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SHared automation Operating models for Worldwide adoption

SHOW

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Deliverable 12.3: German CCAV demonstrators

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Executive Summary

The German pilot site was one of the five Mega sites in the SHOW project. According to the vision “Operation in complex scenarios in urban and peri-urban environments”, the overall mission was to integrate automated mobility in PT operations in order to enhance flexibility and availability for the Public Transport domain. In addition, the potential of DRT to replace underutilized buses in suburbs was investigated. In this sense, various mobility services were proposed, demonstrated and evaluated at the German Mega site. Like many other SHOW pilot sites, the German pilot site also faced the problem of site replacement, mainly due to the impact of the unexpected COVID 19 pandemic on the economy and the delay in delivery of the automated shuttles and related components such as sensors. Even under these conditions, the site search and site replacement were quite successful. The number of test sites at the current German Mega site remains unchanged as in the original plan, i.e. 3 sites. These pilot sites were located in Frankfurt, Karlsruhe and Monheim am Rhein. In addition, the original Aachen pilot site became part of the Frankfurt pilot site and one use-case related to vehicle merging and energy consumption were conducted using the data collected at the Frankfurt pilot site.

In general, all piloting activities successfully demonstrated fixed and non-fixed mobility services and the technical possibilities to run shuttles without a predefined virtual track and to handle with a ride-booking application within the piloting period varying from 12 months to 20 months. Both passenger and cargo transport services were also considered. The results have shown that the shuttles operated with promising performance. No critical failures occurred. The enthusiasm of passengers and the high acceptance of the AVs were remarkable. In total, about 110,000 km were travelled by 12 AS and a modular vehicle, and approximately 50,000 passengers were transported, 523 of whom were carried in the pre-demo phase. In addition, 1,629 cargo deliveries were executed. The activities carried out at each of the pilot sites are summarized below.

The Frankfurt pilot site was located in the Riederwald district and provided the passenger transport service to connect the district with limited access to public transport to the nearby metro station Schäfflestrasse, creating real added value for local residents. The local public transport authority Rhein-Main-Verkehrsverbund (RMV) and the consulting company rms operated and managed the activities on site. The main technical objective of this site was to seamlessly connect two software solutions, i.e. the booking app ioki and the automated driving software, and to test two artificial intelligence (AI) systems to improve the service quality in future operations when safety operators are not available. These two systems include an AI-based camera system from T-Systems that detects specific situations in the shuttle and communicates critical situations to passengers, and a voice bot for passenger communication, serving to receive and provide information to passengers regarding PT-connections. The public demonstration period was from November 2022 to October 2023. The service was free of charge, but passengers had to book their trips via a smartphone app. While the local population is socio-demographically very diverse, older residents in particular used the service. The operating hours ranged from Monday to Saturday between 8 a.m. and 3 p.m. with no fixed schedule and flexible booking via the booking app ioki. The vehicles used were 2 EasyMile automated shuttles EZ10 Gen3. These two AS followed a pre-defined virtual rail during their operation. A safety operator was always on board to meet legal requirements. In addition, the shuttle data collected at the Frankfurt Pilot site were further used as input for the use case activities in Aachen. The use cases were conducted at the Aldenhoven Test Center in Aachen. The automated merge-in/-out manoeuvre of a shuttle in flowing traffic was addressed. The potential to reduce energy consumption through a

coordinated, collaborative merge-in/-out manoeuvre was investigated using a simulative approach. The results have shown that an energy-saving potential of 21% was achieved in the real vehicle test with the specified speed profile of the preceding vehicle (shuttle) and savings of up to 34% could be revealed in stop and go sections.

The Karlsruhe Pilot site mainly comprised two areas. The first area Weiherfeld-Dammerstock was a semi-urban district in Karlsruhe, which involved interactions with pedestrians, cyclists and e-scooter riders. Two modified EM automated shuttles EZ10 Gen2 with the booking app ioki were deployed for DRT-oriented automated driving from December 2022 to September 2023. The FZI Research Institute for Information Center **developed the required software to allow the AS to run freely according to traffic conditions, instead of following a pre-defined virtual track**, thus allowing the shuttles to manoeuvre around obstacles independently. The last-mile aspect was also emphasized, with the shuttle service connecting the target area to the tram station. Passengers varied from tourists to research scientists to the majority of local residents. In addition, a smart infrastructure was available, facilitating remote monitoring of the vehicles. Through V2X interfaces, intersections exchanged data with vehicles and vice versa, which was then visualized in FZI's control centre.

The second area administratively connected to Karlsruhe was located at the Federal Garden Show in Mannheim. DLR's modular vehicle U-Shift was presented as part of an accompanying exhibition and hosted 85,000 visitors between April and October 2023. Two driveboards with different functionalities and stages of development, two passenger capsules, a cargo capsule and a multi-purpose platform were displayed. The U-Shift shuttle operated on a daily basis to transport visitors of the garden show, the test route was not exclusively intended for the U-Shift vehicle, but was shared with pedestrians and small electric road trains. With the focus on leisure traffic on the premises of the garden show, the shuttle ran according to demand without a fixed schedule.

The Monheim Pilot site was located in Monheim am Rhein with around 45,000 inhabitants in the Rhine region between Cologne and Düsseldorf. The PT operator Bahnen der Stadt Monheim (BSM) started automated driving in February 2020. The target group for AS included residents (including elderly citizens) and tourists. The pilot period within the SHOW project was from May 2022 to December 2023. The AS line A01 with 8 fixed stops has been already integrated into the local public system and connected Monheim's old town and the central bus station Monheim Mitte. The AS fleet consisted of 5 EM automated shuttles EZ10 Gen2, supplemented by 3 additional EM shuttles EZ10 Gen3 since 2023. The AS ran daily from 9 a.m. to 9 p.m. according to a fixed schedule and had to cope with narrow streets, a pedestrian zone and even a passage through an old tower. More than 30 specially trained safety operators worked to provide this special service.

Overall, the tests of the German SHOW sites have provided important insights into how to meet citizens' needs with regards to this innovative and new form of mobility. One of the key challenges for the future success of these services will be to guide and support passengers on the way to full acceptance of automated PT. In order to achieve fully automated operation, further technical challenges still need to be addressed and overcome, particularly with regard to interaction with other road users.

