Automated Vehicles to Evolve to a New Urban Experience

DELIVERABLE

D8.5 Third Iteration Environmental Impact

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Acronyms

ADS	Automated Driving Systems
AI	Artificial Intelligence
AM	Automated Mobility
API	Application Protocol Interface
AV	Automated Vehicle
BM	Bestmile
BMM	Business Modelling Manager
CAV	Connected and Automated Vehicles
CB	Consortium Body
CERN	European Organization for Nuclear Research
D7.1	Deliverable 7.1
DC	Demonstration Coordinator
DI	The department of infrastructure (Swiss Canton of Geneva)
DMP	Data Management Plan
DSES	Department of Security and Economy - Traffic Police (Swiss Canton of Geneva)
DTU test track	Technical University of Denmark test track
EAB	External Advisory Board
EC	European Commission
ECSEL	Electronic Components and Systems for European Leadership
EM	Exploitation Manager
EU	European Union
EUCAD	European Conference on Connected and Automated Driving
F2F	Face to face meeting
FEDRO	(Swiss) Federal Roads Office
FOT	(Swiss) Federal Office of Transport
GDPR	General Data Protection Regulation
GIMS	Geneva International Motor Show
GNSS	Global Navigation Satellite System
HARA	Hazard Analysis and Risk Assessment
IPR	Intellectual Property Rights
IT	Information Technology
IoT	Internet of Things
ITU	International Telecommunications Union
LA	Leading Author
LIDAR	Light Detection And Ranging
MEM	Monitoring and Evaluation Manager
MT	MobileThinking
NREL	National Renewable Energy Laboratory
OCT	General Transport Directorate of the Canton of Geneva
ODD	Operational Domain Design
OEDR	Object And Event Detection And Response
OFCOM	(Swiss) Federal Office of Communications

PC	Project Coordinator
PEB	Project Executive Board
PGA	Project General Assembly
PRM	Persons with Reduced Mobility
PSA	Group PSA (PSA Peugeot Citroën)
PTO	Public Transportation Operator
PTS	Public Transportation Services
QRM	Quality and Risk Manager
QRMB	Quality and Risk Management Board
RN	Risk Number
RSU	Road Side Unit
SA	Scientific Advisor
SAE Level	Society of Automotive Engineers Level (Vehicle Autonomy Level)
SAN	(Swiss) Cantonal Vehicle Service
SDK	Software Development Kit
SLA	Sales Lentz Autocars
SMB	Site Management Board
SoA	State of the Art
SOTIF	Safety Of The Intended Functionality
SWOT	Strengths, Weaknesses, Opportunities, and Threats.
T7.1	Task 7.1
TM	Technical Manager
TPG	Transport Publics Genevois
US	United States of America
UITP	Union Internationale des Transports Publics (International Transport Union)
VANET	Virtual Ad-Hoc Networks
V2C	Vehicle to Cloud
V2G	Vehicle to Grid
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
V2P	Vehicle to Pedestrian
V2X	Vehicle to Everything
WP	Work Package
WPL	Work Package Leader

Executive Summary

This deliverable presents the final AVENUE environmental impact assessment concerning the deployment of automated minibuses (AM) in urban public transport sytems. Therefore, this deliverable presents the final environmental life cycle assessment of the automated electric minibus and presents a study of the potential energy demand and savings of automated driving.

Section 1 introduces the context of the AVENUE project and the deployment of pilot-tests of AM, seen as a complementary mode of transport to be integrated into public transport. Section 2 elaborates the energy demand of automated driving technology and particularly focuses on connectivity-related demand. It also presents the potential energy savings through predictive driving functions. Section 3 summarises the final outcome of a life-cycle assessment (LCA) study, and section 4 presents the latest version of environmental indicators as part of the pilot sites' sustainability assessment. Section 5 offers overall conclusions.

The main findings:

- Predictive, adaptive and information sharing through vehicle communication with infrastructure and other vehicles improves vehicle braking performance and consequently energy consumption. However, a highly connected vehicle means more processing required by the infrastructure, remote or cloud servers which may outweigh the V2X sustainability.
- Based on results from the AVENUE pilots, the automated driving components for an AM driving at 30 km on an 8-hour day 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}.
- The data transmission and energy consumption for 3GPP and 5GAA use cases were estimated for automated driving connectivity for eleven scenarios: platooning, sensor and state map sharing, remote driving, lane change, infrastructure-based preception of environment, collision avoidance, collective information sharing, see-through for passing, emergency trajectory alignment, intersection crossing, and cooperative driving.
- Significant potential in energy savings can be achieved in particular from intelligent route optimisation and velocity control.
- Data on energy saving for predictive functions are presented for selected cases based on literature. Among the functions, the eco route planning and traffic light assistant are cited for being urban scenarios that require little exchanged information between the vehicles and the infrastructure. This makes them very promising candidates for real energy savings achieved through the implementation of automated urban mobility.
- The energy efficiency for exchanging data within the automated mini-buses ecosystem depends on the number of connections and the advancement of the deployed technologies.
- The cooperative V2X is undoubtedly the key sustainable communication mode and plays an important role in energy demand.
- A fixed route or a mature on-demand service would have different energy consumption due to different numbers of involved servers.

The Life Cycle Assessment (LCA) of the AM shows that the automated technologies in the AM, as deployed in the AVENUE pilots, are around 5% of the total energy used. When considering the near-future use case, the study points that 59% of the AM impact stems from the use phase, while component production accounts for 39%. The use phase climate impacts are mostly due to the burning of fossil fuels to produce the electricity required for driving the AM. The global warming potential for each pkm is 78 g CO2eq .

The assessment of the AM based on the environmental indicators shows that at the current stage, the AM face challenges to be deployed as an environmentally friendly mode of transport. These results are confirmed by the LCA study, pointing that the AM at the current deployment does not show significant environmental benefits, but future use cases are likely to improve substantially. In addition, the AM qualification as environmentally friendly depends on many factors such as occupancy, vehicle speed, mileage, and lifetime. Taking into consideration the perspective on the mobility system, the AM are seen as a complementar service in public transport. In combination with door-to-door, on-demand and driverless services, the AM are expected to improve and strenghthen public transport, hence bring benefits by reinforcing shared, multi and intemodal mobility as well.

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 operates only 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 organisation.

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

1.2 Fully Automated Vehicles

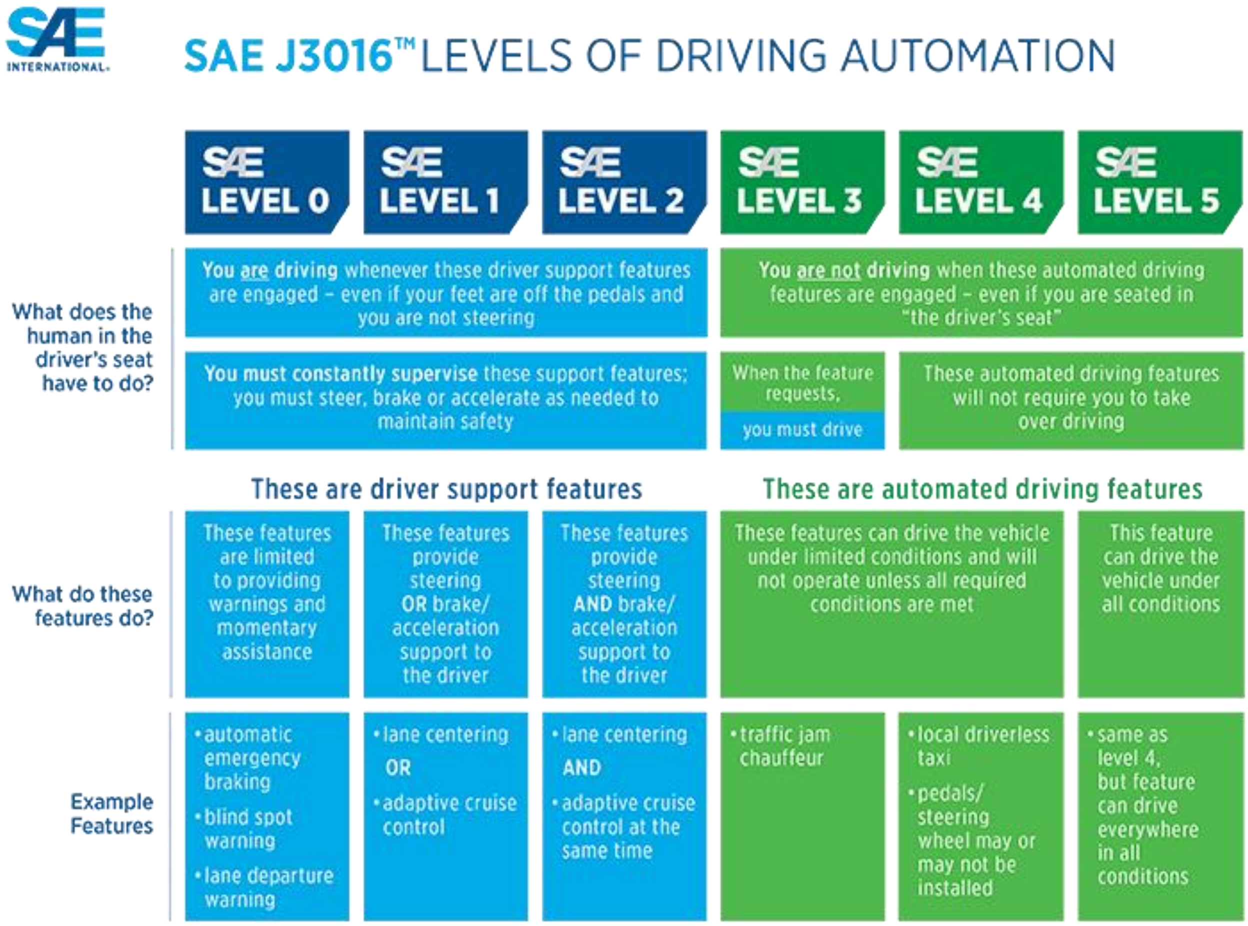
A self-driving car, referred in the AVENUE project as **a Fully Automated Vehicle** (**AV**), also referred as Automated Vehicle, is a vehicle that is capable of sensing its environment and moving safely with no human input.

The terms *automated vehicles* and *fully automated 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 automated capacity:

- An "automated vehicle" means a motor vehicle designed and constructed to move automatedly 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 automatedly without any driver supervision

In AVENUE we operate ***Fully Automated minibuses for public transport***, (previously referred as Automated shuttles, or Automated 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.



