	Passenger Kilometer
DC	Demonstrator case	PRM	People with Reduced Mobility
DK	Denmark	SAE	Society of Automotive Engineers
DS	Dynamic space		
EPD	Environmental Product Declaration	Sb_{eq}	Antimony-equivalents
EU	European Union	SC	Scenario
EV	Electric Vehicle	SE	Sensitivity
FR	France	SO_2	Sulfur dioxide
GHG	Greenhouse Gas	SUMI	Sustainable Urban Mobility Indicators
GNSS	Global navigation satellite system	SUMP	Sustainable Urban Mobility Plan
GPS	Global Positioning System	TCM	Total Cost of Mobility
GWP 100	Global Warming Potential 100	TCO	Total Cost of Ownership
$H+_{eq}$	Proton equivalents	TDM	Transportation Demand Management
ICE	Internal-combustion engine	TTW	Tank-to-Wheel
ICEV	Internal-combustion engine vehicles	VKm	Vehicle kilometre travelled
IES	Institute of Environment and Sustainability		
ILCD	International Reference Life Cycle Data System	VOLY	Value of life year
IPA	Impact Pathway Approach	WBCSD	World Business Council for Sustainable Development
ISO	International Organization for Standardisation	WHO	World Health Organization
LCA	Life Cycle Assessment	WP	Work Package
LiDAR	Light Detection and Ranging Sensors	WTP	Willingness to pay
LU	Luxembourg	WTT	Well-to-Tank
NEEDs	New energy externalities development for sustainability	WTW	Well-to-wheel

Executive Summary

This deliverable presents the second iteration of environmental impact assessment and has as objective to deepen the environmental Life Cycle Assessment (LCA) for the electric automated minibuses. This document is a continuation of the environmental impact assessment, as presented in the D8.1 first iteration environmental impact assessment. The environmental impact assessment is part of AVENUE WP8 Sustainability assessment.

The study is structured in four main sections. Section 1 introduces the context of AVENUE project and the deployment of pilot-tests of automated minibuses, seen as a complementary mode of transport to be integrated into public transport.

Section 2 provides new insights and findings regarding the environmental performance of the EASB based on the current demonstrators' sites as well as for near-future scenarios and an ideal scenario of deployment. Further sub-sections widen the investigation of the impacts of the automated minibuses by comparing the automated minibuses with other modes of transport, addressing their potential impacts stemming from infrastructure and digital environment for AVs, and potential changes in the modal split triggered by the introduction of automated minibuses into the mobility system.

Section 3 presents the background methods for externalities calculations of the automated minibuses, and Section 4 sets forth the performance of the automated minibuses according to main environmental indicators, applied as well as part of sustainability assessments.

Main findings from the study point:

- Main parameters that influence the overall results are the electricity mix for operating automated minibuses and component production, automated minibuses lifetime, lifetime mileage of the vehicle, and the average passenger occupancy.
- The manufacturing phase of the automated minibus dominates the climate impacts in the current demonstrator case. In near future cases, the use phase becomes the most important contributor as the relative per passenger kilometre (pkm) contribution of the manufacturing, assembly and end of life phase diminishes due to higher overall pkm. The unit of pkm is suited to best represent the function of means of transport according to product category rules for public and private buses and coaches (Environmental Product Declaration [EPD] International AB, 2018). Within an ideal future use case scenario, those phases gain in importance as a consequence of increased vehicle energy efficiency and use of renewable electricity for charging it.
- When comparing the automated minibus with other modes of transport, the climate impacts of the current automated minibuses demonstration case (pkm) are significantly lower than those of a diesel bus but much higher in comparison to most other means of public transport. However, in the near future, the automated minibus performs better than all other means of transport at off-peak and better than all individual vehicles at average operation. Compared to other public transportation vehicles' peak and average operation, automated minibuses are on similar levels.
- The deployment of automated and connected vehicles could impact the overall travelled kilometres and lead to drastic modal shifts. In this regard, different estimates are discussed.
- On the one hand, AVs have a higher energy consumption compared to conventional vehicles (sensors, communication, digital infrastructure, etc.). On the other hand, energy savings from connectivity, optimisation of fleet operations, intersection V2I, platooning, eco-driving could offset the vehicle energy consumption.
- Preliminary results of the environmental indicators point that overall, the energy efficiency and reduction on local air pollution are strong points of the automated minibus. Better performance on climate change indicator can be achieved in the short term through increased mileages and vehicle occupancy. As for local noise pollution, the automated minibus do not present many advantages in comparison to other cars, for example. Therefore, the incentives for soft modes of transport might be more effective.

1 Introduction

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

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

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

1.1 On-demand Mobility

Public transportation is a key element of a region's economic development and the quality of life of its citizens.

Governments around the world are defining strategies for the development of efficient public transport based on different criteria of importance to their regions, such as topography, citizens' needs, social and economic barriers, environmental concerns and historical development. However, new technologies, modes of transport and services are appearing, which seem very promising to the support of regional strategies for the development of public transport.

On-demand transport is a public transport service that only works when a reservation has been recorded and will be a relevant solution where the demand for transport is diffuse and regular transport is inefficient.

On-demand transport differs from other public transport services in that vehicles do not follow a fixed route and do not use a predefined timetable. Unlike taxis, on-demand public transport is usually also not individual. An operator or an automated system takes care of the booking, planning and organization.

It is recognized that the use and integration of on-demand Automated vehicles has the potential to significantly improve services and provide solutions to many of the problems encountered today in the development of sustainable and efficient public transport.

1.2 Fully Automated Vehicles

A self-driving car, referred in the AVENUE project as **an Fully Automated Vehicle** (**AV**), also referred as Autonomous Vehicle, is a vehicle that is capable of sensing its environment and moving safely with no human input.

The terms *automated vehicles* and *autonomous vehicles* are often used together. The Regulation 2019/2144 of the European Parliament and of the Council of 27 November 2019 on type-approval requirements for motor vehicles defines "automated vehicle" and "fully automated vehicle" based on their autonomous capacity:

- An "automated vehicle" means a motor vehicle designed and constructed to move autonomously for certain periods of time without continuous driver supervision but in respect of which driver intervention is still expected or required
- "fully automated vehicle" means a motor vehicle that has been designed and constructed to move autonomously without any driver supervision

In AVENUE we operate ***Fully Automated minibuses for public transport***, (previously referred as Autonomous shuttles, or Autonomous buses), and we refer to them as simply *Automated minibuses* or *the AVENUE minibuses.*

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

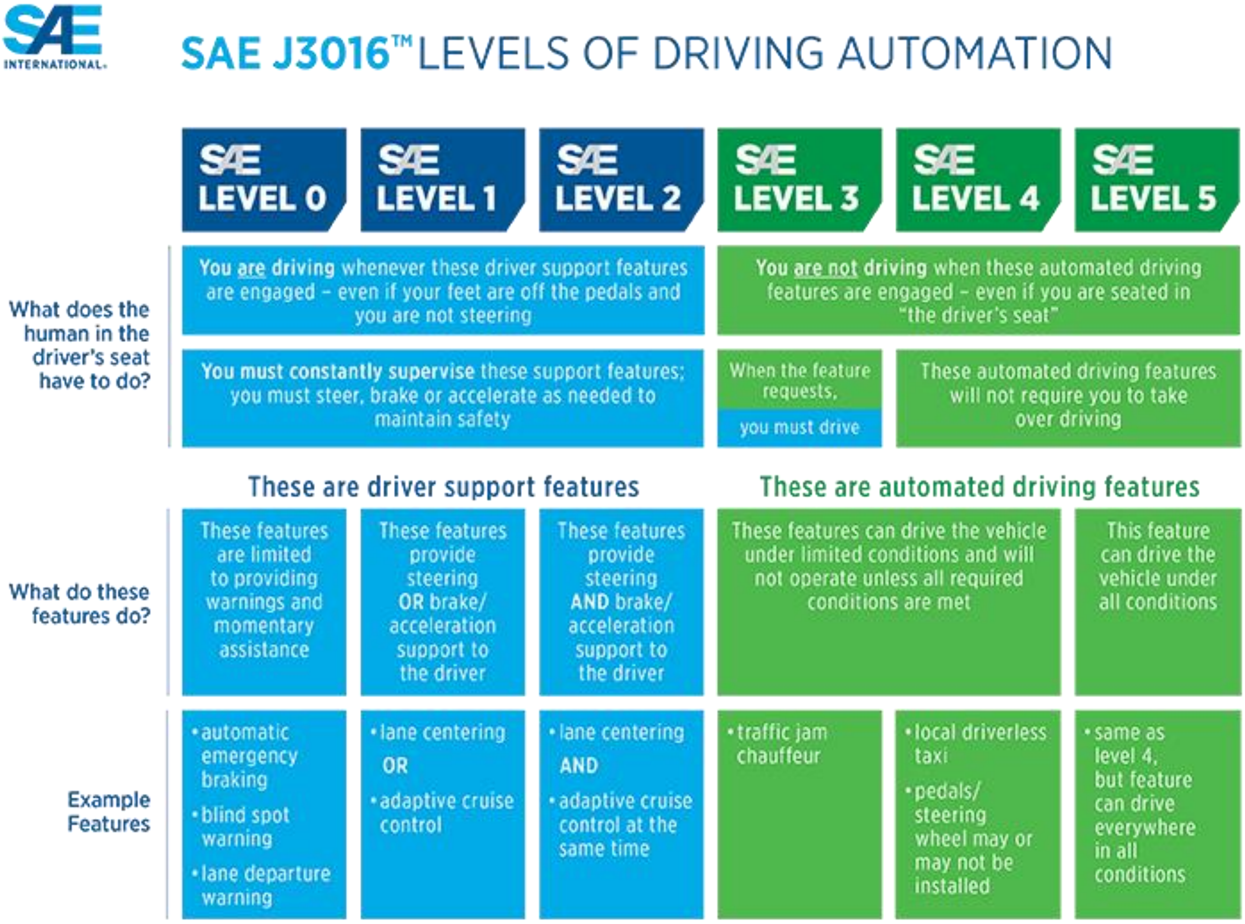

Figure 1: levels of driving automation

1.2.1 Automated vehicle operation overview

We distinguish in AVENUE two levels of control of the AV: micro-navigation and macro-navigation. Micro navigation is fully integrated in the vehicle and implements the road behaviour of the vehicle, while

macro-navigation is controlled by the operator running the vehicle and defines the destination and path of the vehicle, as defined the higher view of the overall fleet management.
For micro-navigation Automated Vehicles combine a variety of sensors to perceive their surroundings, such as 3D video, LIDAR , sonar, GNSS, odometry and other types sensors. Control software and systems, integrated in the vehicle, fusion and interpret the sensor information to identify the current position of the vehicle, detecting obstacles in the surround environment, and choosing the most appropriate reaction of the vehicle, ranging from stopping to bypassing the obstacle, reducing its speed, making a turn etc.
For the Macro-navigation, that is the destination to reach, the Automated Vehicle receives the information from either the in-vehicle operator (in the current configuration with a fixed path route), or from the remote control service via a dedicated 4/5G communication channel, for a fleet-managed operation. The fleet management system takes into account all available vehicles in the services area, the passenger request, the operator policies, the street conditions (closed streets) and send route and stop information to the vehicle (route to follow and destination to reach).

1.2.2 Automated vehicle capabilities in AVENUE

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

1.1 Preamble

This deliverable aims at deepening the environmental impact assessment within AVENUE and aligns it with the overall sustainability assessment. To achieve these goals, this study builds upon a life cycle assessment (LCA) study as presented in D8.1 First iteration environmental impact assessment. The LCA is enhanced and extended to provide new insights and accurate data on the environmental impacts of automated minibuses on public transportation. The assessment of environmental externalities to indicate their societal consequences in monetary terms is another important component of this deliverable and supports the economic assessment tasks of WP8. All of these results support the overall sustainability assessment, and therefore this deliverable furthermore elaborates the environmental indicators that are required within that assessment. See Figure 2 for an overview of the studies and deliverables.

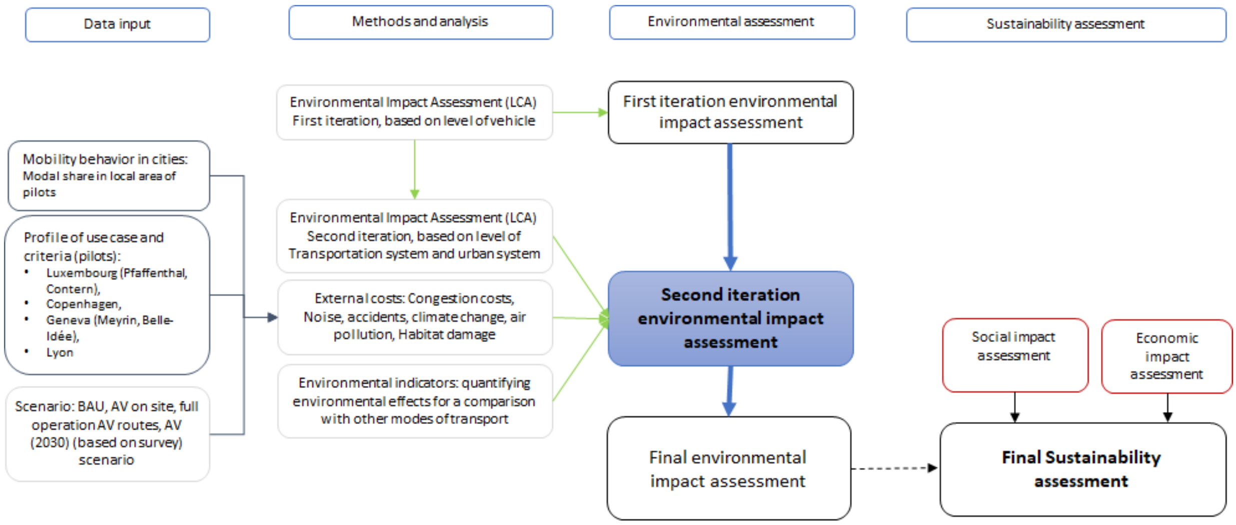

Figure 2: Overview elements of the environmental impact assessment

Section 2 builds upon the description of the LCA research design, goal and scope definition. It presents the results of the LCA study as well as analyses different scenarios and variables (sensitivity analysis) to deploy the automated minibuses. Further, section 2 presents the comparison of the automated minibus with other modes of transport, their potential impacts on modal shares, and addresses the potential impacts of infrastructure and digital environment for Automated Vehicles (AVs).