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Abbreviation List

Abbreviation	Definition
AI	Artificial Intelligence
API	Application Programming Interfaces
ATC	Aldenhoven Test Center (proving ground in Aachen)
AV	Automated Vehicle
BUGA	Bundesgartenschau (national garden show)
C-CACC	Centralized Cooperative Adaptive Cruise Control
CCAV	Cooperative Connected Automated Vehicle
DRT	Demand Responsive Transport
HMI	Human Machine Interface
LCMM	Low Carbon Mobility Management (Tool from T-Systems)
MAMCA	Multi-Actor Multi-Criteria Analysis
NRTK	Network Real Time Kinematic
OEM	Original Equipment Manufacturer
POI	Point of Interest
PT	Public Transport
PTA	Public Transport Authority
PTO	Public Transport Operator
RTK	Real-time kinematics
SLAM	Simultaneous Localization and Mapping
SME	Small and medium-sized enterprises
TMC	Traffic Management Center
TRL	Technology Readiness Level
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-everything
VRU	Vulnerable road user

1 Introduction

1.1 Purpose and structure of the document

The goal of this deliverable is to document the demonstration activities carried out in the three German pilot sites and to give an overview about the results and findings. The three pilot sites Karlsruhe, Monheim and Frankfurt are described with their ecosystem, vehicle fleets, use cases, services and main users. The pilot operations are explained including challenges and lessons learned, and demonstration events at the pilot sites are mentioned.

In the following chapters, the high-level vision of German Mega Site and joint goals will be firstly introduced in Chapter 2. The overview of each pilot site, including e. g. the use cases addressed, vehicle types and operation duration, is then given in Chapter 3. Chapters 4 to 7 elaborately describe each pilot site's ecosystem, operation setting, services and use cases carried out, fleet and infrastructure used, performance and demonstrations achieved, collected data, findings and lessons learned. At the end, the conclusions and prospective are given in Chapter 8.

1.2 Intended Audience

The public Deliverable 12.3 summarizes insight about demonstrations and findings in three different German pilots and provides information for an external audience. Experts in the field of automated driving are addressed as well as PT operators and other stakeholders in the transport sector.

1.3 Interrelations

The pilot sites in the SHOW project have established a fruitful exchange and the shared learnings enhanced operations, events, data collections, interactions with users and fostered the internal interrelations. External interrelations include the interaction with local stakeholders in the pilot cities and the extensive collaboration of the German test sites.

The execution of pilot operations and demonstrations was based on the planning in WP9 (experimental plans). Results of the pilot demonstrations, collected data, key findings on user experiences and assessment of impact is feeding towards deliverables in WP12 and WP13.

2 High-level vision of German Mega Site and joint goals

In the context of the shared mobility domain, the overarching vision of the German Mega site is to show the possibility and scalability of automated vehicles on the greatest possible scale. Various automated services and operations were carried out in complex scenarios combining urban and peri-urban environments, and the deployment of the vehicles considered the unique characteristics of the different German pilot sites. The scope of the services offered included not only services for passengers, ranging from local residents, students, commuters, visitors and business customers, but also for logistics. It also demonstrated the technical possibilities of running shuttles without a pre-defined virtual track, handling a ride-booking application and running a mixed passenger and freight service.

The German demos included:

- Automated on-demand service as feeder of PT in Frankfurt in a real-traffic environment, where passengers could make a booking with the IOKI on-demand booking software linked with the operation of the shuttles
- AI based added value services for Passengers in Frankfurt to offer passengers information about the PT schedule and the project via an AI-based virtual bot, and to offer operational information about the shuttle and passengers (e.g. dangerous situations) via a camera system
- Operation Centre for automated on-demand services in Frankfurt to gain experiences in the implementation of a control center for the operation of automated shuttles and further prepare the development for a driverless operation
- Automated Covid-free PT with accessibility for everyone in Frankfurt with the implementation of an electric ramp, a wheelchair device, and the marking of accessible virtual stops, where the on-board camera system detected when someone was not wearing a mask and displayed a corresponding message
- Energy applications demo in Aachen showing technical validation and short user trials on collaborative driving manoeuvres (merge-in and merge-out) based on V2V communication at simulated bus stops in controlled environment to reduce energy consumption and simulate energy saving potential with real LCMM Data from Frankfurt site
- Demo in Karlsruhe for handling complex traffic scenarios with the support of tele-operated manoeuvres and without pre-defined virtual rails
- Mixed passenger – cargo transport (temporal, spatial) and platooning demo in Karlsruhe with new approach with passenger and goods capsules and demonstrating urban platooning function between two vehicles
- Operation of a semi-automated DRT as part of the regular PT service in Monheim and integrating automated & connected fleets into the existing mobility systems

3 Overview of pilot sites

The operation duration, vehicle types, conducted use cases and transported passengers at each pilot site are summarized in Table 1.

Table 1: Overview of German Mega Site contributing pilot sites

Pilot site	Duration of operation	Leader	Vehicles	Use Cases (by ID and name)	Number of passenger rides/freights transported in PUBLIC OPERATION
Karlsruhe	Dec. 2022 – Nov. 2023 (12 months)	FZI	2 modified EasyMile EZ10 Gen2 1 Audi Q5 (AV passenger car) 1 U-SHIFT modular vehicle from DLR	UC 1.1 / 1.2 / 1.6 / 1.7 / 1.9 / 2.1 / 2.2	13477 (passenger rides), 523 of whom were carried in the pre-demo phase 1629 (cargo deliveries)
Monheim	May 2022 – Dec. 2023 (20 months)	BSM	5 EasyMile EZ10 Gen2 Additional 3 EasyMile EZ10 Gen3 since 2023	UC 1.1 / 1.2 / 1.3 / 1.4 / 1.5 / 1.6 / 3.2 / 3.4	32069 (passenger rides) (around 59804 passenger rides since the start of operation in Monheim in 2020)
Frankfurt	Nov. 2022 – Oct. 2023 (11 months)	rms	2 EasyMile EZ10 Gen3	UC 1.1 / 1.6 / 1.7 / 1.10 / 3.1 / 3.2 / 3.4 / 3.6	3051 (passenger rides)
Aachen (part of Frankfurt site)	Aug. – Sep. 2023 (2 months)	FEV	2 modified BMW i3 automated vehicles (L4 passenger cars; leading and following)	UC 1.4	20 test users (controlled site)

4 Karlsruhe Pilot site

4.1 The ecosystem

An overview of the ecosystem at the pilot site is given in Table 2.

Table 2: Pilot site ecosystem of the Karlsruhe pilot site

Participating Entity	Internal to the Consortium (√)	External to the Consortium (√)	Role
FZI	√		Lead pilot site, vehicle provider
DLR	√		Vehicle provider, technical know-how
VBK		√	Public Transport Provider
KVV		√	Operator of test area autonomous driving Baden-Württemberg

4.2 Operation setting

The information about the operation environment and setting at the Karlsruhe site are shown in Table 3.