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1.2.1 Automated vehicle operation overview

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

1.2.2 Automated vehicle capabilities in AVENUE

The Automated vehicles employed in AVENUE fully and automatically manage the above defined, micro-navigation and road behaviour, in an open street environment. The vehicles are Automatically capable to recognise obstacles (and identify some of them), identify moving and stationary objects, and Automatically decide to bypass them or wait behind them, based on the defined policies. For example, with small changes in its route the AVENUE mini-bus is able to bypass a parked car, while it will slow down and follow behind a slowly moving car. The AVENUE mini-buses are able to handle different complex road situations, like entering and exiting round-about in the presence of other fast running cars, stop in zebra crossings, communicate with infrastructure via V2I interfaces (ex. red light control).
The mini-buses used in the AVENUE project technically could 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 brake hard at high speeds (40-50 km/h) and stop within 40 metres, but then the break would be 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 at any time. 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 an incident to any of the mini-busses. . Table 2 provides and overview of the AVENUE sites and OODs.

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

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

1.3 Preamble

The current deliverable contributes to the overall sustainability assessment of AVENUE. WP8 sustainability assessment concentrates on the economic, environmental, and social impacts of the AM in public transport, as shown in

Figure **1** . In this D8.5 we continue the life cycle assessment (LCA) first presented in the first and second iterations of the environmental deliverables and summarise the final results. Moreover, the impact analysis is extended to include the potential energy demand of the automated function of the AM. It also considers the environmental indicators based on data from the pilot sites, which is the core of the sustainability assessment.

The first part of the deliverable elaborates the energy demand side of automated driving technologies and the potential energy savings. It describes the energy demand related to the connectivity of automated driving, wireless technologies, cooperative communication modes, and the implemented services. The energy assessment would enrich the environmental assessment and open the discussion about future development in automated driving energy demand. The second provides the final results of the LCA, which was a cornerstone throughout the previous iterations. The third continues the study of the environmental indicators that are crucial components in the sustainability indicators used in the final sustainability iteration and the cumulation of WP8.

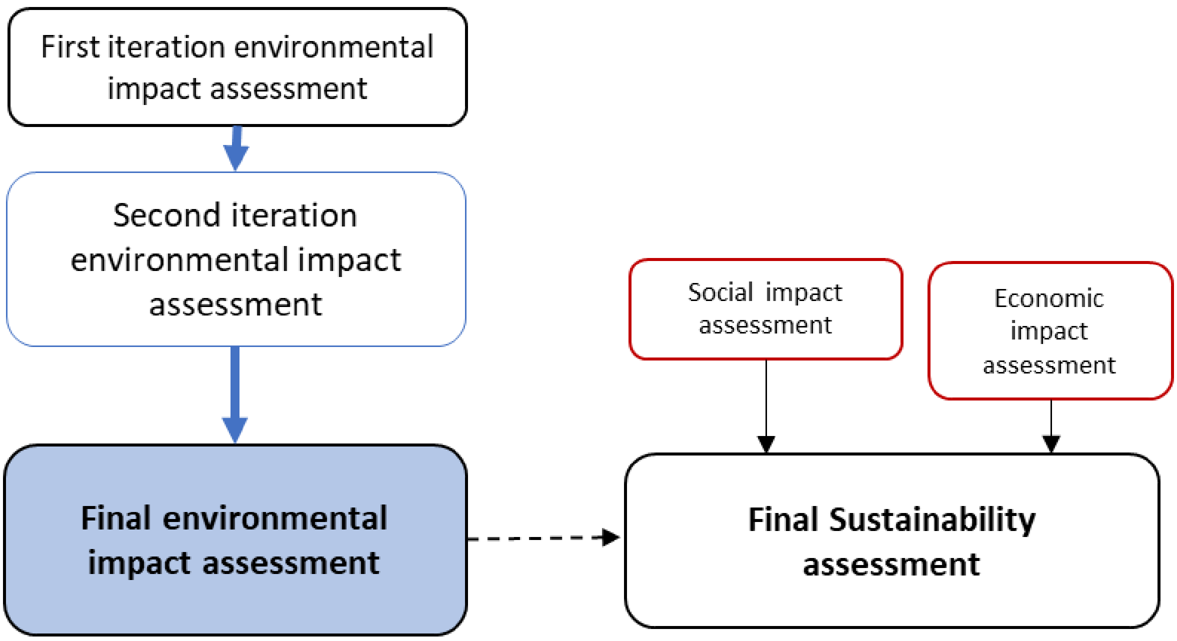

Figure 1: Overview elements of the environmental impact assessment

2 Assessment of energy demand of CAV/AV

Automated driving technologies are likely to reduce energy demand for driving compared to traditional vehicles, e.g. by functions such as platooning and eco-driving. However, the increased demand for data transmission and processing might increase energy demand. This part elaborates on both sides, the energy demand side of automated driving technologies and the potential energy savings of automated driving. Such an assessment is crucial from an environmental perspective as energy increase or decrease effect the overall environmental performance of automated vehicles significantly. In this chapter, we would be mainly referring to automated vehicles as CAV (Connected Automated Vehicles) instead of AV, as we aim to address various aspects of connectivity in automated driving.

2.1 Energy demand of automated driving technologies

Throughout the scientific literature, researchers debated the energy demand of CAV to be either greedy or efficient depending on the implemented automation units, internet technologies and deployed services, though they clearly agreed on the direct impact of the data exchange on the overall energy consumption. This section sheds the light on the key publications that showcased the vehicle connectivity and data transfer impact on energy consumption. It also reported the efforts from literature in translating the exchanged bytes and bits into energy units.

Liu et al. (2019b) provided a quantitative study on the negative effects of smart vehicles on energy consumption. The authors draw attention to the fact that automated and intelligent vehicles are equipped with computing devices, advanced sensors, controllers, and actuators, in combination with connecting communication technologies, resulting in higher energy consumption compared to conventional vehicles. The authors suggest that computing platform performance, connection strength and radar performance are the three main factors impacting the energy consumption of CAV. Their study led to the assessment of fuel consumption per 100 km for different levels of automation - primary, intermediate, and advanced intelligence (corresponding to SAE levels 3, 4 and 5 accordingly) - and the identification of different factors that potentially influence vehicle's consumption costs (see
Figure **2**).

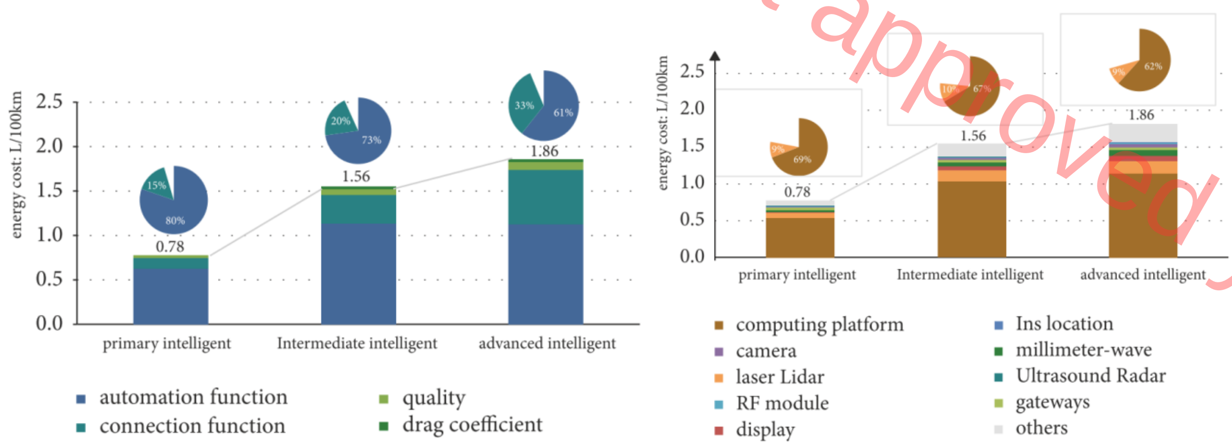

Figure 2: Vehicle fuel consumption cost at different levels of intelligence

Gawron et al. (2018) present a life cycle assessment (LCA) of CAV sensing and computing hardware with SAE level 4 of automation exploring the potential energy and greenhouse gas (GHG) emission impacts of CAV based on six scenarios. Three of the scenarios simulate sensing and computing hardware configurations of Tesla Model S, Ford Fusion (AV test vehicles), and Waymo's Chrysler Pacific respectively integrated into an internal combustion engine vehicle (ICEV) and the other three scenarios simulate the hardware configuration on a battery electric vehicle (BEV). They reported that the additional hardware resulted in an increase of 3% to 20% of energy consumption compared to conventional vehicles. However, when considering the automated driving functions (e.g., eco-driving, platooning, and intersection connectivity) facilitated by the additional hardware, the net result is up to 9% of energy (and emission) reduction based on the Tesla and Ford hardware configuration. The authors claim that data transmission is one of the four factors contributing to an increase of energy consumption. Their research studied data transmission over 4G wireless networks, which was estimated to 1.4 MB/mile and to a consumption of 1.25 MJ/GB.
Figure **3** depicts Gawron et al. life cycle energy estimation for a medium CAV.

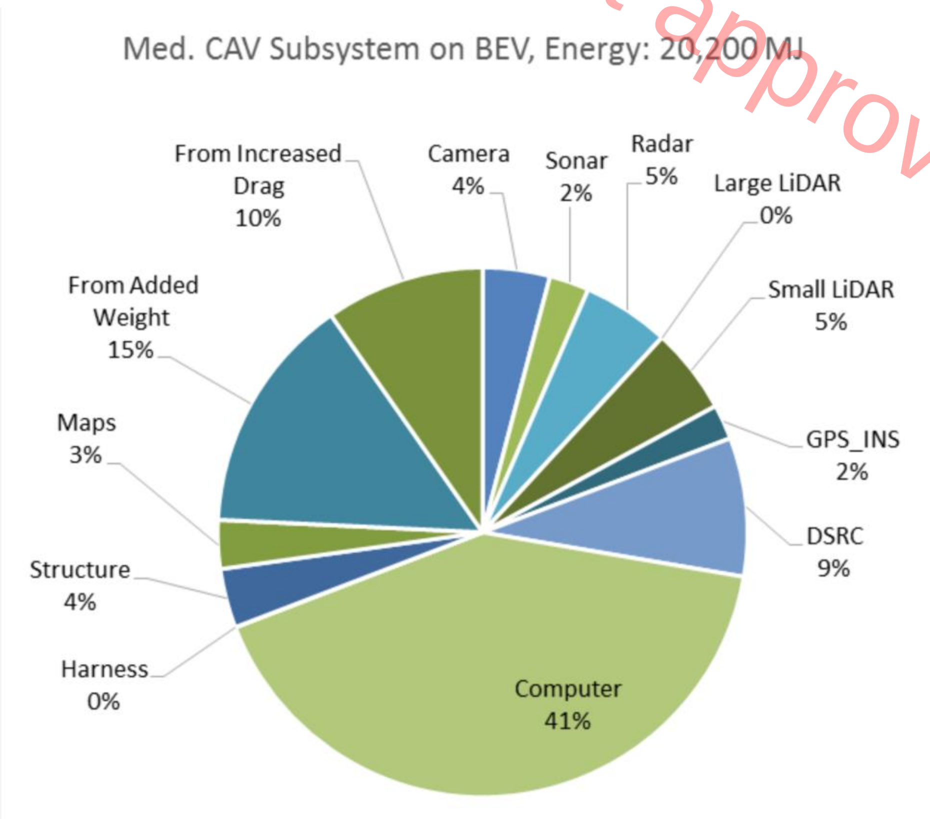

Figure 3 Medium CAV life cycle energy consumption according to Gawron el al. (2018)

Pihkola et al. (2018) evaluated the environmental impact of mobile access networks and sustainability of services within the IoT (Internet of Things) ecosystem using the LCA methodology. In their study, the authors constructed a trend of kWh per transferred gigabyte where they linked the network electricity consumption to the transferred data within the network. However, their computations were limited to the 4G mobile network consumption in Finland that can be extended to any IoT model.