Section 3 presents the building blocks for the calculations of the environmental externalities of the automated minibuses based on the approach of tank-to-wheel and well-to-tank. Section 4 addresses the environmental indicators for sustainability assessment of the automated minibuses.

As part of the WP8, Section 3 and 4 also support the sustainability assessment. Related concepts, as Sustainable Urban Mobility Plan (SUMP), are included in the second iteration of sustainability assessment.

As a starting pointing, it is worth noting that the impacts of the introduction and integration of AVs can be assessed through the different spheres. First, the vehicle itself, and secondly, the vehicle interactions with the mobility system, environment and society (Figure 3). By expanding the spheres of analysis, the uncertainty of estimates and system complexity increases.

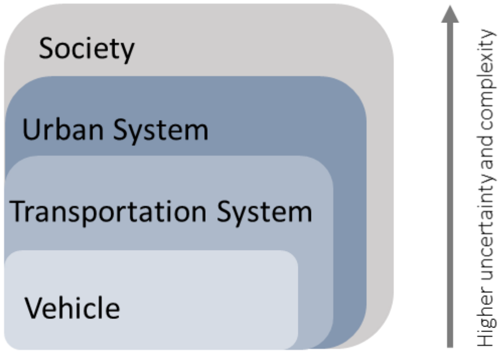

Figure 3: Spheres of interaction between AVs, the environment and society (adapted by the authors from Taiebat et al., 2018)

The First Iteration Environmental Impact focused particularly on the LCA study of the automated minibuses, as a vehicle. This second iteration takes the analysis a step further by expanding it to the potential impact of the automated minibuses on the transportation system and urban system. The impact on wider society is beyond the scope of this deliverable and the environmental assessment.

2 Life Cycle Analysis: continuation

The First Iteration Environmental Impact (Deliverable 8.1; Huber et al., 2019) framed a life cycle assessment (LCA) of automated minibus deployed within the context of AVENUE. It included an analysis of available research results and guidelines as well as preliminary results regarding the environmental performance of the vehicles operated within AVENUE. In this second deliverable, we continue this work by 1) presenting up to date results on the life cycle impacts of an automated minibus, 2) analysing the automated minibus performance compared to other modes of transport and 3) changing key parameters and influence factors that may impact the transportation system and urban mobility.

2.1 LCA results and scenarios

Environmental life cycle assessment (LCA) is a well-established and frequently used set of methods to assess the environmental impacts of products along their whole life cycle from raw material extraction to disposal and recycling. An LCA study is the centrepiece of this research and analyses the entire product life cycle of an automated minibus from raw material extraction via production and use to final disposal and recycling stages.

Core standards for LCA studies are the ISO guidelines 14040 and 14044 (International Organization for Standardization [ISO], 2006a; ISO, 2006b)) accompanied by the International Reference Life Cycle Data System (ILCD) handbook provided by the European Union's Joint Research Centre (European Commission, Joint Research Centre, Institute for Environment and Sustainability [EC JRC IES], 2010). Furthermore, a specific guideline for LCA of electric vehicles by Del Duce et al. (2013) is taken into account.

The study is also based on primary data collection from AVENUE. Hence, a manufacturer of the and public transport operators from the four demonstrator cities provided primary data for this study. Further data has been retrieved from common LCA databases, mostly from ecoinvent 3.5 (ecoinvent, 2020). The LCA software Umberto® (Institut für Umweltinformatik Hamburg GmbH, 2020) has been used to model the product life cycle and analyse the results. Figure 4 summarises the research design and the four stages approach of the study.

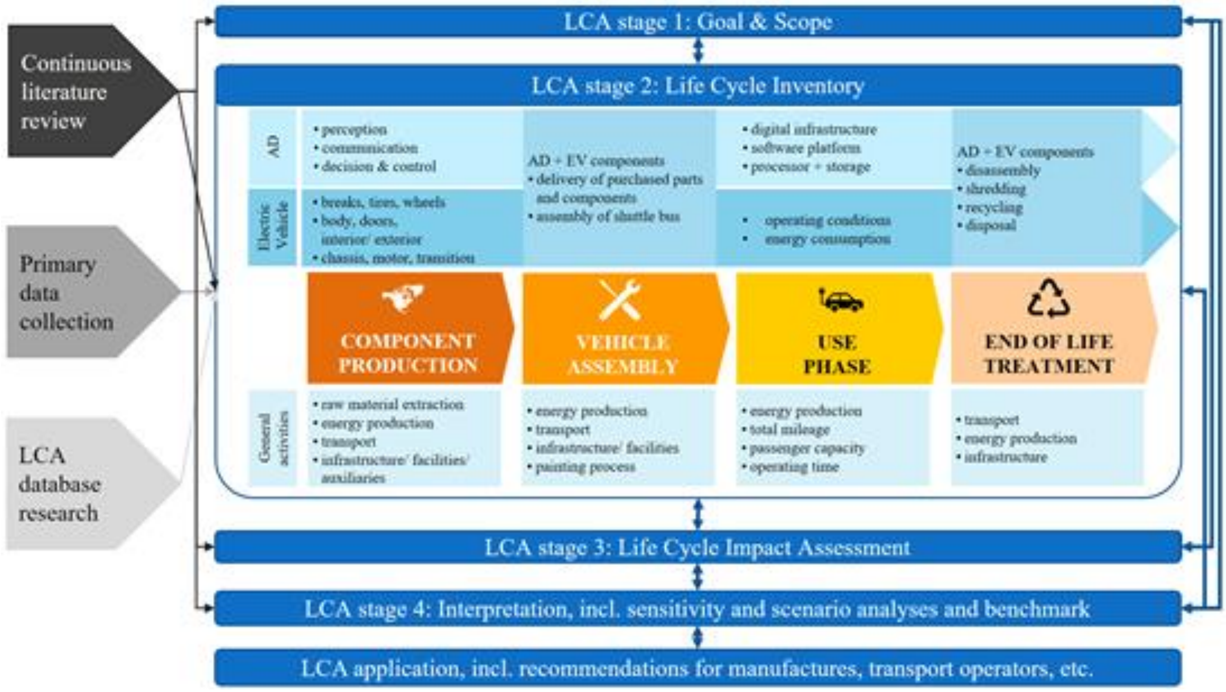

Figure 4: Research design including LCA stages according to ISO, 2006a; AD - automated driving components; EV - electric vehicle components

2.1.1 Goal and scope definition

Goal and scope specify the system under investigation and elaborate the functional unit. The functional unit of an automated minibus is one passenger kilometre (pkm) in public transportation. The study assesses an automated, battery-electric minibus with a total mileage of 42,000 km, which represents the currently expected capabilities of automated minibuses at demonstration sites. Generally, the automated minibus is capable of transporting 15 people and weighs 2,400 kg. To provide this service, a lithium iron phosphate (Li-FePO4) battery is installed in the bus, and it is fuelled with the average European electricity mix if not stated otherwise. For the assessment, a cradle to grave approach is chosen, including raw material extraction and component production, final assembly, use stage and end of life treatment.

Six of the recommended impact categories are used in all of these specifications: Acidification, Climate Change, Eutrophication, Ozone Depletion, Photochemical Ozone Formation, and Resource Depletion. This study focuses on these six environmental impact categories (EC JRC IES, 2011; EC JRC IES, 2012).

As indicated in Fig. 4, this study's product system comprises the main life cycle phases component production, vehicle assembly, use, and end of life treatment in line with recommendations by Del Duce et al. (2013). Component production has been further separated into battery manufacturing, manufacturing of automated driving components, and manufacturing of all other bus components. For each of these life cycle phases and subdivisions, relevant material and energy flow inputs and outputs need to be accounted for at the life cycle inventory stage of LCA.

2.1.2 Life-Cycle Inventory

The life cycle inventory includes all environmentally relevant material and energy flows that enter or leave the system under investigation.

As a starting point, a generic automated minibus model has been built based on literature data (Gawron, Keoleian, Kleine, Wallington, & Kim, 2018; Hawkins, Singh, Majeau-Bettez & Hammer Strømman, 2012; Majeau-Bettez, Hawkins & Hammer Strømman, 2011). In a second step, the model has been refined by adding primary data retrieved from the automated minibus manufacturer and public transport operators involved in AVENUE. Data has been collected for 21 bus components and additional automated driving components. As some automated driving components are very small and light, they have been excluded from this assessment. The weight of these neglected components represents only 0.18% of the total automated minibus weight.

Equally important as the weight is the lifetime of the bus. So far, the lifetime of an automated minibus has not yet been determined because until recently, no automated minibus of the manufacturer has yet reached its life end. According to the manufacturer, one 33kW battery lasts 2000 charging cycles (worst case, conservative approach). Estimating an operation of five days per week for 52 weeks a year results in 7.69 years of theoretical operation. This value is rounded off to seven years in order to account for probable losses and reduced efficiency when the battery is maturing over time (Hadjipaschalis, Poullikkas & Efthimiou, 2008). In case the lifetime of automated minibus extends seven years, the battery would have to be replaced, which brings along additional costs and environmental burden for the transport operators. Transport operators and the automated minibus manufacturer, therefore, assumed that the lifetime of an automated minibus is aligned with the lifetime of its battery while also acknowledging that the rapid technology development of automated minibuses in some cases might make automated minibuses become obsolescent and decommissioned even prior to the battery's end of life. On the other side, some LCA studies of battery for electric vehicles indicate longer lifetimes, e.g. ten years (Deng et al., 2017). The lifetime of seven years, therefore, represents an average value and requires sensitivity analysis.

The calculation of the total mileage is based on estimations of the local transport operators: All automated minibuses of the project are still in trial mode and do not run in full operation. Consequently, they are operating about 200 days a year and drive 30 kilometres per day. Assuming seven years of operation and taking into account a daily distance of 30 kilometres on 200 operating days per year results in total mileage of 42,000 kilometres. Additionally, local transport operators state that there are four passengers on average on board the automated minibus, while the maximum capacity is 15. Another important indicator to assess the material and energy flows associated with running automated minibuses is their energy use. According to test results of the automated minibus manufacturer, driving 1 km at 6.6 km/h, an outside temperature of 30° Celsius, and a temperature of 16° Celsius inside the bus, the automated minibus consumes 520 Wh km-1. This energy use includes all automated components, all components for passenger interaction, and the electric driving components. As speed, temperature, weight, and many other factors influence automated minibuses energy use, it also requires sensitivity analysis.

The vehicle components required for automated driving are of particular interest and listed in Table 1. For each component, reference technologies and nominal power figures have been derived from the component manufacturer's information. In total, automated driving components in automated minibuses demand roughly 300 W. According to Gawron et al. (2018), the additional power required for a medium-sized, automated vehicle sums up to 240 W, while Baxter, Merced, Costinett, Tolbert & Ozpineci, (2018) state 200 W caused by the sensor-layout for a midsized vehicle. The higher value of this study might be explained by a more detailed list of components in comparison to the studies by Gawron et al. (2018) and Baxter et al. (2018), which focus on primary hardware technology, like sensors, radars, cameras, LiDARS, computers, and location detection.

Table 1: Nominal power of automated driving components installed in one automated minibus (Light detection and ranging sensors (LiDARS) -, GNSS -, GPS -)

Automated driving component	*Number of components*	*Nominal power (W)*
180° Mono-Layer LiDARS	6	48.0
360° Multi-Layer LiDARS	2	24.0
Computer	2	160.0
Module GNSS	1	5.6
Inertial Unit	1	0.2
World Shuttle Router	1	25.5
Front/Rear Cameras	4	4.0
Wheel Encoder	4	0.6
3G & Ethernet Router	2	12.0
15" Touchscreen	1	15.0
Steering Encoder	2	1.2
Radio Modul GNSS	1	0.2
4G Antenna	1	5.0
GPS Antenna	2	3.2
Total power consumption (watt)		**304.4**

In the current trial mode of the AVENUE project, an automated minibus drives 30 km on an 8-hour day. The automated driving components require 82.1 Wh km^{-1} (304.4 W x 8 h / 30 km) or 15.6% of the total energy use of 520 Wh km$^{-1.}$

2.1.3 Life Cycle Impact Assessment

At the life cycle impact assessment stage, material and energy flow from the life cycle inventory are linked to their respective environmental consequences, i.e. the environmental impact categories chosen for this study. For instance, greenhouse gas emissions of carbon dioxide, methane or dinitrogen monoxide emitted throughout the automated minibus life cycle are converted into carbon dioxide equivalents (CO_2eq) to indicate the global warming potential as an indicator for climate change impacts associated with providing the functional unit. Table 2 presents all environmental impacts per passenger kilometre (pkm) for the chosen environmental impact categories, broken down to the life cycle phases component production (separated into the battery, automated, and all other bus components), vehicle assembly, use, and end of life. Table 2 shows the percentage contribution of the life cycle phases to the respective overall environmental impacts.

Table 2: Environmental impacts for 1 pkm of automated minibus driving at current trial mode; climate change measured in kg CO2eq (carbon dioxide equivalents).

Acidification in mol H+eq (proton equivalents); eutrophication in kg Peq (phosphorous equivalents), ozone depletion in kg CFC-11eq (trichlorofluoromethane equivalents), photochemical ozone formation (POCP) in NMVOCeq (non-methane volatile organic compound equivalents), resource depletion in kg Sbeq (antimony-equivalents)

	acidification mol H+eq		climate change kg CO_2eq		eutrophication (kg Peq)		ozone depletion (kg CFC11eq)		POCP (kg NMVOCeq)		resource depletion (kg Sbeq)	
Autonomous driving components	*5,27E-05*	*3%*	*5,15E-03*	*3%*	*5,37E-06*	*2%*	*3,10E-10*	*0%*	*2,12E-05*	*3%*	*7,86E-07*	*1%*
Battery production	*3,45E-04*	*21%*	*4,70E-02*	*24%*	*4,24E-05*	*13%*	*1,78E-07*	*94%*	*1,43E-04*	*20%*	*4,81E-06*	*9%*
Further bus components	*7,43E-04*	*46%*	*7,73E-02*	*40%*	*2,07E-04*	*65%*	*5,49E-09*	*3%*	*4,16E-04*	*57%*	*4,90E-05*	*90%*
Raw material extraction and component production	1,14E-03	71%	1,29E-01	67%	2,55E-04	80%	1,84E-07	98%	5,80E-04	79%	5,46E-05	100%
Final assembly	3,67E-06	0%	8,05E-04	0%	3,47E-07	0%	4,46E-11	0%	1,93E-06	0%	1,76E-09	0%
Use (driving)	4,51E-04	28%	5,85E-02	30%	6,16E-05	19%	4,50E-09	2%	1,38E-04	19%	8,54E-08	0%
End of life	1,64E-05	1%	5,30E-03	3%	1,60E-06	1%	1,29E-10	0%	1,07E-05	1%	1,02E-08	0%
Total	**1,61E-03**	**100%**	**1,94E-01**	**100%**	**3,19E-04**	**100%**	**1,88E-07**	**100%**	**7,31E-04**	**100%**	**5,47E-05**	**100%**

Within the current automated minibuses trial mode, the climate change impacts for each pkm are 194 g CO_2eq. Two-thirds of this impact (67%) stem from component production, while the use phase, i.e. driving, accounts for 59 g CO_2eq (30%).