Table 3: Road, traffic and weather conditions at the Karlsruhe site

Variable	Site
Weather	Mixed weather conditions (December 2023 - November 2024), no operation during snow/icy roads
Sight conditions	Operation: unrestricted
Road type	Weiherfeld-Dammerstock: public roads with mixed traffic and parked traffic, partly narrow roads BUGA+Campus Ost: Semi-public area, mixed with pedestrian traffic
Road works	Weiherfeld-Dammerstock: multiple constructions sites during operation
Incidents	1 minor accident Weiherfeld-Dammerstock: 145 hard breaking incidents (mostly intentionally incited by people) BUGA: 5 hard breaking incidents (intentionally incited by people) Campus Ost: none
Traffic conditions	Weiherfeld-Dammerstock: Mixed traffic with Trucks/ Cars/ Bicyclists/ Pedestrians BUGA: Mainly pedestrian traffic
Traffic composition	Weiherfeld-Dammerstock: Semi-public area without crossing private traffic, many pedestrians

Variable	Site
Traffic control	Weiherfeld-Dammerstock: Transmission of diagnostic data utilizing ITS-G5
Area type	Weiherfeld-Dammerstock: public area BUGA: Semi-public area

4.3 Services and use cases

The Karlsruhe pilot included operations on public roads in a neighbourhood in Karlsruhe (Weiherfeld-Dammerstock), in a semi-public testing area in Karlsruhe (Campus-Ost) and on a fairground area in Mannheim (BUGA).

The most important goals for the demonstration in Karlsruhe and Mannheim were the following.

The Karlsruhe site featured two modified EZ10 Gen2 shuttles from EasyMile, an Audi Q5 and the modular vehicle "U-Shift" of DLR, as shown in Figure 1. These vehicles were designed for automated public transportation.

Figure 1: Demonstration of vehicles involved in the pilot, at KIT Campus Ost, 2023 (source: FZI)

The modular U-Shift vehicle concept was put to the test with several DLR prototypes at the Federal Garden Show (BUGA) in Mannheim (BUGA 23[1]), illustrated in Figure 2. The garden show area, while not a public roadway, was a controlled zone with substantial pedestrian traffic and some vehicular movement. Between April and October 2023, the U-Shift vehicles operated on a dedicated route and were displayed as part of an exhibition that also contained video material on the U-Shift development and background information. The prototypes included two driveboards at different stages of development, two passenger capsules, a cargo capsule, and a multi-use platform. The test circuit, a roughly 2 km long asphalt path, was shared with pedestrians and small electric road trains that regularly used the same route. Throughout the testing period, the vehicle's automation capabilities were progressively

[1] "BUGA" is short for "Bundesgartenschau", the German national garden show https://www.buga23.de/englisch/

enhanced. Initially, passengers were driven by a human operator using a joystick-based control system. Following extensive trials in automated mode, the U-Shift IV was showcased in full automated operation, supervised by a safety driver. This vehicle “U-Shift IV” is equipped with a suite of sensors, including LiDAR, cameras, radar, ultrasonic devices, and GPS. Various automation strategies were tested, with the main demonstration focusing on a real-time kinematics (RTK) GPS-guided path planning system, augmented by a LiDAR-based collision detection system. Additionally, a LiDAR-based SLAM system was explored. Over the course of the testing, no major issues were encountered, and more than 10,000 visitors had the opportunity to ride the U-Shift [1]. In addition, the U-Shift IV was also demonstrated together with the FZI vehicles during the demo week in Karlsruhe, as shown in Figure 1. Although the weather was not good all the time, the planned activities and the demonstration were carried out successfully. Both U-Shift IV and the FZI-shuttle ran as planned for one week and completed the intended tasks smoothly.

Figure 2: U-Shift test track at the federal garden show 2023 in Mannheim (source: DLR)

The FZI Research Institute for Information Technology developed the essential software and oversaw operations for both the Audi Q5 and the modified Easymile shuttles. These vehicles showcased a variety of applications, including last-mile passenger transport and cargo delivery. The pilot projects were conducted in Karlsruhe, to enhance automated shuttle rides in terms of speed, comfort, and safety, while also testing innovative vehicle concepts. Additionally, the potential for demand-responsive transport (DRT) to replace underused suburban buses was examined. The shuttles were adapted to navigate independently, responding to traffic conditions like avoiding parked cars and other obstacles, instead of adhering to a fixed pre-learned virtual path. Enhancements included the addition of six LiDAR sensors for better environmental awareness. The core innovation was in the safety and architecture of the automated driving function, which was validated through extensive fleet testing in real-world conditions within the Test Area Autonomous Driving Baden-Württemberg. Passengers could seamlessly book rides using the ioki app.

4.4 Site-specific test cases

In Karlsruhe the following site-specific test cases covered the addressed use cases.

- Automated passenger mobility in cities under normal/complex traffic & environmental conditions (UC 1.1 and 1.2) and Driving in areas with mixed traffic flow (UC1.6)

The operation area in Weiherfeld-Dammerstock is situated in a residential area. By offering automated rides to local Points of Interests like bus stops or tram stations, the goal was to enhance interest and trust in automated vehicles. Especially the concept of the last mile was targeted by the deployment and the operation of the shuttles. The traffic situation in the pilot area posed different challenges like narrow roads with parked cars and heavy traffic including a great amount of VRUs like cyclists. These conditions were met by the automated vehicles computing their respective trajectories simultaneously without a virtual rail.

- Connection to Operation Centre for remote supervision and decision aid (UC1.7)

To facilitate the Connection to Operation Centre for tele-operation and remote supervision, the automated vehicles of FZI provided the possibility for a tele operator to supervise it. The operator has the possibility to investigate the current state of the vehicle and can support the vehicle in its decision process. There is no direct control of the driving shaft. The control is only possible through the planning process which is running on the vehicle. This feature/ process was tested, demonstrated and used on numerous occasions throughout the pilot period phase.

- Evaluation of Cargo platooning in restricted areas (UC1.9)

Regardless of business models or the freight being transported, platooning with automated vehicles is a challenging technical task. To highlight current possibilities and challenges, the FZI demonstrated platooning with different automated vehicles at varying speed. The focus of this work was on the communication between two vehicles and the respective data exchange. Because of the nature of the experimental characteristics of the automated driving functions, the test runs and the demonstration of platooning took place in the restricted area (KIT Campus Ost). For early integration and rapid deployment into test platforms, a simulation was used. In this simulation, the virtual coupling of two vehicles was tested. The coupling was established via a communication interface using V2X (Vehicle-to-Everything) technology. Both vehicles must implement the same coupling interface; otherwise, a successful coupling is not possible. This is intended to prevent unintentional coupling. As soon as the pairing is successful, the vehicles are recognised as a convoy and can exchange further information with one another.