Greenblatt and Shaheen (2015) focused their research on environmental impacts of CAV's on-demand services, which reduce the vehicle ownership, the number of households owning a car and the vehicle miles (kilometres) travelled.

Based on some environmental background data from Gawron et al. (2018) and Baxter et al. (2018), we calculated the specific energy usage of fully automated minibuses used within AVENUE. 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 about 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 et al (2018) state that 200 W is 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, such as sensors, radars, cameras, LiDARS, computers, and location detection.

Table 1: Nominal power of automated driving components installed in one automated minibus

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, the distance-weighted average speed of all sites equals 11.4 km/h (this calculation is based on Table **4** in chapter 3). Assuming that all automated components run at full nominal power, the energy demand for 11.4 km of driving is 304.4 Wh, which equals 26.7 Wh/km. The distance-weighted average of the trial site's energy demand is 554 Wh/km. Hence only 4.8% of total energy demand is caused by the use of components required for automated driving.

2.2 Energy demand of CAV connectivity

To compute CAV's energy consumption, it is important to consider the connection operations and strength. Such calculations depend on the connection hardware and its related power and time, the vehicle automation level and the amount of exchanged data (Liu et al., 2019b). The following subsections present an in-depth classification of the different sources of consumption related to the vehicle data exchange. It addresses the energy consumption of the vehicle communication to external servers or devices, including the vehicle communication to other vehicles (V2V), to the infrastructure (V2I), to the cloud (V2C), to pedestrians (V2P) and to the grid (V2G).

2.2.1 CAV connectivity technologies

The CAV's connectivity is built through multiple channels (El-Rewini et al., 2020): radio (AM/FM/DAB/RFID), WIFI (IEEE 802.11), bluetooth, cellular (3/4/5G), bidirectional communication (IEEE 802.11p, DSRC, WAVE) or using IoT networks (IEEE 802.15.4, Zigbee). With the presence of wireless connections, Virtual Ad-Hoc Networks (VANET) can be spontaneously created among CAVs, leading to V2V communication. With the increase of modern concepts, infrastructure (V2I) and additional devices (V2X) are required to assist the VANETs for data storage and data transmission for long distances (El-Rewini et al., 2020; Lee and Atkison, 2021). V2X also compasses cloud (V2C) and grid (V2G) communication in addition to any further devices or peripherals interacting with the vehicle such as smartphones (V2P), car keys or bluetooth devices (Lozano Domínguez and Mateo Sanguino, 2019). Being hyper-connected by nature, CAVs sustainability embeds the inherited energy consumption of data transfer technologies through their communication networks. Furthermore, the V2X network topology requires further processing either at the RSU (roadside unit) or at a remote server, would cost additional computation resources, cause delays and hence increase the energy consumption (Belogaev et al., 2020).

In academic literature, multiple approximations and estimations are used to quantify wireless cellular networks' energy consumption. In 2020, the 4G energy consumption was assessed to be around 0.1 kWh/GB (Andrae and Edler, 2015; Pihkola et al., 2018; El-Rewini et al., 2020), including the network, data centre computations and data storage. Masoudi et al. (2019) added that 5G networks promise higher efficiencies (up 1Mbit/J) to the energy consumption within the IoT ecosystem.

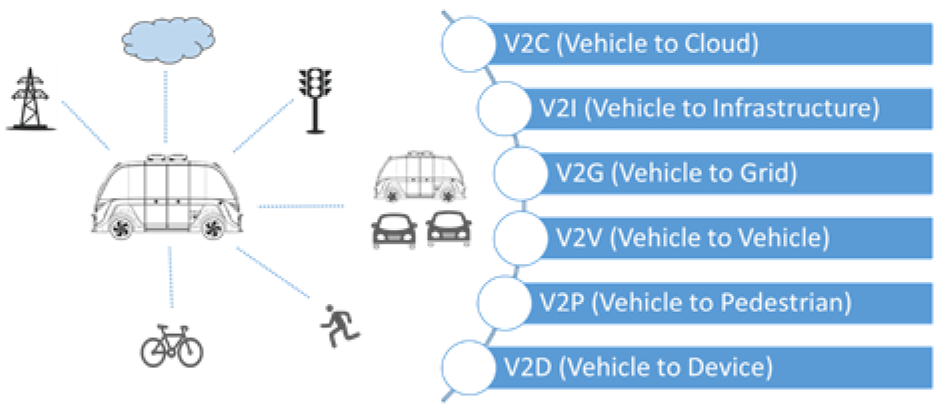

Figure 3: CAV external communication and connectivity

Further research recommends new IoT technologies such as Zigbee for efficient energy consumption (Gheorghiu and Minea, 2016).

To improve the vehicular energy consumption related to data transmission, researchers have studied some protocols for higher energy efficiency. Pihkola et al. (2018) highlight that new efficiency measures that have been deployed within the last decade lower the energy consumption of internet data transmission to 0.1 kWh/GB in 2020 instead of 12.35 kWh/GB in 2010. Dong et al. (2016) proposed an optimum cluster management method to reduce the V2V transmission power while using DSRC and LTE. Passafiume et al. (2020) proposed a battery less transponder plugged to an RSU supporting the V2I communication.

2.2.2 Data transmissions of CAV

In the last decades, various consortia have been active in defining and studying various V2X data transmission technologies and protocols and their application in real world use-cases of automated driving with 3GPP and 5GAA alliances have been the most active in this domain. An early 3GPP report (3GPP, 2015) defined data transmission use-cases using 4G-based Long Term Evolution-Vehicle (LTE-V) and 3GPP (2018), 3GPP (2019), as well as 5GAA (2020), defined data transmission use-cases using 5G based C-V2X technologies. More advanced real-world scenarios with real traffic situations are being evaluated in various EU-funded telecommunication projects such as METIS 2020 and METIS 2020-II and V2X projects such as 5GCAR, 5GCroCo, and 5G CARMEN. It is not clear, though, whether these projects measure data transmission levels and whether such measures are accessible. Furthermore, simulation platforms such as Fraunhofer's Simulation Platform for Cellular V2X Fraunhofer IIS (2021) may also be useful as tools to collect data about real-world traffic situations.

Based on 3GPP and 5GAA use-cases and data and a summarisation by Kanavos et al. (2021), we defined the energy consumption for V2X based on 5G technologies for various automated drivings. We employed the 4G energy consumption of 0.1 kWh/GB (Andrae and Edler, 2015; Pihkola et al., 2018; El-Rewini et al., 2020) to calculate the average energy usage of automated driving connectivity based on eleven scenarios (see Table 2).

Table 2: Data transmission and energy consumption for different automated functions

		Data Transmission		Energy Consumption	
UC	Title	5GAA	3GPP	5GAA	3GPP
1	Platooning	8–48 kbps		0.0001-0.0006W	0.00002-0.004W
2	Sensor and State Map Sharing	4–47 Mbps	25 Mbps	0.05-0.59W	0.31W
3	Remote Driving	400 kbps–36 Mbps	1–20 Mbps	0.005-0.45W	0.013-0.25W
4	Lane Change	120 kbps	-	0.0015W	-
5	Infrastructure-based Perception of Environment	4–155 Mbps	1 Gbps	0.05-1.9W	12.5W
6	Collision Avoidance	10 Mbps	-	0.125W	-
7	Collective Information Sharing	120 kbps	50 Mbps	0.0015W	0.625W
8	See Through for Passing	8 Mbps	10–700 Mbps	0.1W	0.125-8.75W
9	Emergency Trajectory Alignment	48 kbps	30 Mbps	0.0006W	0.375W
10	Intersection Crossing	8–25 kbps	50 Mbps	0.0001W	0.625W
11	Cooperative Driving	-	384 kbps	-	0.0048W

2.3 Potential energy savings through predictive driving functions

Automated and connected driving functions do not only control the perception, decision-making and driving command execution to move the vehicle in a safe and convenient way, but they also enable energy savings by optimising the driving route selection, motion planning and powertrain operation. This is an important aspect when considering the connectivity options to be implemented since a few additional data provided by the infrastructure plus a few megabytes of additional bandwidth needed might pay off significantly in terms of energy saved.

Hu et al. (2017) and Connor et al. (2021) discussed the direct correlation between the vehicle connectivity, velocity and the battery consumption and their impacts to the environment. The authors studied real world driving scenarios for electric buses using V2I and V2V technologies. According to their findings, the V2I and V2V communications provide energy savings that are up to 27% of battery cost reduction. Bo et al. (2019) also asserted the beneficial impact of V2I to have an optimal energy control. The US Department of Energy, through the NREL study (Stephens (2016), reported 2% to 6% fuel savings by adopting the V2I smart intersections.

The predictive functions typically combine models of the vehicle and its powertrain with external data such as the upcoming driving route characteristics and traffic conditions to predictively control the vehicle. Examples of such functions are provided in Table 3 below, including published data on corresponding energy savings. Considering the literature for energy saving potentials indicated in Table 3, it is noteworthy that

- the achievable energy savings are generally heavily dependent on the defined vehicle and use cases, resulting in wide ranges of savings typically being published for similar functions by different authors; and that
- the energy savings also strongly depend on the particular baseline to which they are calculated, which often consists of different types of human drivers or non-predictive control algorithms.

Nevertheless, the available published results demonstrate that a significant potential in energy savings can be achieved in particular from intelligent route optimisation and velocity control.