Component production is also the dominant phase in all other environmental impact categories, wherein further bus components (arch, framework, etc.) have the highest contribution except for ozone depletion. Here, the battery production dominates the results due to the use of polytetrafluoroethylene or “teflon” in the anode production, which is associated with emissions of ozone depletion in its pre-chain.

The use phase’s environmental impacts are fully dominated by the electricity supply for charging the automated minibus. An average European electricity mix has been used to calculate the impacts of electricity generation. Due to incomplete data, the final assembly phase is mostly represented by literature data (Hawkins et al., 2012). Within this phase, prefinished components are assembled, connected, screwed together and so forth. The impact results confirm the rather low overall environmental relevance of this phase and justify the use of average literature data. The end of life phase is of similar insignificance compared to the use and component production phases.

2.1.4 Sensitivity analysis, Scenario analysis, and Interpretation

Within the interpretation stage, the outcomes of previous stages are further analysed, discussed and refined.

Previous sections have revealed that there are a couple of parameters that might influence overall results, for instance, the electricity mix for operating automated minibus and also within component production, lifetime and lifetime mileage of the vehicle, or average passenger occupancy. In the following sections, such parameter variations are covered in sensitivity analysis and then linked with assumptions for automated driving in future public transportation within scenario analyses. Table 3 provides parameter settings for these sensitivity and scenario analyses.

In the sensitivity analysis, one parameter at a time is varied, while all other parameters remain unchanged. Sensitivity analyses have been conducted for total mileage, passenger occupancy, utilisation of a renewable energy mix in the use stage, vehicle lifetime changes, utilisation of a renewable energy mix in battery production, and higher vehicle energy efficiency. Some of the parameter variations reflect expectations of transport operators within AVENUE concerning the future, e.g. higher passenger occupancy and higher yearly mileage, but also shorter lifetimes of buses for reasons of technical obsolescence. Other variations consider new studies on batteries for electric vehicles, which report lower environmental impacts and higher lifetimes compared to past studies (Emilsson & Dahllöf 2019).

In scenario analyses, six scenarios have been developed, with the current demonstrator case forming the reference scenario. The first scenario (*SC NF EU)* describes an expected near future use case where average passenger occupancy rises moderately (six instead of four passengers on average) and total mileage increases due to automated minibus maturity and increased operation of 60 km per day at 360 days a year. Four further scenarios are based on this near-future use case and consider the respective electricity mixes of the four countries automated minibuses demonstrators of AVENUE are in operation. The last scenario (*SC IDEAL*) describes an ideal future use case with a more energy-efficient automated minibuses driving 60 km per day over ten years, transporting nine passengers on average, and using electricity from renewable resources, for both battery production and battery charging.

Table 3: Parameter settings of sensitivity and scenario analysis

	Total mileage in km (distance/day operating days/a*a)*	*Passenger Occupancy*	*Energy consumption kWh/km*	*Electricity mix in use stage*	*Battery production renewable energy mix*	*Explanation*
Current Demonstrators	42,000.00 (30*200*7)	4	0.52	Europe (current)	No	Information about current transport operators from demonstrator sites
SENSITIVITY ANALYSIS						
SE1	151,200.00 (60*360*7)	4	0.52	Europe (current)	No	Expected increase in lifetime mileage
SE2	42,000.00 (30*200*7)	9	0.52	Europe (current)	No	Expected increase in passenger occupancy
SE3	42,000.00 (30*200*7)	4	0.52	100% renewables	No	Assuming renewable energy mix for battery charging
SE4	18,000.00 (30*200*3)	4	0.52	Europe (current)	No	Reduced lifetime (3 years) due to technical obsolescence of vehicles
SE5	60,000.00 (30*200*10)	4	0.52	Europe (current)	No	Increased lifetime (10 years) due to longer battery life, following Emilsson & Dahllöf (2019)
SE6	42,000.00 (30*200*7)	4	0.52	Europe (current)	Yes	100% renewable energy in battery production, following Emilsson & Dahllöf (2019)
SE7	42,000.00 (30*200*7)	4	0.30	Europe (current)	Yes	Increase in energy efficiency for driving and automation
SCENARIO ANALYSIS						
Current Demonstrators	42,000.00 (30*200*7)	4	0.52	Europe (current)	No	Information on current transport operators from demonstrator sites
SC NF EU	151,200.00 (60*360*7)	6	0.52	Europe (current)	No	Near future use case with higher passenger occupancy and increased daily mileage
SC NF CH	151,200.00 (60*360*7)	6	0.52	CH	No	Near future use case, Swiss electricity mix
SC NF DK	151,200.00 (60*360*7)	6	0.52	DK	No	Near future use case, Danish electricity mix
SC NF FR	151,200.00 (60*360*7)	6	0.52	FR	No	Near future use case, French electricity mix
SC NF LU	151,200.00 (60*360*7)	6	0.52	LU	No	Near future use case, Luxembourg electricity mix x
SC IDEAL	216,000.00 (60*360*10)	9	0.30	100% renewables	Yes	Ideal future use case; increased daily mileage over 10 years, higher occupancy, renewable energy in use phase and battery production, higher energy efficiency

Further, Figure 5 illustrates similar sensitivity analysis results across all chosen environmental impact categories. The selected sensitivity parameters show different effects on the results. Compared to the current demonstrator case, in particular, the increase in lifetime mileage (SE1) and in passenger occupancy (SE2) lead to great environmental improvements, while the reduction of the vehicle's lifetime to three years (SE4) massively deteriorates the environmental performance. Conversely, the increase in vehicle lifetime from 7 to 10 years (SE5) has positive effects, as does the switch to the use of renewable energies in the utilisation phase (SE3). Greater energy efficiency in the use phase (SE7) and more environmentally friendly battery production (SE6) also have a positive impact, but not to the same extent as the increase in occupancy and mileage.

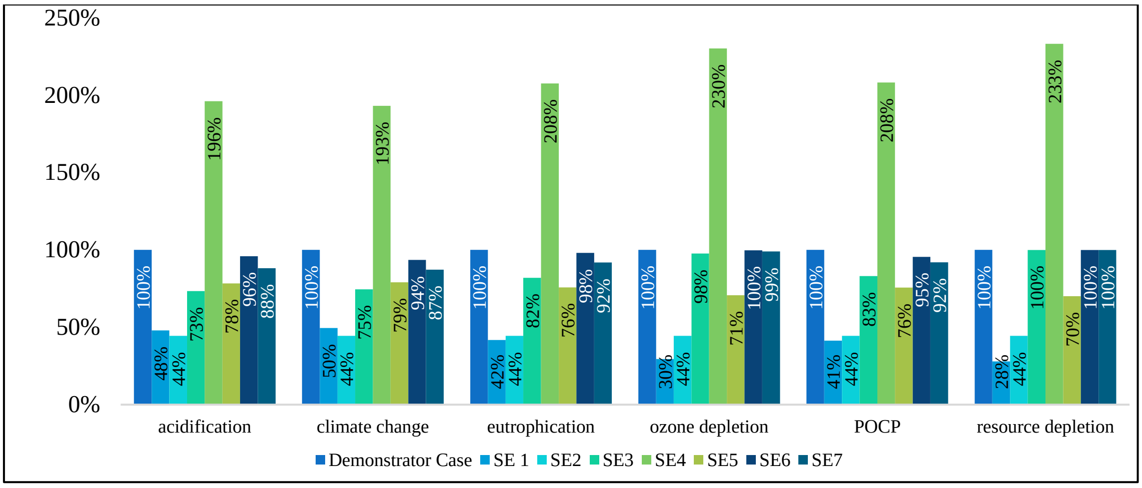

Figure 5: Sensitivity results for all environmental impact categories.

(DC - demonstrator case = 100%, SE 1 - increased lifetime mileage, SE 2 - increased passenger occupancy, SE3 - Charging with renewable energy mix, SE4 - 3 years lifetime, SE5 - 10 years lifetime, SE6 - environmental-friendly battery production, SE7 - lower energy consumption per km)

Next, Figure 6 further details the sensitivity results for the environmental impact category climate change. Increasing passenger occupancy (SE1), using renewable energy in operation (SE3), and increasing vehicle energy efficiency (SE7) significantly reduce climate impacts per pkm in the use phase. By contrast, increasing total mileage daily (SE2) and changes in vehicle lifetime (SE4 and SE5) affect climate performance in the manufacturing and end of life phase as these phases are allocated to a larger amount of pkm.

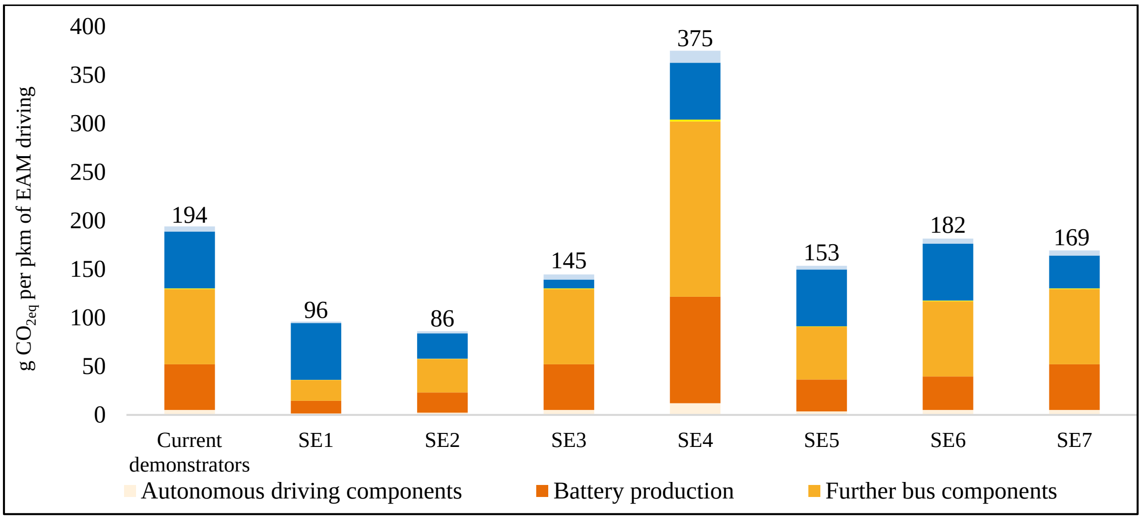

Figure 6: Sensitivity results for climate change in g CO_2eq per pkm of automated minibus driving.

(SE 1 - increased lifetime mileage, SE 2 - increased passenger occupancy, SE3 - Charging with renewable energy mix, SE4 - 3 years lifetime, SE5 - 10 years lifetime, SE6 - environmental-friendly battery production, SE7 - lower energy consumption per km)

Across all environmental impact categories, the chosen scenarios perform significantly better than the current demonstrator case (Figure 7) mainly due to increased lifetime mileage and increased passenger occupancy. An ideal future use case (SC IDEAL) outperforms all near-future scenarios by far as it combines the parameter settings that have performed best in the sensitivity analysis. The ideal case has about ten times lower environmental impacts than the current demonstrator case, and even the expected near future use cases feature three to five times lower impacts. Depending on the country under consideration, certain impact categories vary as a consequence of different electricity mixes. For instance, the higher share of coal-firing power plants lead to higher climate and eutrophication impacts for Luxembourg (SC LU) in comparison to France (SC FR) or Switzerland (SC CH).

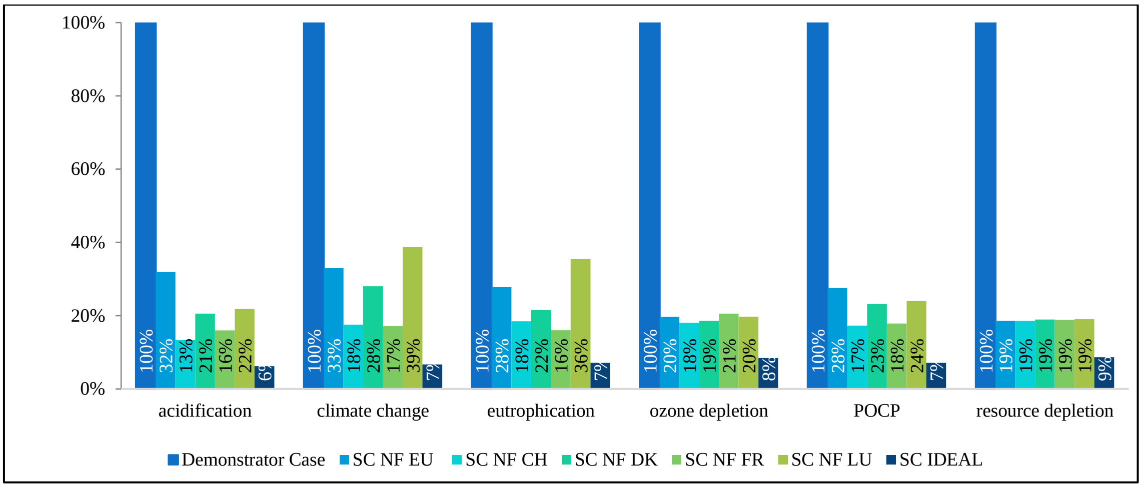

Figure 7: Scenario analysis for all environmental impact categories.

(Demonstrator case = 100%, SC NF - Scenario near future use case, EU - EU electricity mix, CH - Swiss electricity mix, DK - Danish electricity mix, FR - French electricity mix, LU - Luxembourg electricity mix, SC IDEAL - Ideal future use case)

The breakdown of scenario results for climate change (Figure 8) discloses a transition of life cycle phase contributions. The manufacturing phase, i.e. battery, automated driving, and further bus component manufacturing, dominate the climate impacts in the current demonstrator case. In near future cases, the use phase becomes the most important contributor as the relative per pkm contribution of the manufacturing, assembly and end of life phase diminishes due to higher overall pkm. Within an ideal future use case scenario, though, those phases gain in importance relatively as a consequence of increased vehicle energy efficiency and use of renewable electricity for charging.