- Evaluation of automated mixed spatial mobility (UC2.1) and mixed temporal mobility (UC2.2)

To demonstrate the automated mixed spatial mobility the automated vehicles transported cargo and passengers at the same time within the same vehicle. For the demonstration of automated mixed temporal mobility, the automated vehicles transported cargo and passenger at different time within the same vehicle. A custom designed removable cargo hold was installed in the shuttles in order to combine cargo transport with passenger transport.

To evaluate the automated mixed special and temporal mobility, it was studied how the transport of cargo influences passenger transport and vice versa. The time-dependent effects on passengers and cargo throughput were estimated with a set of KPIs, including e.g. the average numbers of passenger/cargo transports per hour. The evaluation of the effects was carried out during student projects and the respective studies took mainly place in the residential area (Weiherfeld-Dammerstock).

4.5 The fleet

The fleet characteristics at the pilot site are shown in Table 4.

Table 4: Fleet characteristics at the Karlsruhe site

Test/Use Case	Deployed fleet characteristics								
	Vehicle brand & model	**Vehicle type (shuttle, …)**	**SAE Level reached for the field trials [1-5]**	**TRL level reached for the field trials [1-9]**	**Summary of upgrades held during the project (in consistency with D7.2)**	**HMI and Hand-over strategies (in consistency with D7.2)**	**Maximum speed reached during the trials (km/h)[2]**	**Average speed during the trials (km/h)**	**Maximum capacity of vehicle**
BUGA/UC1.1	DLR U-Shift	Modular vehicle	NA	NA	NA	NA	15 km/h	NA	8 (15 with standing area)
KIT Campus Ost/UC1.1/1.7/ 1.9 / 2.1 / 2.2	DLR U-Shift	Modular vehicle	NA	NA	NA	NA	15 km/h	NA	8 (15 with standing area)
FZI-Shuttles (Ella and Anna)/UC1.1/ 1.2/ 1.6/ 1.7/ 1.9/ 2.1/ 2.2	Modified EasyMile	Shuttle	2 Plus[3]	8	Localization, Perception and	NA	20	7.66	6

[2] Initial calculations for both maximum and average speeds – perhaps slight differences occur till the end of the project in the context of WP13 analyses.

[3] The automation level in Germany is restricted by the necessity to have a safety driver on board. Even if the vehicles are technically able to fulfil requirements for a higher SAE level, the official grading according to SAE classification can be described as Level 2 plus to 3.

Test/Use Case	**Deployed fleet characteristics**								
	Vehicle brand & model	**Vehicle type (shuttle, …)**	**SAE Level reached for the field trials [1-5]**	**TRL level reached for the field trials [1-9]**	**Summary of upgrades held during the project (in consistency with D7.2)**	**HMI and Hand-over strategies (in consistency with D7.2)**	**Maximum speed reached during the trials (km/h)[2]**	**Average speed during the trials (km/h)**	**Maximum capacity of vehicle**
	EZ10 Gen2				Car2X communication				
CoCar 1.9	Modified Audi Q5	Car	2 Plus	8	Localization, Platooning	NA	20	NA*	4

*: It was only used for the platooning.

4.6 The infrastructure

The physical and digital infrastructure deployed at pilot site is summarized below.

U-Shift: RTK-GPS, 5G, storage, charging, maintenance (+onboard LiDAR, cameras, radar)

FZI-Shuttles: RTK-GPS, V2X-On Board Units for ITS-G5 communication, LiDAR, cameras

CoCar: RTG-GPS, V2X-On Board Units for ITS-G5 communication, LiDAR, Camera

FZI: infrastructure for ITS-G5 communication, remote control center

4.7 Passengers

<u>BUGA</u>

The pilot initiative at BUGA was designed to engage all visitors, with a particular emphasis on families, elderly individuals, and specially invited groups such as municipalities. This inclusive approach aimed to ensure that a diverse audience was able to experience and benefit from the pilot project.

<u>Campus Ost:</u>

The focus was on students and technical experts. This setting addressed persons with knowledge in technical development, providing them with an opportunity to explore and engage with advanced concepts and technologies.

<u>Weiherfeld-Dammerstock:</u>

The pilot targeted local residents and technically interested individuals, including tourists. This allowed the community and visitors with a technical inclination to gain insights and first-hand experience with the project's developments.

4.8 Total number of passengers and freight deliveries

The total number of passenger rides in the Karlsruhe pilot ("BUGA", "Campus Ost" and "Weiherfeld Dammerstock") was 13.477 passengers. The total number of freight deliveries in "Campus Ost" and "Weiherfeld Dammerstock" was 1629.

4.9 Data collection

With the U-Shift, the vehicle data was logged on the vehicle control unit and stored locally. Passenger and trip data were collected using registration forms. The safety operators reported all important information of their shifts in a logbook. In the FZI-Shuttles, the vehicle data was recorded using a middleware software. Passenger and trip data were collected via the ioki smartphone app and by manual counting.

4.10 Pilot operation key findings

4.10.1 Key findings per Use Case

The high-level key findings per use case at the pilot site are summarized in Table 5.

Table 5: High level findings per Use Case

High level findings per Use Case		
Use Case	**Overall qualitative performance score (1-3[4])**	**Justification**
Use Case 1.1: Automated passengers/cargo mobility in Cities under normal traffic & environmental conditions	**3**	Under normal conditions the AVs performed well.
Use Case 1.2: Automated passengers/cargo mobility in Cities under complex traffic & environmental conditions	**2**	Interaction with other road users must be improve and mechanism for deadlocks has to be improved.
Use Case 1.6: Mixed traffic flows	**2**	Interaction with other road users must be improved
Use Case 1.7: Connection to Operation Centre for tele-operation and remote supervision	**2**	Issues with different car2x hardware supplier. Standards are not implemented always the same
Use Case 1.9: Cargo platooning for efficiency	**1**	Platooning has many challenges (perception, controlling, interaction with VRUs). Reliability of V2X communication. Missing standardized message format for platooning. So, only isolated solutions for platooning can be developed, rather than a scalable solution that could be widely deployed.
Use Case 2.1: Automated mixed spatial mobility	**2**	The concept was successfully tested and has the potential for widespread use. However, improvements could be made in handling the cargo cage. To evaluate the entire transportation chain, collaboration with a transportation partner would be necessary for comprehensive testing.
Use Case 2.2: Automated mixed temporal mobility	**2**	same as above

4.10.2 Key challenges

The key challenges have been identified below and summarized in Table 6.