Table 3: Predictive automated driving (AD) functions and their energy saving potential

Function	Description	Main Application Area	Potential Energy savings	Source	Required Infrastructure or Data
Eco route planning	Identifies routes with lowest predicted energy consumption based on upcoming routes and traffic conditions, optionally including charging point selection	Routes with multiple paths and varying traffic conditions	Average 12.5% Up to 48%	(Kubicka et al., 2016; Fiori et al., 2018)	Communication with off-board digital maps including route topography, road network and live traffic speed data provided by vehicle fleet
Traffic Light Assistant (TLA) or Green Light Optimal Speed Advisory (GLOSA)	Predictively adjusts velocity to reach upcoming traffic lights at the start of their expected green phases	City driving with traffic lights	Average 23% - 36%	(EU Horizon 2020 EVC1000, 2018)	V2I communication for upcoming Signal Phase and Timing (SPAT) information, e.g. provided by traffic light roadside units
Predictive Adaptive Cruise Control	Predictively adjust velocity to maintain appropriate headway distances to a preceding target vehicle	Motorways driving with multiple connected vehicles	Average 13% - 15%	(EU Horizon 2020 EVC1000, 2018)	Onboard sensors for target object and motion detection, optionally V2V
Platooning	Cooperatively maintains efficient headway	Motorway driving with multiple	Average 4% *	(Bichiou and Rakha, 2020)	V2V with low latency

	distances between multiple connected vehicles reducing accelerations and aerodynamic drag	connected vehicles		(Hussein and Rakha, 2020)	
Predictive Cruise Control or Eco-driving	Predictively adjust velocity based on upcoming hills, speed limits and/or curves, including efficient gears election in case of multi-ratio gearboxes	Hilly motorways without traffic ahead	Average 5% **	(Volvo, 2021)	Onboard navigation system maps or electronic horizon system with cloud communication for time-varying data such as dynamic speed limits
Predictive Thermal Management	Predictively adapts thermal management of battery, e-motor and inverter using future velocity and ambient conditions	Driving routes with cold or hot ambient conditions	Up to 11% ***	(Auer et al., 2015)	Communication with off-board digital maps including route topography and traffic speed data for the driven route
Predictive Hybrid & Fuel Cell Control	Predictively plans when to charge or discharge the battery over the route, as well as the power distribution between powertrain components (ICE, electric motor, fuel cell).	Hybrid, Range Extender & Fuel Cell Vehicles	Up to 5%	(Huss et al., 2021)	Communication with off-board digital maps including route topography and traffic speed data for the driven route

* Results for conventional (ICE-driven) car at 100km/h cruising speed

** Results for conventional (ICE-driven) commercial vehicles, smaller savings expected for lights vehicles with electric recuperation potential

*** Results assuming full preview of route velocity available and excluding energy consumption required for component preconditioning i.e. energy provided by the electrical grid before driving

2.4 Discussion and implications for environmental impact assessment

The nexus of data processing and exchange within the automated driving landscape raises challenges to consider while assessing CAV's sustainability. To this end, the energy consumption related to CAV's data transfer depends on wireless technologies, the cooperative communication modes and the implemented services. Automated minibuses may support different types of internet connections which result in large differences in energy consumption. The driverless wireless network can vary from 4G, 5G to DSRC, which definitely impact the amount of exchanged data and hence the vehicle energy consumption (Masoudi et al.(2019). Cooperative V2X is expected to be the favourable communication mode with regard to energy use, according to Bo et al. (2019) and Stephens (2016). Predictive, adaptive and information sharing provided through vehicle communication with infrastructure and other vehicles improve vehicle's braking performance and consequently its energy consumption. However, a highly connected vehicle also requires more processing within its infrastructure, remote or cloud servers. This may outweigh the V2X sustainability. A fixed route or a mature on-demand service would not have comparable energy consumption as the number of involved servers and processing will not be proportionate (Greenblatt and Shaheen, (2015). As with every exchanged data within the automated mini-buses ecosystem, the energy efficiency can fall over either to high or low energy demand depending on the number of connections and the advancement of the deployed technologies.

Although the reported potential energy savings through predictive driving functions differ between studies (see section 2.3), it seems evident that the savings are likely to counterbalance and even overcompensate the energy costs associated with the communication modules. It is “common sense” in the European research community that it will be impossible to implement large-scale automated urban mobility in a safe way without infrastructure support, both in-vehicle and infrastructure communication equipment will already be there regardless of the use of predictive functionalities. Consequently, the additional cost for employing predictive functionalities is merely the additional bandwidth used by the additional data which need to be transmitted. Especially the first two functions mentioned in Table 3, *eco route planning* and *traffic light assistant*, apply to urban scenarios and require only a little information to be exchanged between the vehicles and the infrastructure, which makes them very promising candidates for real energy savings achieved through the implementation of automated urban mobility.

3 Final LCA model

This part summarizes the final findings of a life cycle assessment (LCA) study of automated minbuses, which has also been published in Transportation Research Part D (Huber et al., 2022).
The LCA study investigated the environmental impacts of AM to be integrated into the public transport of cities, guided by the following research questions: (1) Which environmental impacts are associated with the operation of an AM? (2) What are the main drivers of these impacts, and how can these be reduced? (3) What conclusions can be drawn from these findings for the role of AM in future public transportation systems?

3.1 Background and research design

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 attributional LCA study is the centrepiece of this research and analyses the entire product life cycle of an AM from raw material extraction via production and uses to final disposal and recycling stages. Core standards for LCA studies are the ISO guidelines 14040 and 14044 (International Organization for Standardization, 2006a, 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, 2010). Furthermore, a specific guideline for LCA of electric vehicles (Duce et al., 2013) is taken into account.

Figure **4** summarises this study's research design.

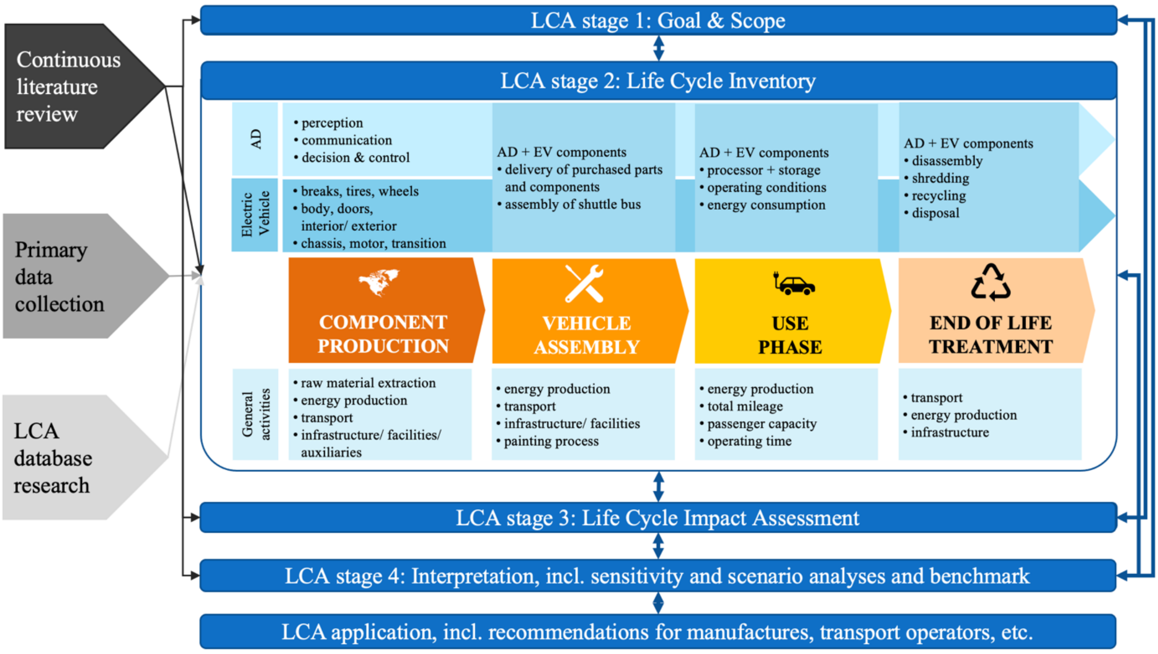

Figure 4: Research design including LCA stages according to ISO, 2006a; automated driving (AD) components; electric vehicle (EV) components

3.1.1 Goal and scope of the LCA study

The goal and scope stage specifies the system under investigation and elaborates the functional unit, i.e. the quantified benefit of the given product system. The functional unit of an AM is one passenger kilometre (pkm) in public transportation. This common functional unit enables comparison across numerous vehicle types and means of transport.

The AM under investigation is capable of transporting 15 people (11 seated and 4 standing). It's a compact size vehicle (4.75 m length, 2.11 m width, 2.65 m height), which weighs 2,400 kg and reaches a maximum speed of 25 km/h. The architecture of the AM includes LiDAR sensors for 2D and 3D mapping of the environment, odometry for speed measurement, GNSS antenna, and cameras. All these components allow the AM to analyse its environment and operate within mixed traffic.

The current operation of the AM happens on fixed routes where passengers use them as part of public transport. Moreover, on-demand, door-to-door, and pooling trials are in place where passengers could summon the vehicle to a pick-up point using an app (Navya, 2018). The AM are not meant to replace individual vehicles but are supposed to be applied in a public transport system.

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. As indicated in Figure 1, this study's product system comprises the main life cycle phases of component production, vehicle assembly, use, and end-of-life treatment in line with recommendations by 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 the LCA.

Six of the recommended impact categories are used, namely Acidification, Climate Change, Eutrophication, Ozone Depletion, Photochemical Ozone Formation, and Resource Depletion. A control calculation revealed that the five remaining environmental impact categories (Ecotoxicity, Human Toxicity, Ionizing Radiation, Land Use, and Particulate Matter / Respiratory Inorganics) show the same direction of results.

3.1.2 Life cycle inventory and data collection

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 AM model has been built based on literature data (Majeau-Bettez et al., 2011; Hawkins et al., 2013; Gawron et al., 2018). In a second step, the model has been refined by adding primary data retrieved from the AM manufacturer and public transport operators involved in the AVENUE project.

Field and primary data for this study were derived from the demonstrator sites of AVENUE project.

An AM manufacturer provided primary data on vehicle components (in particular weight, functions, nominal power), while transport operators provided primary data for the use of these vehicles in public transportation. Data collection took place from 2019 to early 2021 in an iterative manner.

Detailed information about the component production, including battery and automated driving components, originates from Majeau-Bettez et al. (2011), Hawkins et al. (2013) Gawron et al. (2018) and Moreno Ruiz et al. (2020). All vehicle components and corresponding weights were provided by the manufacturer. The sum of all AM components considered in this study accounts for more than 99% of the total AM weight and hence fulfils standard LCA requirements. For the assembly of these components, data from Majeau-Bettez et al. (2011), Hawkins et al. (2013) and Gawron et al. (2018) was used that represents industry scale assembly of electric passenger cars. Further secondary data was retrieved from common LCA databases, mostly from ecoinvent 3.7 (Moreno Ruiz et al., 2020). The supplementary material of this study provides an overview of all components and materials required for vehicle assembly and the life cycle inventories (LCI) for all vehicle components and indicates the respective primary and secondary data sources.

Table 4 provides AM use phase data collected at five trial sites on fixed-route from September 2018 to January 2021. It shows differences in terms of average speed, expected annual mileage per shuttle, average vehicle occupancy (i.e. average number of passengers on board), and average and minimum energy demand. The extremely low average occupancy reflects the trial sites experimental character, where vehicles are also used without transport demand for functional and technical testing purposes.