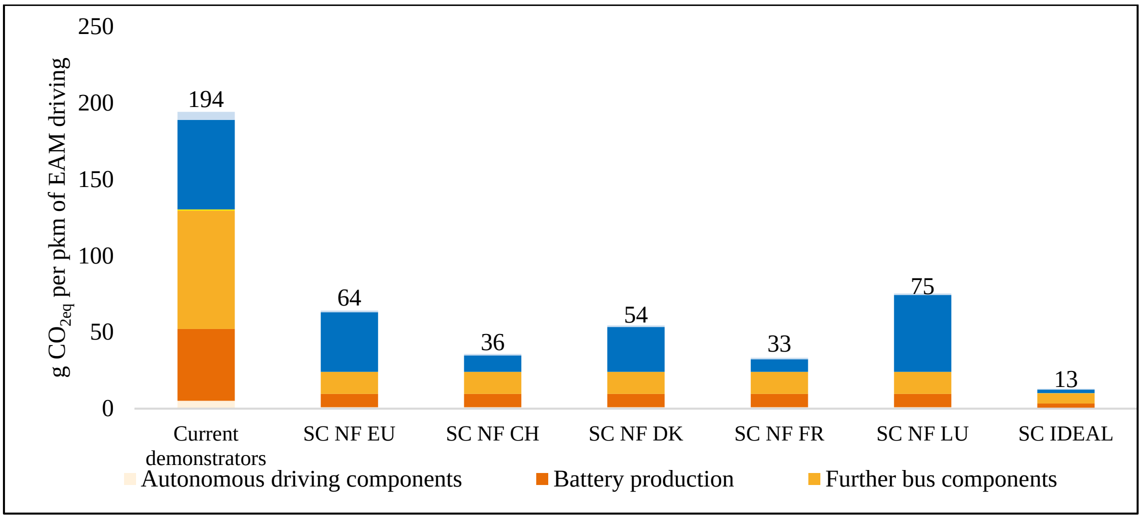

Figure 8: Scenario results for climate change in g CO_2eq per pkm of automated minibus driving.

(SC NF - Scenario near future use case, EU - EU electricity mix, CH - Swiss electricity mix, DK - Danish electricity mix, FR - French electricity mix, LU - Luxembourg electricity mix, SC IDEAL - Ideal future use case)

The following sub-section presents findings of the comparison of the automated minibuses with other means of transport. This topic raises attention since the automated minibuses can be a complementary means of transport as well as it can replace other means of transport in urban mobility.

2.2 Potential competitors of the automated minibuses

As discussed in the sections above, future use cases of automated minibuses have significantly lower environmental impacts per pkm than the current demonstrator use cases. However, the question remains to be clarified whether this improved environmental performance can also be regarded as advantageous in comparison with other means of transport. In this regard, the automated minibuses climate change impacts per pkm are compared with literature values of other vehicles, including four types of vehicle for individual transportation and five for public transportation (Table 4). For all vehicles, off-peak, average, and peak operation is differentiated. The average occupation for individual vehicles of 1.58 passengers is based on Chester & Horvath (2009). automated minibuses assessed within this study have a maximum capacity of 15 passengers. For off-peak operation (average, peak), passenger occupancy has been defined as 3 (6, 12) passengers.

Table 4: Climate impacts, lifetime mileages and passenger occupancies for various individual and public transportation vehicles.

(Based on [1] Hawkins et al., 2012; [2] Gawron et al., 2018; [3] Chester & Horvath, 2009; [4] McKenzie & Durango-Cohen, 2012; [5] this study)

	peak operation	off-peak operation	average operation	peak occupancy	off-peak occupancy	average occupancy	lifetime mileage
Unit	g CO_2eq /pkm	g CO_2eq /pkm	g CO_2eq /pkm	no. of passengers	no. of passengers	no. of passengers	km
Individual BEV - battery electric vehicle, EU electricity mix [1]	41	206	130	5	1	1.58	150,000
Individual ABEV – automated battery electric vehicle, US electricity mix [2]	28	139	88	5	1	1.58	257,495
Individual combustion engine vehicle (ICEV) - internal combustion engine vehicle (Sedan) [3]	94	375	238	5	1	1.58	300,947
Individual ICEV - internal combustion engine vehicle (SUV) [3]	88	442	280	5	1	1.58	300,947
Public diesel bus [3]	65	522	163	40	5	16	651,785
Public BEB – battery electric bus [3]	25	201	63	40	5	16	651,785
Public diesel-electric hybrid bus [4]	22	305	44	70	5	35	627,644
Public – compressed natural gas (CNG) bus [4]	24	316	48	66	5	33	627,644
Public – hydrogen fuel cell using renewable energy sources (HFC) bus [4]	33	273	65	41	5	21	627,644
Public – electric automated minibus current demonstrators (automated minibuses CD) [5]	65	259	194	12	3	4	42,000
Public – electric automated minibus near future use case (automated minibuses NFUC) [5]	32	128	64	12	3	6	151,200

Figure 9 presents the climate changes impacts of all transport modes, including the current automated minibuses demonstrator case and the near future European use case scenario (SC NF EU).

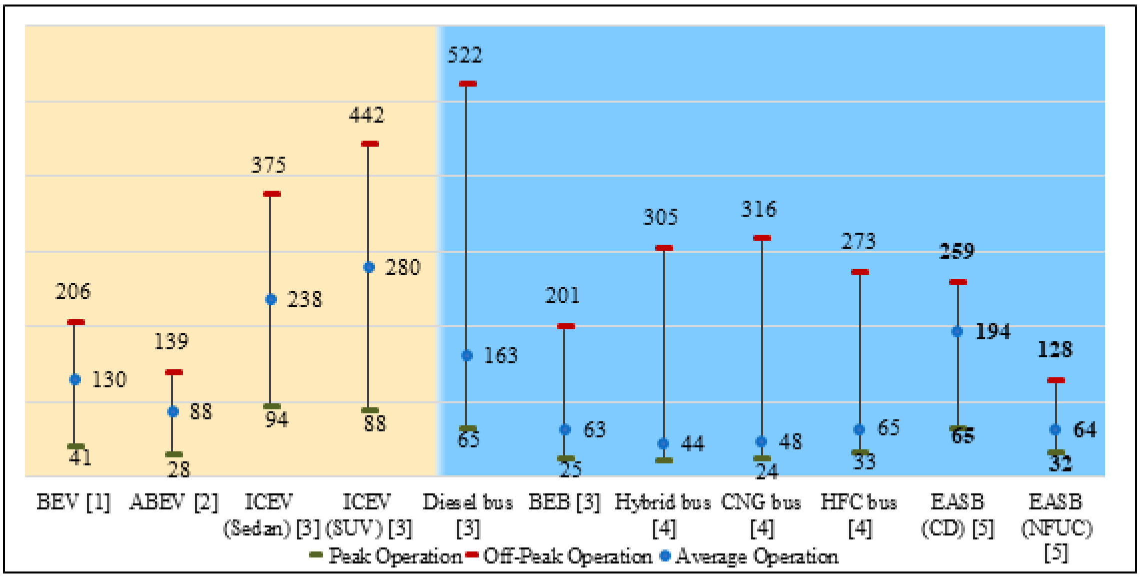

Figure 9: Climate impact of different transportation modes in g CO_2eq/pkm (own compilation, for abbreviations, compare Table4; numbers in square brackets refer to data sources in Table 4)

From the comparison, one can state that the climate impacts (pkm) of the current automated minibuses demonstrator case are significantly lower than those of a diesel bus but much higher at peak and average operation in comparison to most other means of public transport. While current automated minibuses perform better than individual combustion engine vehicles, their climate impacts are higher in comparison to individual battery electric vehicles. This changes, though, when considering the near future use case. Here, automated minibus perform better than all other means of transport at off-peak and better than all individual vehicles at average operation. Compared to other public transportation vehicles' peak and average operation, automated minibuses are on similar levels.

As stated, in term of environmental impact, the automated minibus performs better than ICEV. However, it is important to account for the role of the automated minibuses within the overall transportation system and how their deployment could affect the other modes of transportation's use in urban areas. Thus the next sub-section further discusses the potential effects of the automated minibuses on the modal split of cities.

2.3 The potential effects of automated minibuses on modal split

The introduction of the automated minibuses as part of the transportation systems, will have an effect on mobility demand and trip distribution. This effect could occur on 2 levels. First, the deployment of automated and connected vehicles could impact the overall vehicle kilometre travelled (VKm). Second, it will lead to drastic modal shifts. Fagnant and Kockelman (2015) estimate that the deployment of shared automated vehicles could replace up to 90% of private vehicles, and at the same time, lead to an 11% increase in overall VKm. The International Transport Forum (2015) conducted simulations on ridesharing of AVs as well as carsharing in Lisbon, and they came to similar conclusions; the ridesharing scheme reduced the individual vehicles by up to 90%, and caused an increase by 6% however, in this case, the ridesharing was also targeted to replace bus service (Janasz 2018). The influence on mobility demand depends on the service quality, waiting times for an on-demand service as well as fleet size. The automated minibuses could cause a reduction in the overall travelled distances only if passengers are willing to wait up to 10 minutes for their ride (Janasz 2018).

Moreover, the attractiveness, convenience, cost-effectiveness, and comfort of this mode of transport could lead to an induced demand (Medina-Tapia and Robusté 2019b; Bösch et al. 2016). The increase could be attributed to “ghost trips” where the automated minibuses are running empty, as well as the reduction in the value of time which impact the infrastructure capacity and lead to increased travel time.

It is important to note that the majority of research, whether based on real trials or simulations, focus on the effect of the AVs (shared or self-owned) on the internal combustion engine vehicle ICEV modal share (Janasz 2018; Fagnant and Kockelman 2015; Moreno et al. 2018; Fournier et al. 2020; Fagnant and Kockelman 2018; Filiz 2020; Medina-Tapia and Robusté 2019a). However, limited studies delve into the potential implications on non-motorised transport (NMT) and public transport (Llorca et al. 2017; ITF 2020; Fagnant and Kockelman 2015). The use of the minibuses for short distances is bound to put them in competition with active mobility. This is further apparent from the current pilot testing, the public transport operators for Lyon, Copenhagen, and Luxembourg expressed that the minibuses in the current operation schemes are attracting passengers that would have walked. This could be justified by the low speed and the limited mileage. Further insights fro the local surveys are needed to better decipher mobility behaviour and future preferential transport choices. Also, new mobility such as electric scooters and the shared electric bikes could provide a better suitable solution for short distances.

Furthermore, even if the minibuses serve long-distance trip, it will contribute, along with individual AVs, to urban sprawl because of the reduction in the cost of travel time, which leads to longer distances between work and home (Duarte and Ratti 2018). Urban sprawl reflects low-density areas and the expansion of human settlements over more land (UN 2016). This goes against Compact city principles which favour high-density urban areas and encourage walking and biking. In conclusion, it becomes less accessible and less convenient to commute with NMT, buses, or trams.

In addition, It is arguable that the increased safety due to the automation technology could encourage more people to walk and bike due to reduced risk of accidents (Alessandrini et al. 2015). Nevertheless, the manoeuvrings of on-demand minibuses such as more pick/ups and drop-offs present a challenge to pedestrians (Fraedrich et al., 2019). Thus, the efficient integration of the minibuses within the transportation systems hinges on the complementarity with public transport and NMT. It should be utilised as a first/last mile solution to fill gaps in urban mobility. The coupling with transport demand management (TDM) and sustainable urban planning policies could mitigate the negative effects of their deployment and avoids the replication of the car model.

Furthermore, beyond the potential effect on the modal split, the automated minibuses introduction is poised to affect digital and physical infrastructure. In general, automated minibuses are part of the larger AV-technology which will require integration within the internet of things IoT network. This will have ramifications in term of energy use as well. The following part elaborates on the impacts of digitisation and infrastructure due to AV.

2.4 The impacts of infrastructure and digital environment for AVs

This section aims to describe the infrastructure related to AVs communications and connectivity, and their potential impacts, by considering that AVs are embedded in a digital environment, different from regular vehicles. At the end of the section, we interpret these general insights within the specific context of AVENUE.

The deployment of AVs will be accompanied by a digitalisation process which is the transformation from physical to digital state as defined by Noussan and Tagliapietra (2020). The research related to the digitalisation of transportation systems focuses mostly on how the advances in the Internet of Things (IoT) will affect energy efficiency and decrease the overall travelled distances. One overlooked aspect is the energy consumption due to the communication and navigation systems of these vehicles.

Indeed, Liu et al. (2019b) investigated the negative impact of vehicular intelligence on energy consumption. The authors draw attention to the fact that automated and intelligent vehicles are 'equipped with advanced sensors, controllers, and actuators, in combination with connecting communication technologies', therefore, resulting in higher energy consumption compared to conventional vehicles. The sensors and the processors' components of the automated vehicle (AV) require auxiliary supply energy.

The automated and connected vehicles may entail further impacts when considering required infrastructure, e.g. road infrastructures such as road sensors and special signalling devices (Liu et al., 2019a; McKinsey & Company, 2019), additional digital infrastructure (5G network, additional capacity for data transmission and storage, data centres etc.), and the infrastructure implications regarding the different vehicle communications, external connections, and the availability of long-distance wireless network (McKinsey&Company, 2015). The vehicle-to-X connections are illustrated in Figure 10.

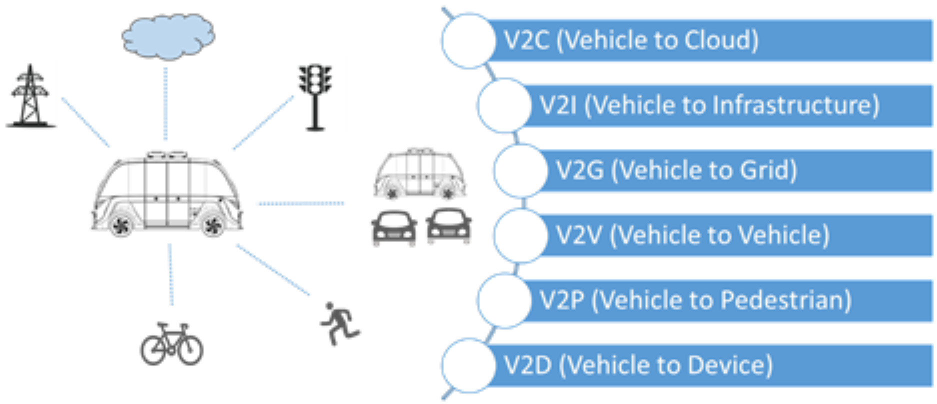

Figure 10: Automated vehicles' external communication and connectivity

The Vehicle to Infrastructure (V2I) concerns the constant exchange of information between vehicle and surrounding infrastructure, e.g. signalised intersections, traffic lights, sensing the environment and sharing information within the Internet of Things approach (Harrington et al., 2018). The connected vehicle and infrastructure will allow monitoring traffic flow, road capacity and creating digital maps in real-time (ibid). Further, those data could support the estimate of impacts of AVs on mobility as well.