Ride-pooling and dynamic routing have posed significant challenges in developing and operating automated vehicle systems. The complexity lies in efficiently matching multiple passengers with similar destinations, optimizing routes in real-time, and ensuring a smooth and timely journey for all users. This requires advanced algorithms and seamless communication between vehicle, backend system, and passengers.

Automated vehicles must navigate/overcome a variety of obstacles in mixed-traffic environments, including other vehicles, pedestrians, cyclists, and unexpected road obstructions. Automated shuttles travelling on virtual rail systems face major challenges when unexpected road obstructions, such as improperly parked vehicles, block their path. These obstacles can lead to safety stops and require manual driving interventions by a safety operator, disrupting the smooth operation of the shuttle. Ensuring that the shuttles can navigate around such obstacles without compromising safety or efficiency is crucial for the success and acceptance of automated transportation systems.

Table 6: Key challenges at pilot site

Challenge	**Type** (Operational, Technical, Business, Other)	**Mitigation**	**Mitigation outcome**
Scenarios arose in which people came so close to the vehicle that it was not possible to continue driving and the danger zone was cleared again by means of an acoustic warning signal. Unfortunately, there were also situations in which people deliberately ran in front of the vehicle, which led to emergency braking.	Operational	Speed limit, acoustic warning signal, communication	No persons were harmed; Road users will be informed in advance about the existence of the shuttles and must maintain an appropriate distance.
No clear traffic regulations within the framework of visitor guidance at the garden show.	Operational	Setting up traffic signs	Mitigation was implemented during pilot phase after initial issues, after that the situation improved.
Weather influences such as thunderstorms and rain with reduced GPS precision.	Technical	/	/
Access control to the vehicle / attempts to join a trip without registration.	Operational	Supervision in the vehicle and at the bus stop	Mitigation was implemented during pilot phase after initial issues, after that the situation improved.

4.10.3 Key incidents and impacts

During the operation at BUGA, there were only a few difficulties on site. Some operational and technical adjustments helped to improve the service quality. Five hard breaking events were intentionally provoked by guests at BUGA, who wanted to try the automation features.

During the operation in Weiherfeld-Dammerstock, several challenges were encountered. Pedestrians and cyclists deliberately provoked hard braking events to test the shuttle's automation features. Additionally, impatient drivers frequently overtook the FZI shuttle in a risky manner and cut off close in front of it. This caused the shuttle to brake abruptly as the safety distance could not be maintained. A minor accident occurred during the test phase, but it did not take place during operational hours and did not involve any passengers. There were no injuries and there was only minimal property damage (minor paint damage to the FZI shuttle). The accident could not be attributed to either the driving function or the safety operator, as the other party did not notice the shuttle.

4.10.4 The passengers' point of view

During the test operation, passenger satisfaction was continuously surveyed when passengers got off the shuttle. If passengers were actively asked for feedback, this was usually given, otherwise the opportunity was rarely used. Technically, the SHOW surveys were conducted using a Lamapoll online survey. Passengers were able to scan a QR code to access the survey or use a mobile device from the stand staff. Overall, the ride on the U-Shift was rated very positively (see Figure 3). The innovative character and design were highly appreciated. Passengers felt safe and were very satisfied with their rides.

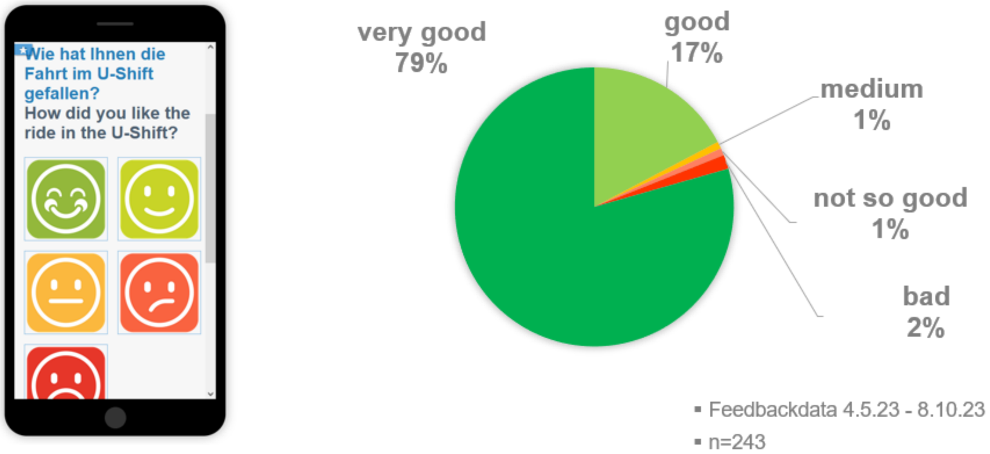


Figure 3: Satisfaction with the U-Shift ride (source: DLR)

During the public trial in Karlsruhe, passengers could rate their rides and provide feedback via ioki's smartphone app. The ratings were very positive and most passengers stated that they would use the shuttle service again. A QR code was also displayed inside the shuttle, which led to the passenger questionnaire for the SHOW project.

4.10.5 The safety drivers' point of view

U-Shift: The safety drivers were very committed. From an operational point of view, they took on important tasks, particularly in explaining the vehicle functions, features and assisting passengers. Due to the novelty of the technology, they were an important factor in explaining automated driving and making passengers feel safer. The few incidents, in which the garden show visitors intentionally provoked hard breaking, were psychologically very challenging for the safety operators.

FZI-Shuttles: The safety operators were very committed. They played a crucial role in explaining the vehicle functions and assisting passengers. Given the novelty of the technology, they were crucial in clarifying automated driving and reinforcing the passengers' sense of safety. On the other hand, the newly developed driving function reduced interventions between the safety operators and the shuttle, as the automated driving function can handle almost all scenarios.

4.10.6 The other road users’ point of view

The visitors at BUGA, who encountered the U-Shift as pedestrians during the test drives, showed predominantly positive interest and an open-minded, curious and generally approving attitude. A few visitors attempted to test the reaction of the automated driving system by deliberately stepping into the path of the vehicle and triggering an emergency stop. Overall, interaction with other participants was rather straightforward, even when pedestrians came too close to the vehicle, forcing it to slow down and with the exceptions mentioned above.