Table 4: AM use phase data

Site	Lyon, Groupama (France)	Contern (Luxembourg)	Luxembourg, Pfaffenthal (Luxembourg)	Copenhagen Nordhavn (Denmark)	Oslo, Ormoya (Norway)
Data collection period	November 2019 - January 2021	September 2018 - January 2021	September 2018 - January 2021	September 2020 - January 2021	December 2019 – January 2021
Route length [km]	1.3	2.2	1.2	1.3	1.6
Average driving speed [km/h]	10	15	17	8	10
Total mileage during data collection [km]	12,492	1,900	9,000	2,000	23,000
Annual mileage during data collection [km]	9,994	786	3,724	4,800	19,714
Total passengers	5,545	650	25,060	1,300	6,600
Average passenger trip length [km]	1.3	2.2	1.0	0.4	0.8
Average vehicle occupancy	0.6	0.8	2.8	0.3	0.2
Average energy demand [Wh/km]	480	780	510	590	590
Minimum energy demand [Wh/km]	No data	480	350	300	300

The software Umberto® was used to model the product life cycle and analyse the results. The overall AM LCA model includes 198 processes and 42 subnets on four hierarchical levels. Excerpts of the overall model are shown in Figure 5.

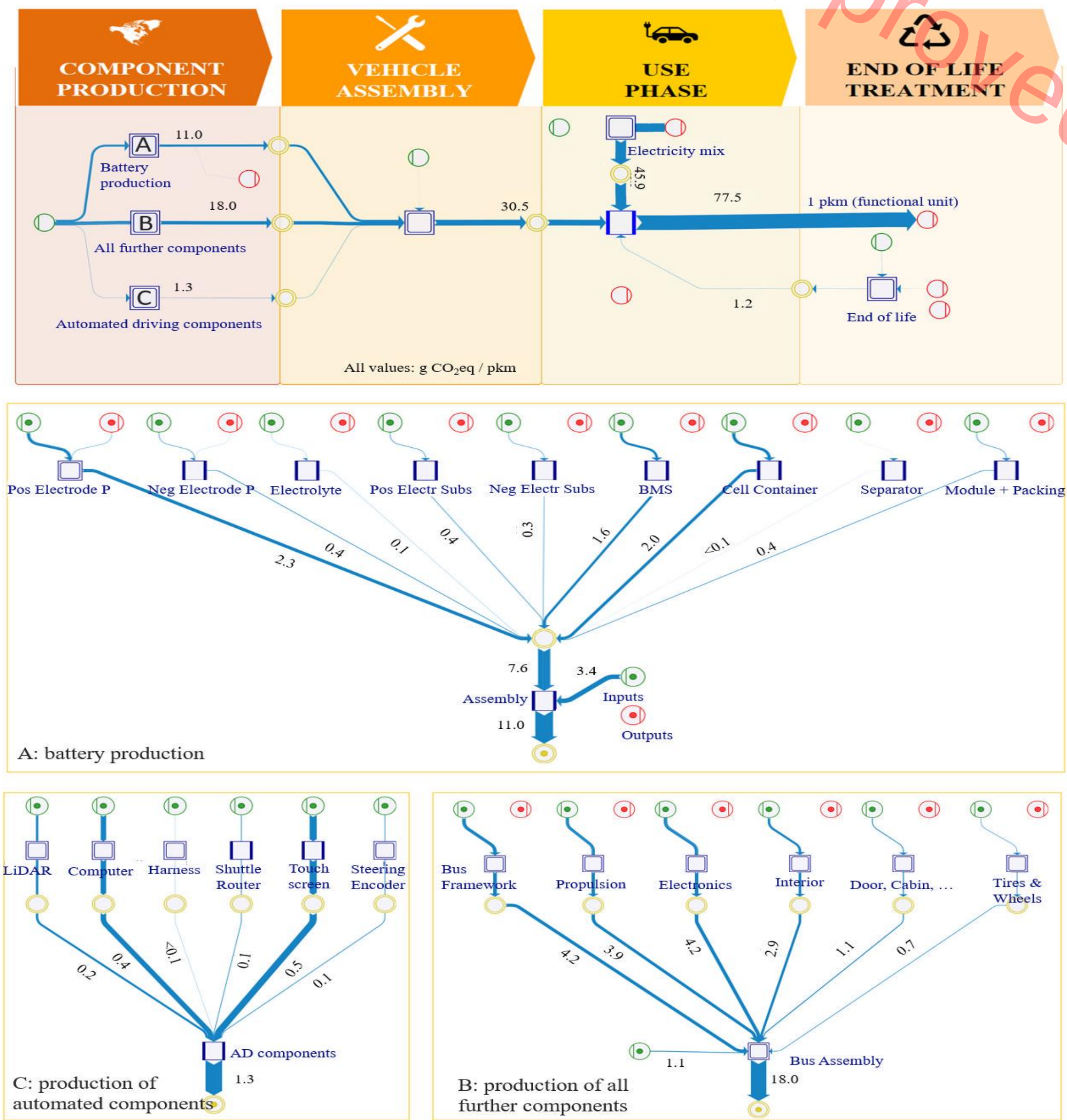

Figure 5: AM life cycle model main model with subnets for battery production (A), production of all further components (B), and production of automated components (C). Sankey diagrams depict global warming potential in g CO2eq per pkm for the AM near-future use case. In the Petri-net based material flow network approach underlying the Umberto LCA software, blue squares represent processes or subnetworks, and circles represent input points (green), output points (red) and connection points (yellow). All values have been rounded to one digit.

3.1.3 Scenario setting

Based on the primary data collected at the trial sites, a near-future use case and worst- and best-case values for scenario analysis were derived. The best-case values can also be combined to form an ideal use case. Relevant parameters for the use cases and scenario comprise the AM's expected lifetime, annual mileage, average passenger occupancy, energy demand, energy source, and the used battery LCA data. The parameter settings are explained in the following and summarised in

Table 5.

As reported by the AM manufacturer and the transport operators involved in this study, the lifetime of the battery can serve as a proxy for the overall AM lifetime. Assuming one charging process per day and an operation of five days per week leads to a lifetime of 7.7 years. This has been further rounded off to seven years to consider probable losses and reduced efficiency when the battery is maturing over time (Hadjipaschalis et al., 2009; Oliveira et al., 2015). Due to high battery costs, transport operators and the AM manufacturer assumed that the lifetime of an AM is aligned with the lifetime of its battery while also acknowledging that the rapid technology development of AM in some cases might make AM become obsolescent and decommissioned even prior to the battery's end-of-life. On the other side, some LCA studies of batteries 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 is varied from three to ten years in a scenario analysis.

The near-future use case assumes an annual mileage of 20,000 km, while scenario analysis ranges from 5,000 km (rough average of other trial sites in

Table 5) to 36,500 km, assuming a daily operating distance of 100 km.

While the maximum capacity of the AM is 15 passengers, the near-future use case assumes an average occupancy of five passengers at any given time. This is above the current trial data but in line with the expectations of transport operators with regard to economic feasibility. For scenario analysis, the worst-case value is one passenger onboard on average, while the best case is a very optimistic average occupancy of ten passengers.

The near-future use case's energy demand is 554 Wh/km, which represents the distance-weighted average of the trial site's average energy demand. This corresponds to the AM manufacturer's specifications for energy consumption of 520 Wh/km. According to the manufacturer, this energy consumption was measured with one person on board, at an average speed of 6.6 km/h and an outside temperature of 30 degrees Celsius, while the AM's inside was cooled down continuously to 16 degrees Celsius. The energy demand includes all automated components, all components for passenger interaction, and the electric driving components. As speed, temperature, weight, and many other factors influence AM energy use, scenario analysis is required. The distance-weighted average of the trial site's minimum energy demand (332 Wh/km) equals the best-case value, while the highest average energy demand of a trial site (780 Wh/km) equals the worst-case value for scenario analysis.

The near-future use case assumes a European electricity mix (418 g CO2eq/kWh), while for scenario analysis, a mostly fossil electricity mix (1037 g CO2eq/kWh) sets the worst-case and almost entirely renewable electricity mix the best-case value (23 g CO2eq/kWh; all values are taken from ecoinvent 3.7 databases with low voltage electricity market datasets for Europe, Poland, and Norway respectively). The battery production within this study has been modelled using and adopting detailed data from the literature.

Table 5: Parameter setting for near-future use case and scenario analysis

parameters	near-future use case	scenario analysis	
		worst case	best case
expected lifetime [years]	7	3	10
annual mileage [km]	20,000	5,000	36,500
average passenger occupancy	5	1	10
energy demand [Wh/km]	554	780	332
energy source	electricity mix Europe	fossil energy mix (using Poland as approximation)	100% renewable energy mix (using Norway as approximation)

3.2 Results

This section presents environmental impacts of AM, scenario analysis results, assessment outcomes for the automated components and a comparison of AM with other means of transport to better contextualise the findings.

3.2.1 Life Cycle Impacts of AM

Table 6 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 battery, automated, and all other bus components), vehicle assembly, use, and end-of-life.

In the near-future use case, the global warming potential for each pkm is 78 g CO_2eq (see Figure 5 for a Sankey visualisation of the global warming potential within the AM life cycle model). 59% of this impact stems from the use phase, while component production accounts for 39%. The use phase climate impacts are mostly due to the burning of fossil fuels to produce the electricity required for driving the AM. For the same reason, the use phase accounts for 54% of the overall acidification potential. In all other environmental impact categories, component production either dominates moderately (eutrophication potential and photochemical ozone depletion potential) or by a wide margin (ozone layer depletion potential and resource depletion potential). Neither the assembly nor the end-of-life phase is of any significance in any of the chosen environmental impact categories, which also justifies their modelling based on average literature data (see section 3.1.2).

Based on the best-case parameter settings from

Table 5, an ideal use case with very high AM lifetime mileage and passenger occupancy, low energy demand, and renewable energy supply can be set up and calculated. Table 6 includes the total environmental impacts for this ideal use case and shows significantly reduced impacts of 80% (resource depletion) to 91% (climate change) across all environmental categories.

Table 6: Environmental impacts for 1 pkm of AM in a near-future use case and in comparison to an ideal use case; climate change (global warming potential 100 years) measured in g 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).