Further, considering that vehicle electrification is gaining momentum, the Vehicle to Grid (V2G) envisages that EVs can be connected to the power grid. And through coordinated charging and discharging, the vehicles could improve grid efficiency and reliability and better match energy consumption and generation (Clement-Nyns et al., 2011). This is possible because EVs can provide storage of the excess of produced energy and use it for driving or releasing back to the grid later on (ibid). In addition, automated and electric vehicles can present synergies regarding certain aspects as data sharing and mobility efficiency (Sprei, 2017; Harrington et al., 2018).

The Vehicle-to-vehicle (V2V) communications enable the information exchange about the speed and position of surrounding vehicles, being helpful to provide real-time traffic information to avoid crashes, ease traffic congestion, enhance mobility and improve the environment (NHTSA, 2020).

The V2P (Vehicle to Pedestrian) and V2D (Vehicle-to-device) provide communications with vulnerable road users, such as pedestrian and cyclists. It can include as well in-vehicle warning systems, handheld devices for pedestrians in order to improve safety (USDOT, n.d.).

Ultimately, the V2C (Vehicle to Cloud) inserts the vehicles into the digital and Internet of Things (IoT) ecosystem. This way, vehicles are able to communicate and connect to different devices, which requires as well as high volumes of data communication (AECC, 2020).

Existing studies have investigated how better communication and vehicle's connectivity could contribute to reducing energy impacts in mobility. For instance, Lee and Kockelman (2019) pointed that energy savings resulting from Vehicle-to-vehicle connectivity & platooning can represent - 2% to -19%, and from vehicle-to-infrastructure connectivity & smart intersection, from - 6% to - 30%, thanks to improvements on traffic interactions and better fuel-efficient driving.

Taiebat et al. (2018) explain that the impacts of connected AV remain uncertain depending on the level of interaction with the environment. On the one hand, AVs can add benefits through the optimisation of fleet operations, more efficient vehicle utilisation, shared rides and boosting the integration of EVs and charging infrastructure into power grids. On the other hand, the authors draw attention to a potential increase in vehicle kilometre travelled (VKT) and to the fact that AVs also 'require communications with large-scale data centres, which are generally energy-intensive (ibid).

The study from Wadud et al. (2016) points out that vehicle automation offers the potential for reductions in energy consumption and emissions. In addition, it highlights that many savings may stem from vehicle connectivity, being combined or not with automation. The study shows, for instance, that platooning and eco-driving present a substantial change in energy consumption, performing reductions from - 5to -20%. In this regard, regulations and standardise V2X communication are enablers (ibid).

From an LCA perspective, it is also relevant to investigate the potential increase in energy consumption related to the infrastructure surrounding AVs and required for their communications and connectivity. In the long term, by considering a wide deployment of AVs, it is important to take into account, for instance, the need for additional computers on supervision centres for AVs, additional capacity on data centres, structure and servers for data transmission and storage, use of 5G and data transmission network, and other devices related digital infrastructure.

To our knowledge, no LCA study to date has comprehensively reported the potential impacts related to the additional infrastructure for AVs. It points to a knowledge gap and room for further research on this domain.

In the context of AVENUE, transport operators were asked to quantify additional infrastructure compared to non-automated vehicles at the pilot sites. They reported the use of an additional computer to supervise the vehicles and, in some cases, minor infrastructure adaptation to connect the automated minibuses to traffic lights, for example. Full quantification of such additional infrastructure energy requirements was not possible at this stage, but the effort was unanimously considered negligible compared to the energy expenditure of the vehicles themselves. The energy consumption data of the vehicles includes all vehicle components that are exclusively necessary for automated operation. The operators' statements are in line with the manufacturers' statements, according to which the majority of the computing power takes place within the vehicles, while the communication to the outside and the associated installation and operating costs for infrastructure are low.

Minor additional environmental impacts due to required infrastructure outside the vehicles might well be offset by previously mentioned environmental savings of AV driving, e.g. eco-driving or platooning. Evidence from the current pilot sites, as well as the current state of research, does not yet provide a clear answer on the environmental effects of outside vehicle infrastructure but indicate a comparatively low significance. This is particularly true when the share of AVs increases substantially, and the same infrastructure is shared by more vehicles and results in higher passenger-kilometres.

3 Societal costs savings due to environmental impact improvements

Externalities provide a framework to estimate the societal impacts of introducing innovations. In this part, the environment-related external costs of deploying automated minibuses are investigated. This help in understanding the implications of the deployment on a macro-scale. The monetisation of the environmental impact of the automated minibuses within the transportation system and within the city gives insight into the ideal scenario for deployment. A scenario that is characterised by maximising the potential savings due to the environmental impact.

The goal is to define external cost factors expressed in €-cent per pkm and combine them with different predicted modal shifts in pkm to better estimate the externalities of deployment of these vehicles in different scenarios.

The environmental externalities follow the analysis from CE Delft studies conducted for the European Commission. In this first stage, it focuses on the tank-to-wheel emissions (emissions of the use phase of the vehicle), well-to-tank (emissions for energy provision), well-to-wheel (i.e., the sum of both), while later phases will include all life cycle stages including production and recycling/disposal of the vehicle itself. The externalities assessment considers the categories of air pollution, climate change, noise, and habitat change.

Well-to wheel assessment

The LCA focuses on the environmental assessment during the life cycle of a product: primary material extraction, production, use, and disposal or recycling. Ramachandran and Stimming (2015) explain that "*Well-to-wheel (WTW) analysis is an application of LCA which is used to compare drivetrains/vehicles from a global perspective*". The Well-to-wheel represents the energy flow and the associated emissions. It starts from the mining phase or the raw materials extraction phase: "the well" until the use phase "the wheel".

The well-to-wheel (WTW) is composed of 2 parts: well-to-tank (WTT) and tank-to-wheel (TTW). The WTT has 5 steps: extraction of primary materials- well, the primary fuel production, transport of the fuel, production of vehicles fuel, distribution of road fuel, and fuelling the vehicle. The TTW represents the driving of the vehicle: the burning of the fuel in the vehicle and the wheel phase (JCR, 2016; Woo et al., 2017). See Figure 11.

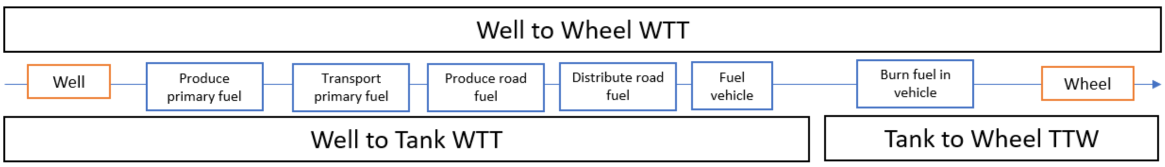

Figure 11: Well-to-wheel analysis

The scenarios build upon mobility surveys of the AVENUE cities and their future mobility targets. It is assumed that the total vehicle kilometre travelled (VKM) will not be increased due to the introduction of AV for public transport as they will be accompanied by a travel demand strategy. This means that the deployment fills mobility gaps and supports public transport. Thus, they will not increase the overall travel demand. The potential increases due to induced travel demand will also be considered in future iterations.

Thus, this part starts by defining the considered impacts in the environmental externalities: climate change, air pollution, well-to-tank, noise, and habitat loss. Then, it specifies the methods to calculate the externalities values for each impact and provides the values of externalities (factors in €-cent/pkm) per the mode of transport (bus, car, and the automated minibus) for the four cities of AVENUE. Moreover, a test case is included that is based on one scenario to replace 18% of the projected increase in ICEV in 2040 in Geneva to better test the analysis.

3.1 Environmental impacts considered in externalities calculations

Urban traffic causes major environmental toll on cities. These impacts affect health, urban environment, biodiversity, crops, and ecosystems (Jochem et al., 2016). The following determines which impacts are accounted for in the marginal external costs. It also describes the methods used to measure and monetise these effects based on the assessment from van Essen et al. (2019).

3.1.1 Air pollution

Air pollution leads to harmful health effects. Up to 30% of strokes, lung and heart disease are caused or aggravated by air pollution (Jochem et al., 2016; WHO, 2016, 2018). The pollutants in question are $PM_{2.5}$, PM_{10}, NO_x, SO_2, and non-methane volatile organic compound NMVOC. The analysis focuses on 4 types of impacts caused by air pollution:

- Health effects (medical costs, loss of work productivity due to sickness),
- Crop losses (lower crop production),
- building damage (damage to building surfaces and building façades and materials - corrosion due to NOx),
- and biodiversity loss (soil and water acidification, eutrophication of ecosystems).

3.1.2 Climate change

The transportation sector alone is responsible for almost 25% of GHG emissions in the EU. Road transportation emissions constitute 70% of that share in 2017 (European Commission, 2016).

The calculations for climate change costs, in line with the CE Delft report, accounts for costs related to global warming:

- sea-level rise,
- biodiversity loss,
- water management difficulties,
- extreme weather conditions,
- and crop failures.

The emissions of CO_2, N2O, and CH4 are leading factors of global warming.

3.1.3 Noise

The noise, according to van Essen (2019), is defined as "unwanted sounds of varying duration, intensity or other quality that causes physical or psychological harm to humans". According to the European Environment Agency, around 72,000 people are admitted to hospitals, while 16,600 fatalities could be attributed to noise pollution. Road transportation remains the leading cause. It is even considered as the second most environmental stressor in the EU (EEA, 2014).

The model accounts for:

- the annoyance
- and health effects caused by road traffic noise.

The WHO (2011) describes annoyance as one of the lead burdens of environmental noise from road traffic. It inflicts irritation and stress, which could disturb daily activities. As for health effects, noise pollution is a culprit in cardiovascular diseases and sleep deprivations (van Essen et al., 2019). Other potential effects such as breast cancer, depression, productivity loss are not part of the considered health effects because of the lack of strong correlation between them and noise.

3.1.4 Habitat damage

The habitat damage incurred because of transportation systems has long-lasting impacts on the natural landscape. Habitat loss is caused by:

- the construction of infrastructure
- and the damage to the natural wildlife.

Specifically, habitat fragmentation affects biodiversity. Moreover, transport emissions aggravate the effects on natural species. The estimation for habitat damage focuses on:

- habitat loss: the loss of natural ecosystems. The land use of transport leads to negative effects on biodiversity. Habitat loss is caused during the building phase of transport infrastructure, but its effects are continuing during the lifetime of the road.
- habitat fragmentation: fragmentation has a bad influence on animals and on biodiversity. Habitat fragmentation is the result of the transport infrastructure and the transport demand on the infrastructure.

The degradation due to the emissions is not part of this assessment because it was accounted for in air pollution and climate change impacts.

3.2 Social costs of environmental impacts

The impacts described previously are monetised for the sake of the assessment of the external costs.

The following defines the methods used to calculate the external costs for each impact. It also presents the values adopted for the road vehicles for the 4 cities, and it specifies the values to adopt for the automated minibuses.

The accuracy of the values hinges on using these methodologies to produce the differentiated costs based on case-specific input values. Nevertheless, due to the unavailability of specific data and evaluation models for each impact, we opted to use the outputs presented in the CE Delft handbook by selecting the closest-possible cases similar to Avenue. The values are based on the differentiation made for vehicle and the pilot sites specifications (such as the speed of circulation, traffic situation, etc.).

Moreover, based on the results from WP7 and interviews with the public transport operators, the automated minibuses are circulating in urban areas and on urban roads. The speed is between 12 km/h and 30 km/h. The ideal average rate (before Covid-19 times) is around 6 passengers. These parameters help select the cost factors to be used in the case of AVENUE.

Thus, the following presents the average costs for air pollution, climate change, noise, and the aggregated emissions of well-to-tank.

3.2.1 Air pollution costs

The methodology used to estimate the external costs of the impacts of air pollution described previously is a damage cost estimation. A damage cost estimation estimates all damage borne by individuals as a result of the existence of an externality. It relies on cost factors from an adapted version of NEEDS approach, the emission factors from COPERT data, and transport performance data from Eurostat. The cost factors are computed based on the impact pathway approach (– IPA, see also Figure 12). The IPA clarifies the impact of the pollutants emission from the source to the individuals; from dispersion to intake at specific sites, it better suited for tank-to-wheels (TTW) emissions (Jochem et al., 2016; Matthey and Bünger, 2019; van Essen et al., 2019)

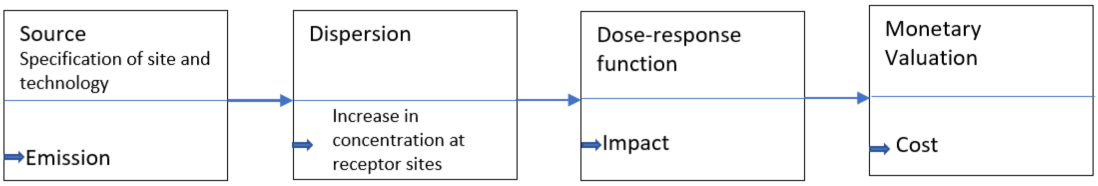

Figure 12: Impact pathway approach

The marginal costs are taken on a national level for the values for the passenger cars and the standard buses. They are presented in Table 5.

Table 5: Marginal costs for air pollution in €-cent/pkm

	Average costs in €-cent per pkm			
	Pass car - petrol	Pass car - diesel	Pass car - total	Bus
Denmark	0.292	0.809	0.483	0.513
France	0.387	1.260	1.001	1.010
Luxembourg	0.429	2.630	1.880	1.846
Switzerland	0.311	1.461	0.626	0.755

Notably, using national values for the city-level assessment could skew the results because of the differences in emission between rural and urban areas, especially for the PM emissions. However, this could be improved using the European values for urban and rural parts in a sensitivity analysis in Table 6.

Table 6: EU level average costs for air pollution in €-cent per pkm

Vehicle	Urban areas- urban roads

Petrol passenger car	0.11
Diesel passenger car	0.99
Standard bus	1.07

As for the automated minibuses, the values are based on the potential competitors mentioned previously. The emissions of an electric automated minibus are comparable to those of an automated one. Thus, the values used are those of urban electric mini-bus. For now, we use the values on a European level because the limited deployment of automated minibuses will not vary immensely from one European country to another. All the values for the well to wheel emissions are also presented in Table 10.