4.10.7 The stakeholders’ point of view

The testing of the U-Shift prototypes at BUGA in Mannheim was accompanied by scientific research in order to (1) identify application scenarios for U-Shift and (2) discuss them with various stakeholders including citizens and various interest groups, such as small and medium-sized enterprises (SMEs), traffic planners or municipalities. In addition to the different purposes of use, the question of spatial areas of application and the requirements of different stakeholders for the vehicle design were also considered.

The U-Shift concept met with great interest and a very positive response from all stakeholders surveyed. The flexibility offered by U-Shift’s modular design has been reflected in the possible applications identified by the municipal stakeholders: the area of local public transport was mentioned first, e.g. as an on-demand operation. Another application scenario identified was the use of the capsule as a (mobile) service station for various purposes. Examples cited here include post/parcel stations, ATMs, sanitary facilities (e.g. at events or in public spaces), charging stations, etc. What all examples have in common is that the capsule is placed by the U-Shift at designated locations for a specific purpose in order to fulfil a specific task or provide a supply service without the need for personnel. While the capsule fulfils this function at the place of use, the driveboard is free for other transport tasks. Another application scenario is the use of the U-Shift capsule for stationary services to supply the population in a specific area. This is similar to the aforementioned application with the difference that personnel are also deployed to provide the service. Examples given by the participants included a mobile healthcare centre/doctor's surgery, pharmacy, post office, library, supermarket, bakery, food bank and others.

The testing of the FZI shuttle was supported by scientific research to identify potential application scenarios for various stakeholders, including citizens and interest groups such as public service providers. In particular, the implications of the on-demand service, such as the need for additional interaction points for passengers, provided a good insight for both sides.

The PTOs are highly interested in autonomous driving technology. They also see the use case of last-mile services in combination with on-demand operations as promising for the future. However, it is not yet profitable for them as PTOs, since a safety operator is still required on board for operation on public roads. Both the reliability of the shuttles and the capabilities of the automated software still need to be improved.

The feedback from the participants at the MAMCA workshop at the Karlsruhe pilot site was particularly positive. The exchange with other PTOs and the perspectives of the various stakeholders were particularly valuable.

4.11 Key local demonstration events

U-Shift BUGA operation event

What: U-Shift BUGA operation event, illustrated in Figure 4

Who: DLR

When: April - October 2023

Objective: Making automated driving tangible, providing insights into technical development, collecting user feedback

Outcome: High visibility, valuable information from various stakeholders

Figure 4: U-Shift at the federal garden show (BUGA) (source: DLR)

Student day in Karlsruhe Campus Ost

What: During the extensive operational demonstration week of the U-Shift vehicle together with the FZI vehicles, one day was dedicated to an event targeting students. This “Student day” focused on research into new vehicle concepts and automation technologies. An invitation flyer and the activities are shown in Figure 5 and Figure 6 respectively.

Who: DLR, FZI

When: 14.11.2023, 10 am - 16 pm

Objective: Give students and employees of the KIT research center and other universities the possibility to get to know the vehicle and provide students the opportunity to:

- Experience prototypes live and ride in automated vehicles
- Meet scientists and learn about automated vehicles, development and scientific work
- Exchange ideas: what possible applications are desirable?

- Get to know career opportunities (internship, student assistant position, bachelor's or master's thesis or as a scientist after graduation

Outcome: Raising interest in automated services, increased visibility and knowledge about automated driving, recruitment of students as assistant scientists

Figure 5: Invitation flyer for the student event, distributed via social media, contact networks and at various universities (source: DLR)

Figure 6: Campus Ost students day impressions (source: FZI and DLR)

IT Trans 2022 and 2024

What: IT Trans fair and conference, as shown in Figure 7

Who: FZI

When: 10.-12.5.2022 and 14.-16.5.2024

Objectives:

- 2022: Initial presentation of the cargo delivery box and first test drives in the target area
- 2024: Present the capabilities of the FZI shuttles and the possibilities by communicating via C2X standards

Outcome:

2022: Interest in automated services raised, increased visibility and knowledge of automated driving

2024: High visibility, networking with other stakeholders (city, C2X developers, shuttle operators, public service providers etc.)

Figure 7: FZI and SHOW at the IT Trans 2022 (source: FZI)

Visit of Federal Minister Wissing

What: Visit of Volker Wissing (Federal minister of Transport, Germany), shown in Figure 8

Who: FZI

When: 1.3.2024

Objective: Present the accomplishments of the FZI-Shuttles and the capabilities

Outcome: Increased visibility of the shuttle project in the federal ministry

Figure 8: Visit of Federal Minister at the pilot site Karlsruhe (source: FZI)

4.12 Lessons learned & Recommendations

U-Shift:

After refining the vehicle control system and basic functions, as well as optimizing the controls, the U-Shift has demonstrated increased reliability. When operating on roads shared with pedestrians, various conflict scenarios emerged, all of which were accident-free. There were cases in which pedestrians came so close to the vehicle that it had to stop and clear the danger zone with an acoustic warning signal. Unfortunately, some people deliberately stepped in front of the vehicle, which resulted in emergency braking. Despite these challenges, one important finding is the passengers' enthusiasm and the high acceptance of automated vehicles [1].

FZI-Shuttles:

Breaking out of the virtual track was a major advantage in the target area Weiherfeld-Dammerstock. As there are many parked vehicles along the road, the automated driving function is able to drive around them without any intervention of the safety operator. This increases the flow of traffic and the shuttle can flow with it. Increase the maximum speed to 20 km/h also increases the acceptance of other road participants and passengers.

Technical:

- Improvement of chassis technologies
  - Improve LiDAR-Sensors for Perception and Localization (4D, higher range, better resolution)
    - As part of SHOW, upgrades to resolution have already been carried out and performance improvements were demonstrated. Thanks to the latest 4D Lidars, performance in critical situations has been increased even further.
  - High-precision GPS for fusion with local methods (Lidar-Slam, odometer)
    - In the context of SHOW, the high-precision GPS was utilized for evaluation purposes. The measurements were already used during the mapping process. Online usage is a redundant system and would therefore be necessary for operation without a safety operator.
  - V2X communication devices
    - As part of SHOW, the interactions with smart infrastructure was executed. This revealed improvements for a comfortable ride through anticipatory driving.
- Improvement of algorithms for shuttle operation
  - Improved accuracy of LiDAR localization through better mapping utilizing the GPS measurements
    - In the context of SHOW, the additional constraints imposed on the mapping process by the redundant information from GPS have resulted in a more consistent and accurate map.
  - Utilizing the V2X communication with the smart pedestrian crossing for a more comfortable and anticipatory driving
  - Implementing remote diagnostics transmitted via V2X communication
    - Within SHOW, a remote operator could monitor the current status of the shuttle and diagnose the error.
    - In future it would be advantageous, if a remote operator could restart the software.
  - The introduction of remote control for external assistance in situations that the shuttles cannot handle themselves would be advantageous in the future.
- In future, optimization is required for robustness in different weather conditions, especially in rain and fog (perception and vehicle technology, IP protection class).