	Climate change (g CO_2eq)		Acidification (mol H+eq)		Freshwater Eutrophication (kg Peq)		Ozone Layer Depletion (kg CFC-11eq)		Photochemical Ozone Creation (kg NMVOCeq)		Resource depletion (kg Sbeq)	
Automated driving components	1.25	2%	9.11E-06	2%	1.08E-06	1%	7.30E-11	0%	4.96E-06	2%	2.32E-07	2%
Battery production	11.00	14%	6.99E-05	15%	9.59E-06	9%	4.39E-08	92%	3.43E-05	14%	1.44E-06	11%
Further bus components	18.00	23%	1.30E-04	28%	4.68E-05	45%	1.27E-09	3%	9.32E-05	39%	1.06E-05	83%
Component production	30.30	39%	2.09E-04	45%	5.75E-05	55%	4.53E-08	95%	1.32E-04	55%	1.23E-05	97%
Final assembly	0.19	0%	8.51E-07	0%	8.03E-08	0%	9.22E-12	0%	4.56E-07	0%	4.65E-10	0%
Use (driving)	45.90	59%	2.51E-04	54%	4.59E-05	44%	2.34E-09	5%	1.05E-04	44%	4.19E-07	3%
End-of-life	1.17	2%	3.77E-06	1%	3.69E-07	0%	2.47E-11	0%	2.53E-06	1%	2.80E-09	0%
Total near-future use case	77.50	100%%	4.65E-04	100%	1.04E-04	100%	4.77E-08	100%	2.41E-04	100%	1.27E-05	100%
Total ideal use case	6.92	9%	4.48E-05	10%	1.18E-05	11%	8.84E-09	19%	2.84E-05	12%	2.49E-06	20%

3.2.2 Scenario analysis

Scenario analyses have been conducted for all parameters given in

Table 5 and for all environmental impact categories under examination. Figure 6 shows the results of the scenario analyses for two contrasting environmental impact categories: resource depletion potential and global warming potential. The results highlight the significance of non-technical parameters for the overall environmental performance of AM. Low passenger occupancies and low annual mileage increase resource depletion and climate change dramatically. In contrast, the vehicle's energy demand is not affecting resource depletion much. Even for climate change, the effect of energy demand is smaller than most other parameters. The single most important parameter for reducing climate impacts is the energy source, i.e. the electricity mix used to load AM batteries. Operating the AM within a fully renewable energy system reduces the global warming potential by 58%.

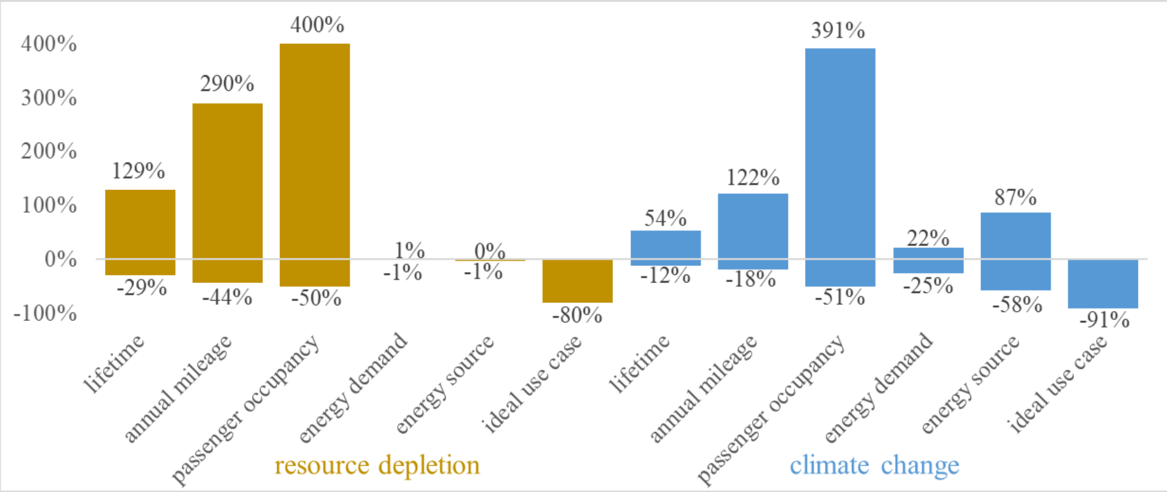

Figure 6: Scenario analyses for resource depletion potential and global warming potential (near-future use case = 0%)

For the environmental impact category climate change, the breakdown of the scenarios into production and use phase clearly shows the disparate effects of different parameters (see Figure 7). While vehicle lifetime and mileage only influence the climate impact of production, the energy demand and the energy mix influence the use phase. Occupancy influences the production and use phase equally. The relationship between the use phase and the production phase, also shown in Figure 7, reveals strong fluctuations. In extreme cases (very high mileage, highly fossil energy mix), the use phase dominates, while in the case of the use of renewable energies, the importance of the use phase diminishes from a climate perspective and the importance of production for the overall result increases.

Figure 7: Scenario analysis (global warming potential) comparing AM production and use phase (near-future use case = 100%)

3.2.3 Impact of automated components

The vehicle components required for automated driving are of particular interest for a study on automated vehicles. As shown in Table 6, the production of such components does not significantly affect overall environmental performance and stays below 2% of total impact in all the given impact categories. Another aspect is the energy use of these components. Although a fully renewable electricity mix reduces the importance of the use phase in the long run, energy demand and energy mix are important factors of overall performance at present. Table 7 lists reference technologies and nominal power figures for all AM automated driving components (for a detailed table including manufacturers, models and internet sources, please see supplementary material). In total, automated driving components in AM 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 et al. (2018) state 200 W is 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, light detection and ranging sensors (LiDARS), computers, and location detection.

Table 7: Nominal power of automated driving components installed in one AM (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		304.5

Table 7 provides the average speed at the different trial sites. The distance-weighted average speed of all sites equals 11.4 km/h. Assuming that all automated components run at full nominal power, the energy demand for 11.4 km of driving is 304.5 Wh, which equals 26.7 Wh/km. The distance-weighted average of the trial site's energy demand is 554 Wh/km. Hence only 4.8% of total energy demand is caused by the use of components required for automated driving.

3.2.4 Contextualisation

With a high degree of certainty, near- and ideal future use cases of AM have significantly lower environmental impacts per pkm than the current trial cases. To assess its performance in comparison with other means of transport, the AM climate change impacts per pkm are compared with literature values of other vehicles (Table 8). 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 and Horvath (2009). Figure 8 presents the climate changes impacts of all transport modes, including the AM near-future and ideal use case.

Table 8: Climate impacts, lifetime mileages and passenger occupancies for various individual and public transportation vehicles (based on [1] Puig-Samper Naranjo et al., 2021; [2] Gawron et al., 2018; [3] Kemp et al., 2020; [4] Nordelöf et al., 2019; [5] this paper); Abbreviations: Ind. – Individual; ICEV – internal combustion engine vehicle; HEV – hybrid electric vehicle, BEV – battery electric vehicle; BECAV – battery electric connected and automated vehicle; ICECAV – internal combustion engine connected and automated vehicle; SUV – sports utility vehicle; BEB – battery electric bus; PHEB – plug-in hybrid electric bus; HEB – Hybrid electric bus; AM NF - AM near-future use case; AM ideal – AM ideal use case

Unit	peak operation g CO_2eq /pkm	off-peak operation g CO_2eq /pkm	average operation g CO_2eq /pkm	peak occupancy no. of passengers	off-peak occupancy no. of passengers	average occupancy no. of passengers	lifetime mileage km
Ind. ICEV petrol [1]	52	261	131	5	1	1.58	150,000
Ind. ICEV diesel [1]	48	241	121	5	1	1.58	150,000
Ind. HEV, EU electricity [1]	44	222	111	5	1	1.58	150,000
Ind. BEV, EU electricity [1]	27	135	68	5	1	1.58	150,000
Ind. small BECAV, US electricity [2]	44	221	140	5	1	1.58	257,494
Ind. medium BECAV, US electricity [2]	45	223	141	5	1	1.58	257,494
Ind. large BECAV, US electricity [2]	50	250	158	5	1	1.58	257,494
Ind. small ICECAV [2]	74	372	235	5	1	1.58	257,494
Ind. medium ICECAV [2]	75	375	237	5	1	1.58	257,494

Ind. large ICECAV [2]	86	431	273	5	1	1.58	257,494
Ind. BECAV SUV, US electricity [3]	27	134	85	5	1	1.58	321,868
Ind. ICECAV van [3]	60	301	85	5	1	1.58	321,868
Public BEB, EU electricity [4]	7	154	48	105	5	16	780,000
Public PHEB , diesel [4]	13	202	63	80	5	16	780,000
Public HEB, diesel [4]	10	211	66	102	5	16	780,000
Public diesel bus [4]	16	304	95	95	5	16	780,000
Public –AM NF [5]	39	387	77	10	1	5	140,000
Public –AM ideal [5]	7	69	14	10	1	5	365,000

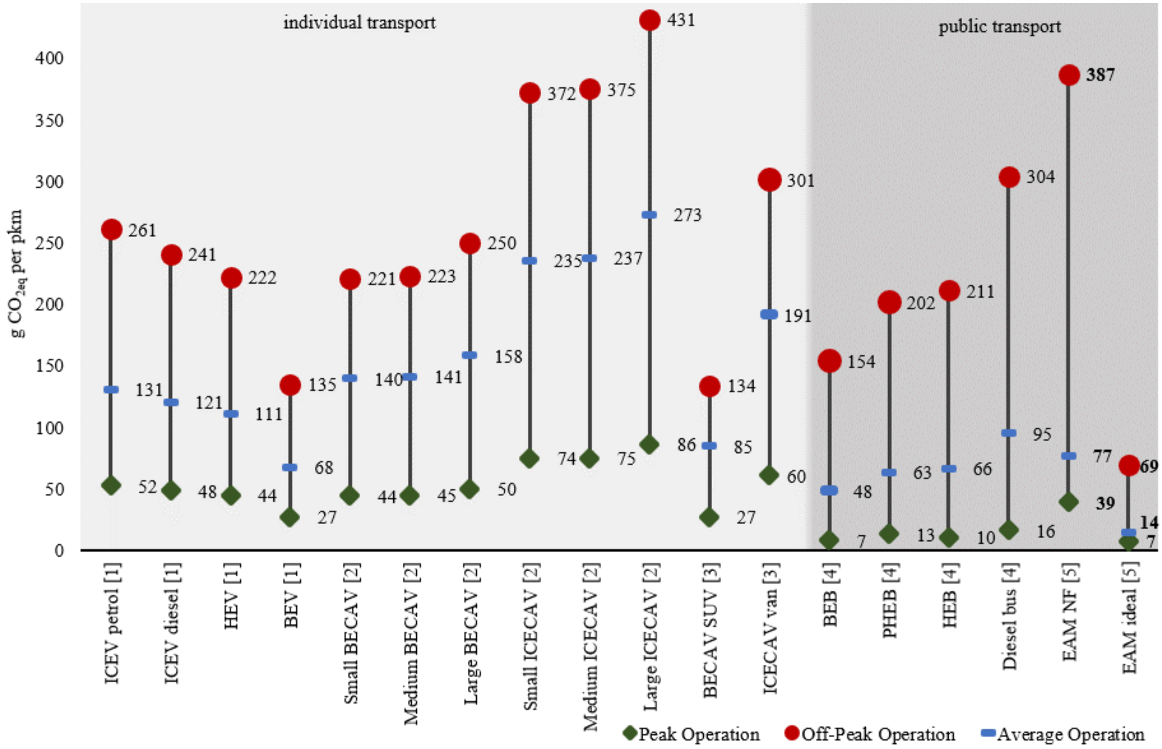

Figure 8. Climate impact of different transportation modes in g CO_2eq per pkm (own compilation, based on [1] Puig-Samper Naranjo et al., 2021; [2] Gawron et al., 2018; [3] Kemp et al., 2020; [4] Nordelöf et al., 2019; [5] this study, all abbreviations are detailed in Table 8)

Comparing the near-future use case of AM to other means of public transportation shows higher climate impacts per pkm except for the comparison to the average operation of diesel buses. It should be noted, though, that all other public means of transport are larger buses with higher passenger numbers for peak, average, and off-peak operation. The AM ideal use case performs better than any other means of transport, which shows the huge potential of EMA for further environmental improvement and optimisation. The comparison of the ideal use case must be viewed with caution, as no ideal use case was calculated for the other means of transport, and a renewable energy mix would also have a positive effect on all other battery-electric and hybrid vehicles, for example.