3.2.2 Climate change costs

The methodology to estimate the marginal external costs of climate change is the avoidance cost approach. The avoidance cost method considers the costs needed to meet the EU CO_2 reduction targets. This presents an indication of the willingness to pay (WTP) to avoid the damage of climate change. According to (Miola et al., 2008) The avoidance costs are defined as "the least-cost option to achieve a required level of GHG reduction."

The proposal made by the EU is to cut GHG emissions by at least 55% by 2030 compared to 1990 levels (McPHIE et al., 2020). The Paris agreement stipulates preventing a raise in temperature above 1.5-2 degrees Celsius. Therefore, the study uses the average central of short-and-medium run costs until 2030 of 100€/t CO_2. The high estimates are 189 €/t CO_2.

The Global Warming Potential (GWP) helps determine the total CO_2 equivalent GHG emissions. This is done to simplify the comparison between CO_2 and non- CO_2 emissions. Comparing the heat trapped by similar amounts of CO_2 and non- CO_2 emissions during 100 years leads to the GWP measurements. Table 7 shows the GWPs for the GHG emissions potency compared to CO_2 over 100 years, according to IPCC, (2013).

Table 7: GWPs for GHG emission potency compared to CO_2

Emission	GWP
CO_2	1
CH_4	30
N_2O	265

First, the study uses the emission factors from COPERT data of CO_2, CH_4, and N_2O, and transport performance data from Eurostat. Then, it applies the GWP to sum up the total emissions of the GHG in a tonne of CO_2 equivalent. Finally, the cost factors from the NEEDS approach provides the total costs of climate change per vehicle per country.

The values are in Table 8; they present the average costs for climate change.

Table 8: Average costs for climate change in €-cent per pkm

	Average costs (€-cent per pkm)			
	Pass car - petrol	Pass car - diesel	Pass car - total	Bus
Denmark	1.168	1.054	1.126	0.418
Finland	1.503	1.398	1.478	0.418
France	1.122	1.096	1.104	0.519
Luxembourg	1.385	1.206	1.267	0.477
Switzerland	1.358	1.174	1.308	0.438

Following the same comparison with the small electric urban bus from the air pollution costs, the average costs for automated minibuses for climate change are negligible van Essen et al., (2019).

3.2.3 Aggregated emission of well-to-tank

The well-to-tank phase represents the energy provision for driving. Thus, the cost is of energy production. It accounts for the aggregated emissions of fossil fuel as well as electricity extraction, processing, transport, and transmissions (Hagedorn and Sieg, 2019).

The methodology to estimate the costs is similar to that of air pollution and climate change during the tank-to-wheel assessment (using damage cost for air pollution and avoidance costs for GHG emissions). The marginal costs of well-to-tank emissions are in Table 9.

Table 9: Average costs of WTT in €-cent/pkm

		Average costs (€-cent per pkm)			
		Pass car - petrol	Pass car - diesel	Pass car - total	Bus
Denmark	DK	0.374	0.340	0.361	0.158
France	FR	0.425	0.393	0.403	0.191
Luxembourg	LU	0.653	0.603	0.620	0.296
Switzerland	CH	0.430	0.397	0.421	0.190

Similarly to the previous analysis, the marginal cost of WTT for the automated minibus is 0.54 – 0.63 €-cent per pkm.

Finally, the summed average costs of the emissions for the well-to-wheel assessment (aggregated well to tank, air pollution and climate change for tank-to-wheel) for the buses, cars, and automated minibuses are presented in Table 10.

Table 10: The average external cost per mode of transport in €-cent per pkm for the wtw emissions

	Average costs – WTW emissions in €-cent per pkm				
	Passenger car			Bus	automated minibus
	petrol	diesel	total		
Denmark	1.83	2.20	1.97	0.67	0.59
France	1.93	2.75	2.51	1.20	0.59
Luxembourg	2.47	4.44	3.77	2.14	0.59
Switzerland	2.10	3.03	2.35	0.94	0.59

3.2.4 Noise

The estimation of the noise impact relies mainly on noise maps. It depends on the number of people exposed to noise based on 5dB thresholds from noise maps from EEA (2014).

Following the analysis of the Delft report, the annoyance cost is calculated based on willingness-to-pay (WTP). WTP is the price (or below) a person is willing to pay to avoid the nuisance of noise. It estimates a € 14/dB per person as an annoyance cost for people exposed to a range of 50-55 dB. The health values are estimated based on a burden of disease approach from the Defra (2014) report. It accounts for a €40 300 for Value-of-statistical life (VOLY).

Notably, the noise effects depend on the population density, the traffic status, and time of day. Thus, the marginal costs differ from the average costs. However, the data on a country level for theses specific contexts is limited. Thus, the model at hand uses average costs (Table 11) as they reflect more the specifics on the deployment location. The marginal costs for the UE28 (Table 12) level will be used in the sensitivity analysis.

Table 11: Average costs per country for noise per the mode of transport in €-cent/pkm

		Average costs (€-cent per pkm)			
		Pass car - petrol	Pass car - diesel	Pass car - total	Bus
Denmark	DK	0.60	0.64	0.62	0.34
France	FR	0.36	0.38	0.38	0.28
Luxembourg	LU	0.52	0.54	0.53	0.28
Switzerland	CH	1.89	2.00	1.92	0.84

Table 12: Marginal costs for noise per €-cent per pkm

Marginal costs in €-cent per pkm for EU level			
Mode of transport	Time of the day	Traffic situation	Cost
Passenger car	Day time	Dense	0.5
		Thin	1.1
	Night time	Dense	0.9
		Thin	2.1
Bus	Day time	Dense	0.5
		Thin	1.3
	Night time	dense	1
		Thin	2.4

For the automated minibus, the costs depend on the traffic status on the operation time of the day, similarly to an Internal combustion engine vehicle. At higher speeds (higher than 40km/h), there is no significant difference between an electric vehicle and an ICEV. For constant low speed, electric vehicles are quieter (Pallas et al., 2015)

The noise from the electric engine in the vehicle is negligible for speeds between 30-50 km/h. The lion's share of the noise goes to the tires and the aerodynamic components. The automated minibus circulates in a speed between 12 and 30 km/h in urban areas where maximum speed limits are around 50km/h.

Thus, the engine is not going to be causing noise compared to the other forms of traffic. Also, there is a difference in the overall noise between automated minibuses and traditional vehicles.

Hence, there are potential savings in external costs when replacing automated minibuses and ICEV (or standard buses). The automated components do not emit significant noise. Thus, the automated minibus is comparable to an electric vehicle in term of noise pollution.

The research of Jochem et al. (2016) for the external costs of electric vehicles is adopted to estimate the average costs. His research considers the traffic situation in estimating the cost; the operation time during the night leads to higher costs.

The final result for the EU level costs for automated minibuses for noise in €-cent/pkm are in Table 13. Further analysis is required to distinguish the effect of different traffic situation (dense/thin).

Table 13: The average costs for the automated minibus for noise in €-cent/pkm

	Day time	Night time
EU level for automated minibuses	0.2	0.4

3.2.5 **Habitat loss**

It follows the same process for the marginal costs of air pollution. Cost factors from NEEDS are combined with the extent of the road infrastructure. The marginal costs for damage habitat depend significantly on the infrastructure.

The electric automated minibuses are circulating on the same road network. However, their deployment could lead to a reduction in the road space needed. Thus, it is important to estimate the potential urban road space saved by reducing the number of vehicles circulating. This space is called dynamic space. It depends on the width of the roadway as well as the distance of safe driving between vehicles). The estimation of the dynamic space DS needed per vehicle depends on the speed of circulation (Table 14)

Table 14: dynamic space needed per vehicle in m^2 based on the speed of circulation

Speed km/h	10	30	50
DS per car	15	34	66
DS per standard bus	46	78	135
Shuttle	36	75	113

The space saved is then multiplied by the cost factors €/km^2 from Table 15 to produce the overall saved externality). This represents the potential savings from different deployment (or replacement) scenarios.

Table 15: Cost factors for Habitat damage for urban roads in €/km^2

	Road €/km^2
EU-28	4 100
Denmark	5 500
France	4 900
Luxembourg	4 300
Switzerland	6 800

3.3 Test application at the city of Geneva

To better test the estimations from the societal external costs, especially the well-to-wheel emissions and noise, a case study of a scenario in Geneva that accounts for the change in modal shares between 2015 and 2040 is presented. The calculations rely on the data from "The mobility of the residents of Geneva, results from the micro-census of mobility and transportation 2000-2015 "[1] . The survey and report provide daily distances, number of annual trips and modal shares. Further development was needed to estimate the overall annual pkm by determining the average annual distance travelled per person per mode of transport.

The value for the average individual trip per day in Geneva in 2015 is 3.6, while the average distance is 30.3 km per day. It is important to note that the mobility survey is a residential based survey. Thus, it accounts for only the trips conducted by residents of Geneva (does not account for tourists' trips in the canton). The population of Geneva in 2015 was 484 736 residents, and the number of private cars was 221 143 (FSO, 2016). Table 16 shows the different estimation for modal shares and total pkm.

Table 16: Modal shares and total pkm for Geneva 2015

Mode of transport	Percentage of annual trips	Average daily distance per person	Person mobility distance (pkm)
public transport	16.6	7	2555
private cars	33.9	19.2	7008
cycling	5.6	0.9	328.5
walking	39	2.3	839.5

The federal office for spatial development (ARE) of Switzerland[2] estimates an increase of 18% in the modal share of private vehicles by 2040. This value will be applied on the canton level. In this scenario, the automated vehicles for public transport will replace this increase but will not lead to an increase of total vkm as the deployment is part of Transport Demand Management (TDM). The TDM strategy provides efficient use of vehicles in support of public transport. Therefore, the introduction of new mobility modes will not lead to increasing demand but rather a targeted deployment to address the shortcomings of the transportation system.

The vehicles will circulate during the day and on near capacity trunk urban roads. These specifications are important to select the external costs factors.

The estimations and savings are presented in Table 17.

Table 17: Externalities and savings for replacing 18% of ICEV in 2040 in million €

	Externalities in million€ 18% share of pkm by private cars	Externalities in million€ 18% of pkm by automated minibuses	Savings of externalities in million €
TTW Air pollution	3.83	0.306	3.52
TTW Climate change	7.995	0	8
WTT	2.572	3.302	-0.73
overall WTW	14.4	3.61	10.8
Noise	11.747	1.223	10.52

[1] N° 59 – MAI 2019 – COMMUNICATIONS STATISTIQUES

[2] Transport outlook 2040, 2016

For this scenario in 2040 in Geneva, the total savings from replacing the expected increase in private vehicles modal share with the minibuses is around 21.3 million euros. Notably, the circumstances of the deployment such as the vehicles specifications (speed, automated technology), and traffic situation (day/night, type of road, type of traffic), mobility behaviour (modal share, overall vkm), and policies (TDM) play an important role of varying the savings of societal costs of deployment of automated minibuses.

3.4 Conclusions and recommendations for next steps of analysis

The estimations for externalities demonstrate positive results for introducing the automated minibuses when replacing individual forms of mobility. The analysis puts a monetary value on the environmental impacts of deploying this mode of transportation on a city-level. The analysis of mobility surveys is an important step to determine the modal shares and the total pkm. Moreover, the mobility targets for cities provide insights on realistic modal shifts in the future. The study of the external costs should be further developed. The social costs incurred from the production and recycling phases should be addressed in the next step in the analysis. Further development will elaborate on the potential modal shifts caused by the deployment of the automated minibuses. The scenarios of introducing the automated minibuses within the cities of the future will be defined in more detail and tested using the externalities calculations. The environmental indicators for sustainability assessment could further support the development of scenarios and provide important insights for sustainable mobility.

4 Environmental indicators for sustainability assessment

The objective of this section is to investigate the environmental performance of the automated minibus through mobility indicators. Indicators are used to measure performance and progress towards established goals and objectives (Litman, 2007). Sustainability indicators are a powerful tool to simplify, quantify, analyse, and communicate complex information (KEI, 2005; Singh et al., 2009; Innamaa and Salla, 2018). Urban sustainability indicators are fundamental to support target setting, performance reviews and to enable communication among the policymakers, experts and the general public (Verbruggen, H., Kuik O., 1991; Shen et al., 2011). Castillo and Pitfield's (2010) study on sustainable transport assessment tools points to the attractiveness and convenience of indicators due to their ability to capture the multidimensionality of sustainable transport'.

The environmental indicators presented in this section are part of a set of sustainability indicators (see table 18). The sustainability indicators consist, in addition to the environmental indicators, indicators assessing the social, economic, governance and system performance of automated minibuses. The complete set of indicators is introduced and discussed in D.8.10 first iteration sustainability assessment[3] and technical indicators.