- Increase maximum velocity
    - Improvements to motion planning pipeline for better perception/prediction of VRUs were made during the SHOW project. But there is still room for improvements, especially in critical situations.

Operational:

- Improve communication with pedestrians to prevent intentionally provoked hard-breaking incidents

Business:

- Future operation with combined passenger and logistics has potential for successful business models
- Future operation without an operator on board the vehicle is a compelling necessity for the economic realisation of any use case.

4.13 Roadmap beyond SHOW and replicability

The deployment of the innovative vehicle concepts from DLR (U-Shift) and FZI within the SHOW project led to valuable findings for the transfer of research results to the real world with the aim of further adapting automated vehicles specifically for PT operations.

Currently, there are no further AV/AS operational plans and projects at the Karlsruhe pilot site. But the FZI continues to develop automated driving functions with the FZI-shuttles focusing on teleoperation and remote fleet management. Further work on various projects in the U-Shift project landscape is planned. As part of the U-Shift technology transfer project, the aim is to obtain approval for the use of the U-Shift IV on public roads. Besides, various vehicle components will be further developed and the technology transfer to small and medium-sized enterprises (SMEs), medium-sized companies and large companies will be continued.

5 Frankfurt Pilot site

5.1 The ecosystem

The ecosystem at the Frankfurt pilot site is indicated in Table 7.

Table 7: Pilot site ecosystem at the Frankfurt pilot site

Participating Entity	Internal to the Consortium (√)	External to the Consortium (√)	Role
DLR	√		German Mega Site leader
rms	√		Leader
traffiQ	√		Local PTA
EasyMile	√		Vehicle provider
RMV		√	Regional PTA
fahma		√	Technical Know-How
VGF		√	Local PTO
ioki	√		DRT-software provider
T-Systems	√		Software provider

5.2 Operation setting

The information about the operation environment and setting is shown in Table 8.

Table 8: Road, traffic and weather conditions at the Frankfurt pilot site

Variable	Site
Weather	Mixed weather conditions, operation in all seasons of the year
Sight conditions	Only restriction was heavy snow fall
Road type	- Urban roads in a quieter neighbourhood - Mostly one-lane and one-way streets but also two-lane streets - Speed limits: 30 km/h
Road works	No road works that affected the track
Incidents	/
Traffic conditions	Different traffic conditions depending on the time of the day
Traffic composition	cars, delivery vehicles and bicycles
Traffic control	/
Area type	outside area

5.3 Services and use cases

The service has been located in Frankfurt, in the district of Riederwald – which is in the east of the city centre. There are metro stops of two different metro lines close to the neighbourhood of the site (see Figure 9). Further, many POIs are along the track, such as a supermarket, a pharmacy, and a sports club. The route is 2.7 km long and has 30 virtual stops (including wheelchair-friendly stops). Therefore, the automated shuttles served as a first/last mile feeder to those metro stops with an on-demand function. The service was free of charge via the on-demand application “RMV EASY” (virtual stops only). Operation times were Monday to Saturday 8 am to 3 pm. Inside the Shuttles two AI-Systems have been tested, a Camera-system and a voice-bot.

Figure 9: Frankfurt Service Area (Source: rms)

The most important goals for the demonstration in Frankfurt were the following:

- Linking the automated shuttles with an on-demand function
- Testing of AI systems (Camera and Voice Bot)
- Accessibility to the Shuttles

The site dealt with the following use cases:

- UC1.1: Automated passengers’ mobility in Cities under normal traffic & environmental conditions
- UC1.6: Mixed traffic flows
- UC1.7: Connection to Operation Centre for tele-operation and remote supervision
- UC1.10: Seamless autonomous transport chains of Automated PT, DRT, MaaS, LaaS
- UC3.1: Self-learning Demand Response Passengers/Cargo mobility
- UC3.2: Big data/AI based added value services for Passengers/ Cargo mobility
- UC3.4: Automated services at bus stops

- UC3.6: COVID-SAFE Transport

5.4 Site-specific test cases

In Frankfurt the above-mentioned use cases were covered with the following site-specific test cases:

- Automated on-demand service as a feeder of PT in Frankfurt (UC 1.1; 1.6; 1.10):

An On-demand service, based on automated shuttles, served as a PT feeder in a real-traffic environment. EasyMile has developed several functionalities to enable a high degree of autonomy with the aim to simulate driverless operations. For a smooth service EasyMile provided a dedicated maintenance and support service. For the SHOW test site, the operation of the EasyMile shuttles was linked to the ioki on-demand software (which is already used for the existing RMV on-demand services) for the first time. Therefore, EasyMile has set up an API-Interface and supported the integration into the ioki on-demand software.

- AI based added value services for Passengers in Frankfurt (UC 3.1; 3.2):

Aiming to offer the passengers a better and more futuristic service, an AI based virtual bot has been used to offer passengers information about the PT schedule and the project. Further, a camera system has been tested which offered operational information about the shuttle and the passengers (e.g., number of passengers, dangerous situations). Both tools are meant to prepare the perspective operation of the shuttle without a safety driver.

- Automated Covid-free PT with accessibility for everyone in Frankfurt (UC 3.4; UC3.6):

With regard to UC3.4, as part of the PT on-demand service in Frankfurt, the shuttle was to be made accessible to all passengers. For this, an electric ramp, a wheelchair device, and the labelling of accessible stops have been implemented. Wheelchair users who indicated this into their profile in the on-demand app were routed to the wheelchair-accessible start and end point – thus, to those virtual stops with enough space to use the ramp. The shuttle arrived and left the virtual stops automatically that are given by the on-demand app.

UC3.6 was addressed by reminding the passengers to wear their face mask during the ride by the AI-System (Covid-19 rule for PT in Germany until March 2022). The camera system recognized if somebody was not wearing the mask and showed a message accordingly.

5.5 The fleet

2 EasyMile EZ10 Gen3b were deployed. The respective fleet characteristics at the pilot site are shown in Table 9. The average speed during the trials was calculated by dividing the kilometers traveled by the total travel time per shuttle run. Therefore, the stop time spent at each stop was included in the calculation. Due to the technology used, it was not possible to subtract the stop time from the total travel time. Thus, the average speed is much lower than in reality.