3.3 Discussion and limitations

The LCA presented here identifies factors that significantly influence the environmental impact of AM. Analogous to electric vehicles in general (see Helmers et al., 2017), the energy consumption and the electricity mix used for charging the batteries impact climate performance significantly. Beyond such technical parameters, systemic factors play a major role, too, e.g. the utilisation of the vehicles in terms of annual mileage and the utilisation of the vehicles in terms of average passengers per trip (passenger occupancy). Whether AM can be classified as environmentally friendly therefore depends on many factors. While an infrequently used AM with very few passengers on board scores extremely poor in terms of its environmental impact, a heavily used AM that is also fully utilised in terms of its passengers can keep up with all other means of transport or even outperform them in terms of environmental benefits. On the basis of measurement data from AM in operation, a near-future use case was defined, the achievability of which is considered to be very realistic in the next few years. This near-future use case already shows a very good environmental performance under the previously described framework conditions.

An ideal use case calculated in a complementary way also shows the potential that lies hidden in AM in terms of environmental performance, provided that all framework conditions and parameters are optimal. The production of the components and the driving itself are by far the most environmentally intensive phases of the life cycle of an AM. The components required for automated driving play only a subordinate role in both phases and are responsible for less than 2% (production) or approximately 5% (driving) of climate impacts.

The LCA results presented here are promising, in particular, because higher mileages can be achieved in the short term, and a positive attitude (goodwill) of potential users towards the AM is given (Korbee et al., submitted). Yet, it is important to note that the study has some limitations. For instance, it relies on data collected from pilot sites that are provided by public transport operators and vehicle manufacturers. The experimental nature of the pilot sites and COVID restrictions led to limited operation measured and lowered the number of passengers in the vehicles. As data accuracy for LCA studies of emerging technologies is a recurrent concern (Hetherington et al., 2014; Arvidsson et al., 2018), future studies could be based on longer time-series of data from regular operations rather than on demonstration and trial site operations. In this study, the way to mitigate the repercussions of innovative technologies data is to rely on scenario development. The results are not meant to deliver precise figures to be published in product declarations but instead to provide valuable insights on the main drivers of the future environmental performance of AM.

The comparably low relevance of automated driving components mirrors similar studies of automated vehicles (Gawron et al., 2018). However, other studies predict a much higher impact of automated components on overall energy use (Brown et al., 2013; Gonder et al., 2016; Wadud et al., 2016; Saujot et al., 2017; Gawron et al., 2018; Pihkola et al., 2018; inria, 2019; Grisoni and Madelenat, 2021; Krail, 2021). Adaptations in physical and digital infrastructure are needed to deploy automated vehicles (Noussan and Tagliapietra, 2020), and vehicle to everything (V2X) technologies require additional technical infrastructure. Road sensors, special signals to be detected by automated vehicles, and a long-range wireless network are among the out-of-vehicle technical infrastructure needed (Liu et al., 2019a). The AM under examination is neither transmitting large amounts of data to the outside nor requiring extensive additional technical infrastructure, which might change in the future. Notably, the long-term advantages of automated driving compared to human driving were not considered in this study either. Research predicts that connectivity and cooperative technologies will lead to better anticipation of traffic situations, efficiency modulated driving, better manoeuvring (Fagnant and Kockelman, 2015), and better ridematching capacity (Shaheen and Bouzaghrane, 2019). This could further reduce energy consumption. Overall, the use of automated vehicles is likely to simultaneously reduce energy demand by efficient driving and increase it by additional data processing and transmission (see, e.g. Stephens et al., 2019). The current state of research does not allow for a definite conclusion; for the AM under investigation, data processing and transmission has only minor impacts at present.

Innovation and efficiency improvements of batteries are likely to reduce the environmental impacts of AM.

The AM energy demand of 554 Wh per driven km in comparison to other electric vehicles is quite high (Bauer et al., 2015; Puig-Samper Naranjo et al., 2021). Since the components for automated driving are not a significant influencing factor, other factors must be involved that determine this high level of consumption. In particular, the heating and cooling of the vehicles and their low speed are worth mentioning. The entire interior of the vehicle is constantly cooled on warm days and warmed up on cold days, which is associated with high energy consumption. A higher speed, reduced heating and cooling behaviour and further energy efficiency measures on the vehicle could further reduce the overall energy consumption and the associated environmental impacts but are not within this study's scope.

3.4 Conclusion and consequences for future mobility systems

This LCA study shows the potential of AM as part of public transport. If AM are well utilised in terms of mileage and regularly used by many passengers, they have great advantages over individual vehicles from an environmental point of view and also perform better or the same compared to other public transport vehicles. At the same time, it becomes clear that AM play a specific role in an overall mobility system and do not serve as a substitute for all other modes of transport. Given the current performance of AM, featured low speed and low passenger capacity in combination with door-to-door, on-demand and driverless services, so far, the AM are seen as a complementary vehicle in public transport. For example, AM can cover the so-called "first and last mile" or take over the off-peak operation of regular buses. They thus increase the availability, flexibility, efficiency and reliability of local public transport, which brings great environmental benefits, especially when replacing individual motorised transportation. There might be some aforementioned rebound effects, though, if AM replace walking or biking or lead to more travel due to their convenience and comfort (Saujot et al., 2017; inria, 2019; Grisoni and Madelenat, 2021).

From an environmental and sustainability science perspective, the study demonstrates the limitations of LCA studies that purely focus on individual vehicles and vehicle types. The environmental benefits of AM are effected by the individual vehicle performance, but much more depend on the vehicle's utilisation and occupancy and thus on their embedding in an overall transportation system. Comparing different AM types or brands is relatively insignificant in this regard.

The outcome of this study is interesting for decision-makers on different policy levels and for public transport operators. For the latter, the study provides clear insights into the environmental advantages and disadvantages of AM deployment. For policymakers, the study highlights the need to develop plans and frameworks for the deployment of automated vehicles in time to achieve maximum environmental benefits. A multimodal and flexible public transport system that integrates AM at appropriate points seems to be a promising solution.

4 Final environmental indicators for sustainability assessment of pilot sites

The assessment of the pilot sites finalises the analysis presented in the second iteration of the environmental deliverable, and it focuses on the environmental indicators. The assessment presents the data collected from the pilot sites as well as the recent updates of the methodology and results. It serves as background information and data for the final sustainability deliverable 8.12.

The objective of this section is to investigate the environmental performance of the AM through mobility indicators. Sustainability indicators are a powerful tool to simplify, quantify, analyse, and communicate complex information (KEI, 2005; Singh et al., 2009; Innamaa and Salla, 2018). In addition, urban sustainability indicators are fundamental to support target setting, performance reviews and enable communication among policymakers, experts and the general public (Verbruggen, H., Kuik O., 1991; Shen et al., 2011).

The environmental indicators and respective units of assessment are presented in Table 9.

Table 9: The environmental indicators and units of assessment

Environmental indicators	Unit of assessment
Energy efficiency	AM energy consumed for passenger per km (kWh/pkm)
Use of renewable energy	AM use phase, energy source and percentage of renewable energy sources (%)
Noise pollution	AM traffic noise (dB)
Air pollution	AM emissions of air pollutants, PM levels (ug/m3), NOx, CO emissions
Climate change	AM GHG emissions: CO_2eq/pkm

In addition to the environmental indicators, the indicators for the sustainability assessment comprehend the social, economic, governance and system performance of the AM (Nemoto et al., 2021).

Each indicator requires a specific methodology (refer to APPENDIX A), and the value of the indicators is represented on a scale of 1 to 5, with 5 being considered the best score. For each indicator we:

(i) defined a parameter;

(ii) defined 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) calculated the indicator value for the AM 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.

The limitations of the assessment concern the innovativeness of the AM. The technology is still in a test and development phase. Hence, the main limitations concern the fact that the pilot projects are restricted to a local/neighbourhood area, and the AM drive in mixed traffic area at a low average speed (10-18km/h). The AM drive on a fixed route (with the exception of 'Belle Idée' test-site, where on-demand service has been tested), and the safety driver on board the AM is required in case human intervention is required, as well as to report the performance of the AM in general.

These limitations reduce the performance and usability of the AM. In addition, the demonstrator sites have been facing constraints due to Covid 19 pandemic. As a result, there have been interruptions in the pilot tests and some transport companies have limited the maximum number of passengers to four during

certain periods. This factor has a negative impact on AM performance assessed by the environmental indicators.
The next section presents the results for the environmental indicators for five AVENUE demonstrator sites: Pfaffenthal and Contern (Luxembourg City), Groupama Stadium (Lyon, France), Ormøya (Oslo, Norway), Nordhavn (Copenhagen, Denmark). The transport operators provided primary data; therefore, the results and analysis rely on the data presented in Table 4 (Chapter 3), which also provided inputs for the LCA study.

An overview of the pilot trials is present in Table 10, and the results per site are illustrated in Figure 9, followed by analysis and conclusions.

Table 10: Overview of the AVENUE 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

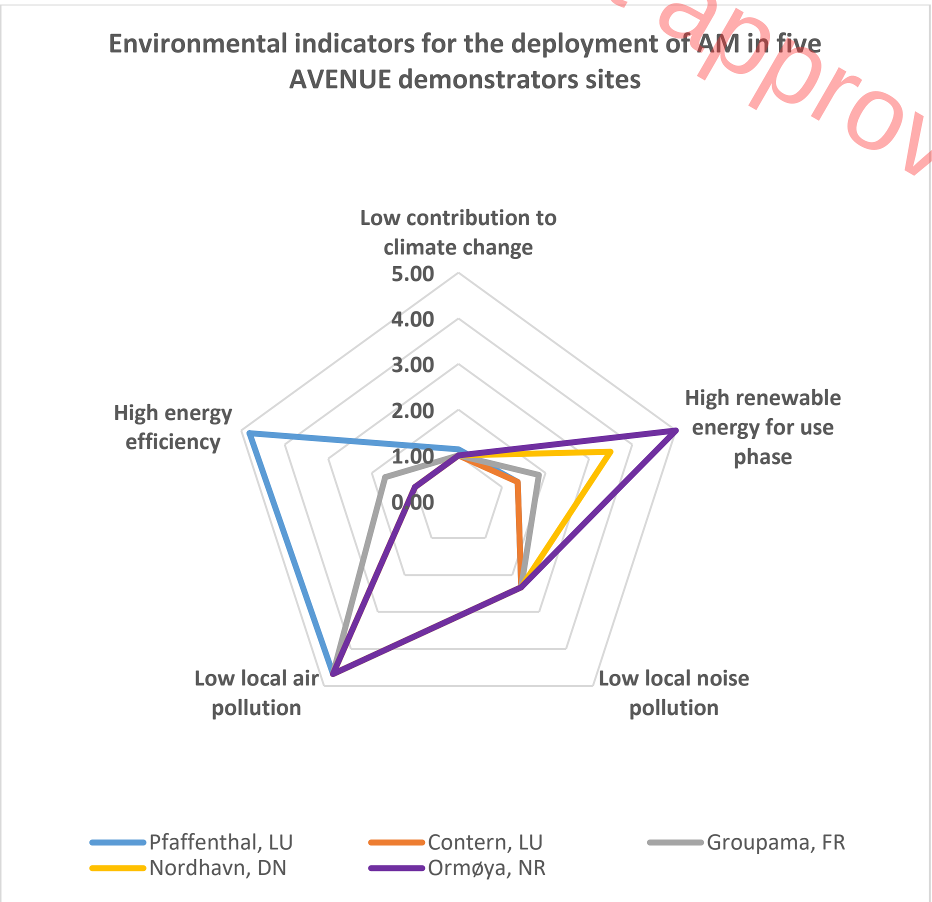

Figure 9: Environmental performance of the AM in the demonstrator sites. The scale ranges from 1 to 5, with 5 as the best score and 1 worst score.