The environmental indicators assessed are:

- energy efficiency,
- use of renewable energy,
- noise pollution,
- air pollution,
- climate change

Table 18: The set of indicators for sustainable mobility assessment of automated electric minibuses

		Multidimensions				
Indicators	**Unit and methods of measurement**	**S**	**En**	**Ec**	**G**	**SP**
Accessibility	• Percentage of the city (area) coverage by the automated minibus service • Percentage of the population that has convenient access (within 0.5 km) to the AS service					
	• automated minibuses accessible digitally (e.g. via apps)					
Accessibility for people with reduced mobility	• External environment facilities e.g., stops adaption for impaired/disabled people; tactile surfaces information • Internal environment facilities e.g., audible warning equipment for visually impaired people; facilities to wheelchair users					
	• Usability of the AS by people with reduced mobility (PRM) • Rating of users with reduced mobility concerning AS experience					
Safety	• Number accidents related to the AS (mild injuries, serious injuries, fatalities); nr/year					

[3] Nemoto et al., Deliverable 8.10. First iteration sustainability assessment. Available at https://h2020-avenue.eu/public-delivrables/

Security	• Number of criminal occurrences; nr/year					
	• Number of cybersecurity threats or attacks; nr/year					
Passenger's affordability	• The price of the ride on automated minibuses (considering fixed itinerary or on-demand) compared to other public transport;					
User acceptance	• User's perception about the readiness of the technology • User's willingness to pay • Safety feeling • Security feeling					
User satisfaction	• User rating concerning automated minibuses experience (comfort, speed, punctuality, information, frequency, connection to other means of transport)					
Energy Efficiency	• Energy consumed for passenger per km (kWh/pkm)					
Renewable energy	• Use phase: Energy source and percentage of renewable energy sources (%)					
Air Pollution	• automated minibuses emissions of air pollutants: PM levels (ug/m3), NOx, CO emissions					
Climate change	• automated minibuses GHG emissions: CO_2eq/pkm					
Noise Pollution	• automated minibuses traffic noise (dB)					
Investments on mobility	• Public and Private annual average investment on transport concerning automated vehicles (Euro/year), e.g. infrastructure, operational expenditures (cost of personnel, software system, etc.), investments on the vehicle R&D					
Economic incentives to AV and sustainable mobility	• Incentives and subsidies for automated and sustainable mobility, e.g., shared, electric, automated, zero-emission, vehicles (Euro)					
Economic profitability	• TCO (Total Cost of Ownership), TCM (Total Cost of Mobility), Cost/km/passenger, revenues (ticketing from passengers, subsides from authorities and companies), and payback period					
External costs related to the automated minibuses	• automated minibuses impacts on congestion avoidance, accidents reduction, noise reduction, air pollution (PM, Nox) reduction, QALY (quality-adjusted life years) reduction, land/parking reduction, vehicle savings					
Institutional development and innovation	• Existence of policies and regulations concerning automated vehicles • Regulations for open data and/or APIS for transport					
Performance and Reliability	• Automated minibus performance: . travel time: trip length, speed, frequency of departure or average waiting time, punctuality/delays, number of journeys per day, bus stops per km^2, average total passenger per km travelled per day, percentage of operational service . performance on different seasons, e.g., number of riding days according to the different seasons . on-demand availability . vehicle occupancy (mean number of people per vehicle) . effective system capacity (maximum of passengers per vehicle) . the average lifetime of the vehicle . number of disengagements in the urban environment, number of km driven autonomously . number of driving situation handled autonomously in the urban environment					
System integration and efficiency	• AS integration with mobility platform of the operator (planning, reservation, booking, billing, digital ticketing) • System interoperability and the existence of open data for AS (access, static and/or dynamic real-time data, diffusion format, data quality, or APIS for transport) • Intermodality: AS integration with other public or private means of transport or with a multimodal platform for one					

	intermodal trip (planning, reservation, booking, billing, digital ticketing)					

S= Social; En = Environmental, Ec = Economic, G = Governance, SP= System performance

The environmental indicators are applied in order to measure the current performance of the automated minibus in the demonstrators' sites. Each indicator requires a specific methodology. These will be described in the subsequent sub-sections. In general, the value of the indicators is represented on a scale of 0 to 5, with 5 being considered the best score. For each indicator we

(i) define a parameter
(ii) define a scale, with minimum and maximum values considering the environmental impacts of main urban modes of transport, e.g. walking, cycling, small and big cars, bus (freight transport and air transport were not comprehended for example).
(iii) Calculate the indicator value for the automated minibus according to the demonstrator site

The results are presented on a spider chart, providing a disaggregated overview of the indicators. This allows for identifying the weaknesses and strengths of each indicator (WBCSD, 2015), also for a comparison between the pilot-sites.

A limitation of the assessment is caused by the innovativeness of the automated minibus. The technology is still in a test and development phase, which sets some limitations to the pilot-sites. These limitations include;

- limitations of the pilot-projects to a local/neighbourhood area;
- automated minibuses drive in mixed traffic area at a low average speed (10-15km/h);
- automated minibuses drive within a fixed route (with the exception of 'Bellé Idée' test-site, where on-demand service has been tested);
- safety operator is inside the automated minibus in case human interventions are necessary, as well as to report the automated minibus performance in general.

These limitations reduce the performance and usability of the automated minibus. In addition, the demonstrator sites are facing constraints due to Covid 19 pandemic. Hence, tests have been facing interruptions, and some sites have limited the maximum numbers of passengers as four, a factor that will influence negatively the performance of the environmental indicators as well.

4.1 Climate Change

Definition: greenhouse gases emitted by the automated minibus per passenger-km

Parameter: gCO_2 eq/pkm

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

gCO_2eq = grams of CO_2 equivalent.

Methodology: the LCA study (section 2) provided the GHG emissions (gCO_2 eq/pkm) for the automated minibus.

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 AVENUE project (Huber et al., 2019). Those studies comprehend the GHG emissions (gCO_2eq/pkm) for two/three-wheelers, buses and minibuses, small/medium and large vehicles as individual transportation or public transport. Following these references, emissions levels equal to or higher than 300 CO_2eq/pkm are defined as maximum scale.

Scale:

0 = ≥ 300 gCO_2eq/pkm

5 = 0 gCO_2eq/pkm

Calculation:

Parameter value:	93,00
Indicator value	3,45

0	5	
min scale	max scale	
300	0	gCO2/pkm

Obs: Example of Pfaffenthal (Luxembourg)

Sources: Huber et al. (2019), International Energy Agency (2020)

4.2 Renewable energy

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

Parameter: percentage of renewable energy in 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). (APPENDIX A)

Scale:

0 = 0%

5 = 100%

Calculation:

Parameter value:	21,2
Indicator value	1,06

0	5	
min scale	max scale	
0	100	% renewable energy

Obs: Example of Groupama Stadium (Lyon)

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

4.3 Noise pollution

Definition: noise emission by the mode of transport.

Parameter: vehicle noise in Decibels (dB) at 30km/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 11-15km/h in areas with a speed limit of 30km/h, the noise difference reported for different vehicles was considered at 30km/h (Lelong and Michelet, 2001; Cai, 2012; Dudenhöffer and Hause, 2012; Marbjerg, 2013). The noise emission for the automated minibus was considered similar for a BEV, as 58 decibels in constant speed at 30km/h.

Scale:

0 ≥ 75dB

5 = 0 dB

Calculation:

Parameter value:	58
Indicator value	1,13

0	5	
min scale	max scale	
75	0	Decibels

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

4.4 Air pollution

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

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

Methodology:

Particulate matter (PM) and nitrogen oxides (NO_x) are the main transport air pollutant emissions along with carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs) and sulphur oxides (SOx). The emissions from road transport are mainly exhaust-emissions arising from fuel combustion, and non-exhaust releases contribute to NMVOCs (from fuel evaporation) and

primary PM due to tyre- and brake-wear and road abrasion (European Environment Agency, 2019). Further, transport is responsible for more than half of all NOx emissions (ibid).

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

Scale:

$PM_{2,5}$

0 ≥ 0,005 $PM_{2,5}$ g/km

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

NO_x

0 ≥ 0,08 NO_x g/km

5 = 0 NO_x g/km

$PM_{2,5}$ Non exhaust

0 ≥ 0,0474 $PM_{2,5}$ g/km

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

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

Table 19: The light-duty Euro 5 and Euro 6 vehicle emission standards (g/km)

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

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

Source: Williams and Minjares (2016)

Calculation:

Air pollution

Indicator value	4,60

PM 2,5

Parameter value:	0
Indicator value	5,00

0	5	
min scale	max scale	
0,005	0	PM 2,5 g/km

NOx

Parameter value:	0
Indicator value	5,00

0	5	
min scale	max scale	
0,08	0	NOx g/km

Non exhaust

Parameter value:	0,0115
Indicator value	3,79

0	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).

4.5 Energy Efficiency

Definition: energy consumption (kWh) by the automated minibus 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: the LCA study (section 2) provided the energy consumption of 0,52kWh/km for the automated minibus.

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:

0 = ≥ 0,97 kWh/pkm

5 = 0,14 kWh/pkm

Calculation:

Parameter value:	0,22
Indicator value	4,54

0	5	
min scale	max scale	
0,97	0,14	KWh/pkm

Obs: Example of Contern (Luxembourg)

Sources: Huber et al. (2019), WBCSD (2015).

4.6 Results and discussion

The environmental indicators were calculated for five different demonstrator sites: Pfaffenthal and Contern (Luxembourg city), Groupama Stadium (Lyon, France), Ormøya (Oslo, Norway), Nordhavn (Copenhagen, Denmark). The sites are further described in Table 20, and the results illustrate in Figure 13.

Table 20: Description of the demonstrator sites

City	Pilot	Characteristics of route	Type of passenger
Lyon	Groupama Stadium	Fixed route with stops 1.3 km. Will become an on-demand, door-to-station service	regular workers, people with reduced mobility (medical centre nearby)
Copenhagen	Nordhavn	Fixed route with stops, 1,2km, will become an on-demand, door-to-door service	Residents of the area, tourists
Oslo	Ormøya	Fixed route with stops, 3,6 km,	Residents of the area
Luxembourg	Contern	Fixed route with stops, on-demand. 2.2 km	Employees working at Campus Contern
	Pfaffenthal	Fixed route with stops, on-demand 1.2 km	Workers, tourists, residents, and visitors of Luxembourg city

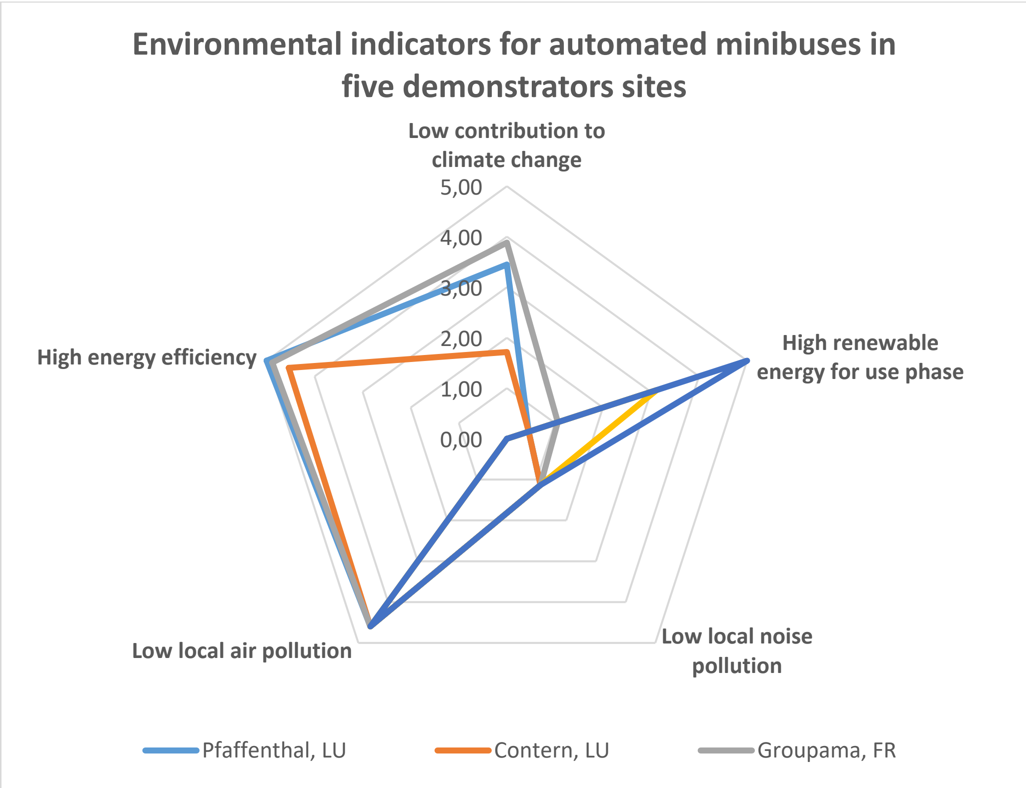

Figure 13: Environmental performance of automated minibuses in the demonstrator sites. Scale 0 to 5, with 5 as the best score and 0 worst score.

The indicators addressing local air pollution and local noise pollution do not vary from site to site because they are assessed according to the vehicle. As an electric vehicle, the EASCB has a good score on local air pollution. It is explained by the fact that BEVs have zero exhaust emissions, e.g. NOx and PM; they just emit PM locally from road, tyre and brake wear, like other motor vehicles (European Environment Agency, 2018). The air pollutant emissions for the electricity generation to charge BEV batteries occur in power stations and tend to impact less densely populated areas (ibid). For this reason, the local air pollution emissions for the use phase is here assessed since it affects the cities (more densely populated areas) and consequently causes greater human exposure and potential health harm.

As for local noise pollution, the automated minibus - as an EV - do not differ significantly from ICEV in the usual traffic, except for urban traffic during the night at low-speed areas (Jochem et al., (2016).

The climate change indicator is affected by the vehicle lifetime, total mileage, vehicle occupancy, electricity mix, as pointed by the LCA study (section 2). In this regard,

Groupama Stadium (Lyon) and Pfaffenthal (Luxembourg) present a better performance due to the higher mileage and higher average of vehicle occupancy. While Ormøya (Oslo) and Nordhavn (Copenhagen) do not perform well due to the very low average occupancy and low mileage in the case of Nordhavn.

However, it is important to mention that those data and performance are also impacted by the Covid 19 pandemic restrictions, the reduction in mobility and in the use of public transport.

The energy efficiency indicator, in particular, is affected by the number of passengers (average occupancy). Therefore Groupama Stadium (Lyon), Pfaffenthal and Contern (Luxembourg) present a good score, in contrast to Nordhavn (Copenhagen) and Ormøya (Oslo).

The indicator of renewable energy for the use phase varies according to the share of energy from renewable sources in gross electricity consumption in each country. In this case, Nordhavn (Copenhagen) and Ormøya (Oslo) present a good score, since Denmark and Norway have a share of energy from renewable sources in gross electricity consumption of 62% and 100% respectively, in contrast to Luxembourg 9% and France 21%.

4.7 Conclusions

The preliminary results point that to improve the attractiveness of the automated minibus as an environmentally friendly means of transport, significant improvements have to be made towards better performance regarding climate change. It can be achieved in the short term through increased mileages and vehicle occupancy. Overall, the energy efficiency and reduction in local air pollution are strong points of the automated minibus. When targeting the reduction of local noise pollution, the automated minibus do not present many advantages in comparison to other cars, for examples. Therefore, the incentives for soft modes of transport might be more effective.

This section presents preliminary results for the environmental indicators. Hence, in the upcoming months, more data will be collected to update the analysis and results.