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 AM has a good score on local air pollution. It is explained by the fact that BEVs in their use phase have zero exhaust emissions, e.g. NOx and PM, and 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 are assessed here for the use phase, as they affect cities (more densely populated areas) and consequently cause greater human exposure and potential health damage. For local noise pollution, the AM as an EV do not differ significantly from ICEV in the usual traffic and from 30km/h speed. This is due to the fact that *"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).* Therefore, the AM as an EV play a role to avoid local noise pollution for urban traffic during the night in low-speed areas (Jochem et al., (2016). Since the AM currently run at a low speed of 11-18km/h, their noise pollution is slightly lower than ICEVs and lower than regular buses.
In all the pilot sites, the AM scored poorly for 'low contribution to Climate Change'. This indicator is highly affected by the low occupancy of the AM, due to the characteristics of the pilots, such as temporary and new services, the newness of the technology, as well as the interruptions of the trials due to the constraints of the Covid 19 pandemic and the reduction in mobility and in the use of public transport. Further, the climate change indicator is affected by the vehicle lifetime, total mileage and electricity mix, as pointed by the LCA study (chapter 3). From all the sites, Pfaffenthal (Luxembourg) presents a better

performance due to the higher average of vehicle occupancy. While Ormøya (Oslo) and Nordhavn (Copenhagen) present the lowest performance for Climate Change due to the very low average occupancy and low mileage in the case of Nordhavn.

Likewise, the energy efficiency indicator is directly impacted by the average occupancy of the AM. Therefore Pfaffenthal (Luxembourg) presents a good score (with an average occupancy of 2,8 passengers), in contrast to the other sites.

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 9% in Luxembourg and 21% in France.

In relation to chapter 2, it is worth noting that the pilot trial at Groupama Stadium (Lyon) comprehends V2I communication, meaning that three traffic light junctions operate in communication with the AM. The V2X communications were not taken into account for the environmental indicators at this stage. However, on a larger scale, vehicle communications and connectivity could contribute to reducing energy impacts in mobility. Lee and Kockelman (2019), for example, pointed out that energy savings resulting from vehicle-to-infrastructure connectivity and smart intersections range from 6% to 30%, thanks to improvements in traffic interactions and better fuel-efficient driving (see more on chapter 2).

The assessment of AM based on the environmental indicators point out that the AM face challenges to be deployed as an environmentally friendly mode of transport at the current stage.

A key factor targeting 'low contribution to climate change' is primarily to increase the vehicle occupancy, and secondly through technology development, to increase the vehicle speed, mileage, and lifetime. Likewise, by aiming at a better energy efficiency, it is crucial to increase vehicle occupancy. Therefore, it is important that the AM are deployed in routes in order to cover real gaps in mobility, with more permanent services and good acceptance. And as mentioned previously, the average occupancy of the AM was also affected by the Covid pandemic, interruptions in the trials and mobility restrictions.

The AM, as a BEV, can highly contribute to the reduction in local air pollution, and while targeting the reduction of local noise pollution, the AM present limited advantages in comparison to regular cars and buses, reducing noise during the night and at low-speed areas.

In the future, the AM has the potential to be deployed as environmentally friendly mobility taking into account technological improvements, better social acceptance and usability, better integration into urban mobility as part of intermodal and MaaS systems, as well as shared and electric mobility.

As part of WP8, the sustainability assessment study aims to set goals for the future deployment of the AM and therefore monitor the progress of the environmental and remaining sustainability indicators towards a more sustainable operation.

5 General discussion and conclusion

The different assessments in this deliverable reach interesting results on the current and future performance of automated minibuses. The energy demand analysis of the automated components in the AM shows that the energy efficiency depends on the wireless technologies, the cooperative communication modes, and the implemented services. The automated technologies in the AM, as deployed in the AVENUE pilots, are around 5% of the total energy used. The potential evolution of the energy demand depends on the different types of internet connections. The driverless wireless network impacts the transmitted data and eventually the overall energy consumption or savings. Moreover, predictive and adaptive driving functions and information sharing in the AM are likely to improve the acceleration and braking processes and hence contribute to overall energy savings. The energy demand also differs if the AM provides an on-demand service. Overall, the energy-saving potential from predictive driving functions is highly likely to outweigh the energy consumption from data transmission energy.

Going beyond the energy analysis related to driving itself, the presented LCA study focuses on environmentally relevant energy flow and materials throughout the life cycle of the vehicle within the public transportation system. The study reiterates findings from other studies that energy consumption and the electricity mix used for charging have significant climate performance impacts. It also shows a low relevance of automated driving components in current deployment circumstances. The LCA study was used to identify factors that contribute to the environmental impact of AM. The environmental benefits of AM rely on the utilisation rate and occupancy factor and thus on their integration in the overall transportation system.

The current deployment of AM does not show significant environmental benefits, but future use cases are likely to improve substantially. The development and assessment of environmental indicators for an overall sustainability assessment corroborate the LCA study's conclusions. Occupancy, vehicle speed, mileage, and lifetime play an important role in reducing environmental impacts. AM are particularly beneficial if they can be deployed to close former public mobility gaps, which would otherwise lead to the use of individual cars.

Appendix A:

Climate Change

Definition: greenhouse gases emitted by the EASB shuttle per passenger-km
Parameter: gCO_2 eq/pkm
pkm = passenger kilometres, a metric of transport activity: when a single passenger travels a single kilometre, the result is 1 pkm of travel.
gCO_2eq = grammes of CO_2 equivalent.
Methodology: the LCA study (section 2) provided the GHG emissions (gCO_2 eq/pkm) for the EASB.
The scale was developed based on values reported on the average GHG emissions of different modes of transport on a well-to-wheel basis by the International Energy Agency, 2020) and the LCA study from the AVENUE project (Huber et al., 2019). 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:
1 = ≥ 300 gCO_2eq/pkm
5 = 0 gCO_2eq/pkm
Calculation:

Climate Change			1	5	
Parameter value:	197,0		min scale	max scale	
Indicator value	1,72		300	0	gCO_2/pkm

Obs: Example of Contern (Luxembourg)
Sources: Huber et al. (2019), International Energy Agency (2020)

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 shuttle is a battery electric vehicle (BEV). Therefore, the electricity mix of each country may influence the percentage of renewable energy used in the vehicle use phase.
For the calculation, it was considered the share of energy from renewable sources in gross electricity consumption 2018 (%) according to the countries of the pilot tests (The Federal Council, 2019; Eurostat, 2020) (refer to appendix D).
Scale:
1 = 0%
5 = 100%
Calculation:

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

Obs: Example of Groupama Stadium (Lyon)

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

Noise pollution

Definition: noise emission by the mode of transport.
Parameter: vehicle noise in Decibels (dB) at 15km/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 shuttle drives at an average speed of 11-18km/h in areas with a speed limit of 30km/h, the noise difference reported for different vehicles were considered at 30km/h (Lelong and Michelet, 2001; Cai, 2012; Dudenhöffer and Hause, 2012; Marbjerg, 2013). The noise emission for the automated shuttle was considered similar for a BEV, as 50 decibels in constant speed at 20km/h.
Scale:
1 ≥ 75dB
5 = 0 dB
Calculation:

Noise pollution		1	5	
Parameter value:	50	min scale	max scale	
Indicator value	2,33	75	0	Decibels

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

Air pollution

Definition: air-polluting emissions by the modes of transport in the use phase.
Parameter: air pollutant emissions, particular matter, $PM_{2,5}$ (g/km), and nitrogen oxides, NO_x (g/km), from exhaust and non-exhaust.
Methodology:
Particulate matter (PM) and nitrogen oxides (NO_x) are the main transport air pollutant emissions along with carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs) and sulphur oxides (SOx). The emissions from road transport are mainly exhaust emissions arising from fuel combustion, and non-exhaust releases contribute to NMVOCs (from fuel evaporation) and

primary PM due to tyre- and brake-wear and road abrasion (European Environment Agency, 2019). Further, transport is responsible for more than half of all NOx emissions (ibid).
The automated shuttle is a BEV, and during the use phase, BEVs have zero exhaust emissions, e.g. NOx and PM (European Environment Agency, 2018). However, BEVs emit PM locally from road, tyre and brake wear, like other motor vehicles (European Environment Agency, 2018). And it is important to mention that air pollutant emissions from BEVs occur for the electricity generation to charge BEV batteries. Nonetheless, the emissions from power stations tend to occur in less densely populated areas, provoking less human exposure to air pollution than in urban areas (ibid). At the same time, the local emissions from combustion engine vehicles in cities 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 shuttle 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:

$PM_{2,5}$

1 ≥ 0,005 $PM_{2,5}$ g/km

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

NO_x

1 ≥ 0,08 NO_x g/km

5 = 0 NO_x g/km

$PM_{2,5}$ Non exhaust

1 ≥ 0,0474 $PM_{2,5}$ g/km

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

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

Table 11: 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			1	5	
Parameter value:	0,00		min scale	max scale	
Indicator value	5,00		0,005	0	PM 2,5 g/km
NOx			1	5	
Parameter value:	0,00		min scale	max scale	
Indicator value	5,00		0,08	0	NOx g/km
Non exhaust			1	5	
Parameter value:	0,01		min scale	max scale	
Indicator value	3,79		0,0474	0	Non exhaust PM2,5 g/km

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

Energy Efficiency

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

Scale:

1 = ≥ 0,97 kWh/pkm

5 = 0,14 kWh/pkm

Calculation:

Energy efficiency					
Parameter value:	0,18		min scale	max scale	
Indicator value	4,74		0,97	0,14	KWh/pkm

Obs: Example of Pfaffenthal (Luxembourg)

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