5 Conclusions

The second iteration of the environmental deliverable presented further insights on the environmental footprint of introducing the automated minibuses in urban areas. The progress in the life cycle assessment solidified the results from the first deliverable. The results prove a significant reduction in environmental impacts despite relying on the circumstances of pilot testing. The sensitivity analysis and the scenarios show promising results for the near future. The increase in occupancy and mileage leads to better environmental outcomes. Moreover, the advances in technology could extend the lifetime of the automated minibus and lead to better energy use, which will reflect the automated minibus's operation. The LCA compares the climate effects of the automated minibus with other individual and public modes of transportations such as ICEVs, BEVs, and HFC buses during peak and off-peak hours. The automated minibus with ideal mileage and occupancy rates fare better than other modes of transportation. This supports the positive impacts of integrating automated minibuses in the transportation system. The assessment also went a step further by contemplating the effects of the automated minibuses on the modal split by considering the effects on individual mobility, NMT, and new mobility. It also presented the potential implications of physical and digital infrastructure. The study demonstrates limitation in accounting for the V2X environmental impacts. Future development will look more in details into the effects on modal splits and potential modal shifts. The complementarity with robotaxis and public transport also opens the door for more opportunities to reduce climate effects.

Moreover, the analysis of these vehicles externalities supports the initial favourable environmental impacts. The macro-scale assessment considers integrating the automated minibuses on a city level and putting monetary values on its emissions and energy consumption. The costs or the savings provide important insights on which scenarios to adopt to reduce further the car-ownership rates and the environmental impact of urban transportation. In the first phase, the external costs factors are fixed. It considers air pollution, climate change, well-to-tank emissions, noise, and habitat damage. For future phases, a study on the potential modal shifts caused by the automated minibuses and the deployment cities' mobility goals will be conducted. It will define future scenarios based on different modal splits and compare the environmental costs incurred in each scenario. Moreover, the production and recycling phases' external costs will be considered for detailed comparison with different transport modes.

Finally, the definition of the environmental indicators from the sustainability assessment helps to measure the sustainable performance of the automated minibuses. The indicators in question address energy efficiency, renewable energy, noise pollution, air pollution, and climate change. The assessment is conducted on the pilot level. The values are set on a scale from 0 to 5. The indicators are presented in this iteration to better connect the environmental assessment to the sustainable one. The choice of methods of measurement is determined to lay the ground for a broader analysis. The future steps include scalability on a city level. It will also relate to potential modal shifts and projected mobility goals for the AVENUE cities. The indicators will further help measure the impact of automated minibuses on urban mobility. The data collection and analysis will help further to build a sustainability radar.

The consolidation of the LCA, the externalities calculations, and the environmental indicators help paint a more detailed picture of the potential implications of the deployment of the automated minibuses. Future studies will focus on deployment scenarios based on worst, best, and ideal cases. It will lead to a realistic approach to integrating this transportation mode within public transport efficiently. Furthermore, it provides insights to policymakers to implement mobility and environmentally friendly policies. However, further attention should be given to potential rebound effects such as induced demand and social exclusion (limited technological access could affect mobility behaviour). Finally, the effects on active mobility also pose a potential risk to environmental gains.

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Appendix A:

Share of energy from renewable sources in gross electricity consumption, 2004-2018
(%)

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
EU-27	15.9	16.4	16.9	17.7	18.6	20.7	21.3	23.3	25.2	26.9	28.7	29.7	30.2	31.1	32.2
EU-28	14.2	14.8	15.3	16.1	16.9	19.0	19.7	21.6	23.5	25.3	27.4	28.8	29.5	30.7	32.1
Belgium	1.7	2.4	3.1	3.6	4.6	6.2	7.1	9.1	11.3	12.5	13.4	15.6	15.9	17.3	18.9
Bulgaria	8.4	8.7	8.7	8.9	9.5	10.9	12.4	12.6	15.8	18.7	18.7	19.0	19.1	19.0	22.1
Czechia	3.7	3.8	4.1	4.6	5.2	6.4	7.5	10.6	11.7	12.8	13.9	14.1	13.6	13.7	13.7
Denmark	23.8	24.6	24.0	25.0	25.9	28.3	32.7	35.9	38.7	43.1	48.5	51.3	53.7	60.0	62.4
Germany	9.5	10.6	12.0	13.8	15.2	17.6	18.3	21.0	23.6	25.3	28.2	30.9	32.3	34.6	38.0
Estonia	0.5	1.1	1.4	1.4	2.0	6.0	10.3	12.2	15.7	12.9	14.0	15.1	15.5	17.4	19.7
Ireland	6.0	7.2	8.5	9.7	10.8	14.0	15.6	18.3	19.8	21.3	23.5	25.5	26.8	30.1	33.2
Greece	7.8	8.2	8.9	9.3	9.6	11.0	12.3	13.8	16.4	21.2	21.9	22.1	22.7	24.5	26.0
Spain	19.0	19.1	20.0	21.7	23.7	27.8	29.8	31.6	33.5	36.7	37.8	37.0	36.6	36.4	35.2
France	13.8	13.7	14.1	14.3	14.4	15.1	14.8	16.2	16.5	17.0	18.5	18.8	19.2	19.9	21.2
Croatia	35.0	35.2	34.8	34.0	33.9	35.9	37.5	37.6	38.8	42.1	45.2	45.4	46.7	46.4	48.1
Italy	16.1	16.3	15.9	16.0	16.6	18.8	20.1	23.5	27.4	31.3	33.4	33.5	34.0	34.1	33.9
Cyprus	0.0	0.0	0.0	0.1	0.3	0.6	1.4	3.4	4.9	6.7	7.4	8.4	8.6	8.9	9.4
Latvia	46.0	43.0	40.4	38.6	38.7	41.9	42.1	44.7	44.9	48.7	51.0	52.2	51.3	54.4	53.5
Lithuania	3.6	3.8	4.0	4.7	4.9	5.9	7.4	9.0	10.9	13.1	13.7	15.5	16.9	18.3	18.4
Luxembourg	2.8	3.2	3.2	3.3	3.6	4.1	3.8	4.1	4.7	5.3	6.0	6.2	6.7	8.1	9.1
Hungary	2.2	4.4	3.5	4.2	5.3	7.0	7.1	6.4	6.1	6.6	7.3	7.3	7.3	7.5	8.3
Malta	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	1.1	1.6	3.3	4.3	5.7	6.8	7.7
Netherlands	4.4	6.3	6.5	6.0	7.5	9.1	9.6	9.7	10.4	9.9	9.9	11.0	12.5	13.8	15.1
Austria	61.6	62.9	63.8	65.7	65.9	68.6	66.4	66.8	67.4	68.9	71.1	71.5	72.5	71.6	73.1
Poland	2.2	2.7	3.0	3.5	4.4	5.8	6.6	8.2	10.7	10.7	12.4	13.4	13.4	13.1	13.0
Portugal	27.4	27.7	29.3	32.3	34.1	37.6	40.6	45.8	47.5	49.1	52.1	52.6	54.0	54.2	52.2
Romania	28.4	28.8	28.1	28.1	28.1	30.9	30.4	31.1	33.6	37.5	41.7	43.2	42.7	42.0	41.8
Slovenia	29.3	28.7	28.2	27.7	30.0	33.8	32.2	31.0	31.6	33.1	33.9	32.7	32.1	32.4	32.3
Slovakia	15.4	15.7	16.6	16.5	17.0	17.8	17.8	19.3	20.1	20.8	22.9	22.7	22.5	21.3	21.5
Finland	26.7	26.9	26.4	25.5	27.3	27.3	27.7	29.4	29.5	30.9	31.4	32.5	32.9	35.2	36.8
Sweden	51.2	50.9	51.8	53.2	53.7	58.3	55.8	59.6	59.8	61.7	63.2	65.7	64.9	65.9	66.2
United Kingdom	2.5	3.2	3.7	4.1	4.7	6.0	6.9	8.3	10.3	13.4	17.5	21.9	24.0	27.4	30.9
Norway	98.0	97.4	100.8	99.1	100.2	105.2	98.2	105.9	104.6	106.9	110.1	106.8	105.7	104.9	106.8
Montenegro	:	39.1	37.7	37.6	38.3	46.6	45.7	41.6	42.8	49.1	51.4	49.6	51.0	50.1	52.4
North Macedonia	14.5	14.0	14.0	13.7	13.8	15.5	15.8	14.8	16.7	18.2	19.3	21.7	24.1	24.8	24.8
Serbia	18.5	22.4	23.6	24.8	25.9	28.3	28.2	27.5	28.5	28.0	30.3	28.9	29.2	27.4	28.7
Albania	70.0	76.1	74.2	79.6	73.3	70.7	74.6	66.1	72.4	62.7	71.0	79.2	82.1	91.0	92.5
Turkey	27.9	26.3	24.7	23.2	22.8	24.7	25.3	25.1	27.1	30.0	30.5	33.2	34.8	35.1	37.5
Kosovo*	0.5	0.6	0.9	1.0	1.0	1.1	1.4	1.4	1.5	1.6	1.9	1.8	4.0	3.6	4.2

Note: ":" means data not available

* *This designation is without prejudice to positions on status, and is in line with UNSCR 1244/1999 and the ICJ Opinion on the Kosovo declaration of independence.*

Source: Eurostat (online data code: nrg_ind_ren)

Source: Eurostat (2020)

Appendix B

Calculation table

The table below includes the linkages to the blue cells of the input tables above.

The starting point for the estimation of air pollutant emissions is the same as the estimation of energy consumption.

transport mode i	vehicle type j	type of energy k	c	A_{ij} (Million vkm)	S_{ijk}	C_{ijkc}	$A_{ij} * S_{ijk} * C_{ijkc}$ (million vkm)	NOx Emissions (tons)	NOx E_{ijkc} (g/km or g/kWh)	Unit	PM2.5 Emissions (tons)	PM 2.5 E_{ijkc} (g/km or g/kWh)	Unit	PM2.5 NE_{ci} (g/km)	non-exhaust PM2.5 emissions (tons)
								air pollutant emissions							
car	passenger	Gasoline	Gasoline pre-Euro/Euro 0	0,0	0,0%	0,0%	0	0,000	2,64		0,000	0,0022		0,0115	0
car	passenger	Gasoline	Gasoline Euro 1	0,0	0,0%	0,0%	0	0,000	0,52		0,000	0,0022		0,0115	0
car	passenger	Gasoline	Gasoline Euro 2	0,0	0,0%	0,0%	0	0,000	0,28		0,000	0,0022		0,0115	0
car	passenger	Gasoline	Gasoline Euro 3	0,0	0,0%	0,0%	0	0,000	0,11		0,000	0,0011		0,0115	0
car	passenger	Gasoline	Gasoline Euro 4	0,0	0,0%	0,0%	0	0,000	0,07		0,000	0,0011		0,0115	0
car	passenger	Gasoline	Gasoline Euro 5	0,0	0,0%	0,0%	0	0,000	0,07		0,000	0,0014		0,0115	0
car	passenger	Gasoline	Gasoline Euro 6	0,0	0,0%	0,0%	0	0,000	0,07		0,000	0,0014		0,0115	0
car	passenger	(Bio)Diesel	Diesel pre-Euro/Euro 0	0,0	0,0%	0,0%	0	0,000	0,75		0,000	0,2209		0,0115	0
car	passenger	(Bio)Diesel	Diesel Euro 1	0,0	0,0%	0,0%	0	0,000	0,80		0,000	0,0842		0,0115	0
car	passenger	(Bio)Diesel	Diesel Euro 2	0,0	0,0%	0,0%	0	0,000	0,83		0,000	0,0548		0,0115	0
car	passenger	(Bio)Diesel	Diesel Euro 3	0,0	0,0%	0,0%	0	0,000	0,90		0,000	0,0391		0,0115	0
car	passenger	(Bio)Diesel	Diesel Euro 4	0,0	0,0%	0,0%	0	0,000	0,67		0,000	0,0314		0,0115	0
car	passenger	(Bio)Diesel	Diesel Euro 5	0,0	0,0%	0,0%	0	0,000	0,70		0,000	0,0021		0,0115	0
car	passenger	(Bio)Diesel	Diesel Euro 6	0,0	0,0%	0,0%	0	0,000	0,24		0,000	0,0015		0,0115	0
car	passenger	CNG	Euro 3	0,0	0,0%	15,0%	0	0,000	0,12		0,000	0,0011		0,0115	0
car	passenger	CNG	Euro 4	0,0	0,0%	14,0%	0	0,000	0,07		0,000	0,0011		0,0115	0
car	passenger	CNG	Euro 5	0,0	0,0%	49,0%	0	0,000	0,07		0,000	0,0011		0,0115	0
car	passenger	CNG	Euro 6	0,0	0,0%	22,0%	0	0,000	0,07		0,000	0,0011		0,0115	0
car	passenger	LPG	Euro 3	0,0	0,0%	14,0%	0	0,000	0,10		0,000	0,0011		0,0115	0
car	passenger	LPG	Euro 4	0,0	0,0%	12,0%	0	0,000	0,07		0,000	0,0011		0,0115	0
car	passenger	LPG	Euro 5	0,0	0,0%	49,0%	0	0,000	0,07		0,000	0,0011		0,0115	0
car	passenger	LPG	Euro 6	0,0	0,0%	25,0%	0	0,000	0,07		0,000	0,0011		0,0115	0
car	passenger	Bio-Ethanol / ethanol	Euro 3	0,0	0,0%	37,0%	0	0,000	0,12		0,000	0,0011		0,0115	0
car	passenger	Bio-Ethanol / ethanol	Euro 4	0,0	0,0%	31,0%	0	0,000	0,06		0,000	0,0011		0,0115	0
car	passenger	Bio-Ethanol / ethanol	Euro 5	0,0	0,0%	17,0%	0	0,000	0,06		0,000	0,0011		0,0115	0
car	passenger	Bio-Ethanol / ethanol	Euro 6	0,0	0,0%	15,0%	0	0,000	0,06		0,000	0,0011		0,0115	0
car	passenger	Gasoline Hybrid	Euro 3	0,0	0,0%	1,0%	0	0,000	0,03		0,000	0,0011		0,0115	0
car	passenger	Gasoline Hybrid	Euro 4	0,0	0,0%	5,0%	0	0,000	0,02		0,000	0,0011		0,0115	0
car	passenger	Gasoline Hybrid	Euro 5	0,0	0,0%	30,0%	0	0,000	0,02		0,000	0,0011		0,0115	0
car	passenger	Gasoline Hybrid	Euro 6	0,0	0,0%	64,0%	0	0,000	0,02		0,000	0,0011		0,0115	0
car	passenger	Diesel Hybrid	Euro 3	0,0	0,0%	1,0%	0	0,000	0,03		0,000	0,0011		0,0115	0
car	passenger	Diesel Hybrid	Euro 4	0,0	0,0%	5,0%	0	0,000	0,02		0,000	0,0011		0,0115	0

Source: European Commission, 2020b. Sustainable Urban Mobility Indicators (SUMI)