Table 9: Fleet characteristics at the Frankfurt site

Test/Use Case	**Deployed fleet characteristics**								
	Vehicle brand & model	**Vehicle type (shuttle, …)**	**SAE Level reached for the field trials [1-5][5]**	**TRL level reached for the field trials [1-9]**	**Summary of upgrades held during the project (in consistency with D7.2)**	**HMI and Hand-over strategies (in consistency with D7.2)**	**Maximum speed reached during the trials (km/h) [6]**	**Average speed during the trials (km/h)**	**Maximum capacity of vehicle**
Same for all UCs:	EasyMile EZ10 Gen3b	Shuttle	3	9	NA	NA	18 km/h	1.51* km/h	6

*: The speed calculation has included the stop times at the shuttle stops for boarding and alighting.

[5] The automation level in Germany is restricted by the necessity to have a safety driver on board. Even if the vehicles are technically able to fulfil requirements for a higher SAE level, the official grading can be described as Level 2 plus to 3.

[6] Initial calculations for both maximum and average speeds – perhaps slight differences occur till the end of the project in the context of WP13 analyses.

5.6 The infrastructure

The physical and digital infrastructure at demo site included 4G, LiDARs and GPS+NRTK. Service was integrated in the on-demand booking app.

5.7 Passengers

In general, the pilot was aimed at all citizens (business travellers, tourists and local residents), with local residents, commuters, and university students as focal target groups. There were also specific groups of interest, such as the elderly and people with reduced mobility.

5.8 Total number of passengers

The total number of passenger rides in the final demonstration (no pre-demo was held for Frankfurt) was 3,051, while the growth curve of passenger rides is shown in Figure 10. As all journeys had to be booked via the DRT software, the exact number of passengers could be determined.

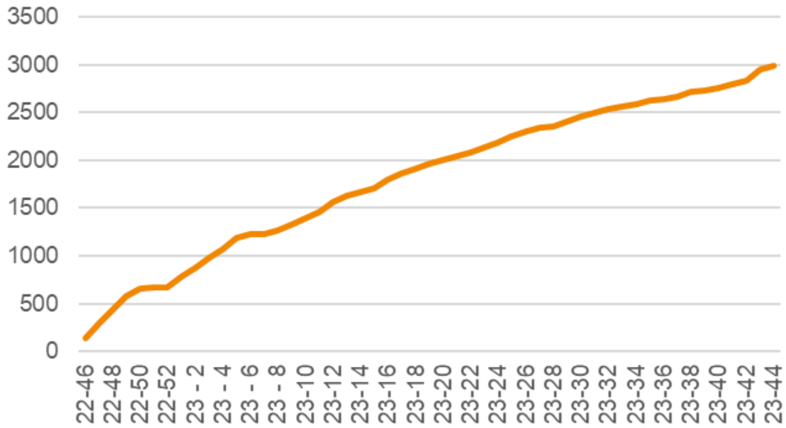


Figure 10: Passenger rides in Frankfurt (Source: rms)

5.9 Data collection

The vehicle data was continuously collected in all vehicles and stored locally. Further operating data was recorded by the booking software ioki, particularly in relation to the number of passengers and their satisfaction. In addition, the safety operators have been reported all important information from their shifts in daily reports, which were evaluated in detail.

5.10 Pilot operation key findings

5.10.1 Key findings per Use Case

The high-level key findings per use case at the pilot site are summarized in Table 10.

Table 10: High level findings per Use Case at the Frankfurt site

High level findings per Use Case		
Use Case	**Overall qualitative performance score (1-3[7])**	**Justification**
UC1.1: Automated passengers/cargo mobility in Cities under normal traffic & environmental conditions	**2**	Automated DRT services have a high potential to optimize mobility within cities in many ways when operating in normal speeds. The less complex the environment, the earlier automated driving can have a real positive impact both on the traffic situation in cities and the change in mobility to a higher share of PT-usage.
UC1.4: Energy sustainable automated passengers/cargo mobility in Cities	**/**	See Chapter 6: Aachen operation (part of Frankfurt Pilot site)
UC1.6: Mixed traffic flows	**2**	With the current state of automated driving technology, an increase in the efficiency of urban transport is not yet recognisable. Safety, on the other hand, is very high due to a cautious driving behaviour. By improving the flexibility of driving technology and an increasing number of automated vehicles on the roads, both can be significantly improved. User acceptance varies, depending particularly on the type of use and the speed of the vehicles.
Use Case 1.7: Connection to Operation Centre for tele-operation and remote supervision	**1**	**Connection to Control Centre failed due to interface issues – instead collection of further requirements for an autonomous Control Centre in PT**
UC1.10: Seamless autonomous transport chains of Automated PT, DRT, MaaS, LaaS	**3**	From a social point of view, people with restricted mobility can be better integrated into daily life. Positive environmental effects are mainly the replacement of private car usage due to a better and more flexible service in PT. Especially the deployment of automated DRT services as PT-feeder can help to increase the comfort of PT-use from a customer's point of view.

High level findings per Use Case		
Use Case	**Overall qualitative performance score (1-3)**	**Justification**
UC3.1: Self-learning Demand Response Passengers/Cargo mobility	**3**	DRT-services have a high potential to offer more flexible services in PT. The offered service was highly appreciated by the customers as it added value to the existing mobility offers in the neighbourhood.
UC3.2: Big data/AI based added value services for Passengers/ Cargo mobility	**2**	AI systems can support driverless public transport services in the future. In addition to steering the vehicle, drivers have other operational and service-based tasks that can be replaced by such systems. The AI-systems used in the Frankfurt project represent a first step in this direction.
UC3.4: Automated services at bus stops	**2**	An electric ramp, a wheelchair device, and the marking of accessible stops were implemented to make the shuttle accessible to all passengers. Wheelchair users who indicated this into their profile in the on-demand app were routed to the wheelchair-accessible start and end point – thus, to those virtual stops with enough space to use the ramp.
UC3.6: COVID-Safe Transport	**2**	Detection of misbehaviour by AI-Systems could help to prevent potential threats in general as the tested system was able to recognise specific situations within the shuttle. The obligation to wear a mask in PT ended during the demo phase; as such, a final justification of the research hypothesis can't be made.

5.10.2 Key challenges

The key challenges have been identified and summarized in Table 11.

[7] 1 [Low] – 2 [Medium] – 3 [High]; success qualitative score, considering all aspects (technical, user acceptance).

Table 11: Key challenges at the Frankfurt pilot site

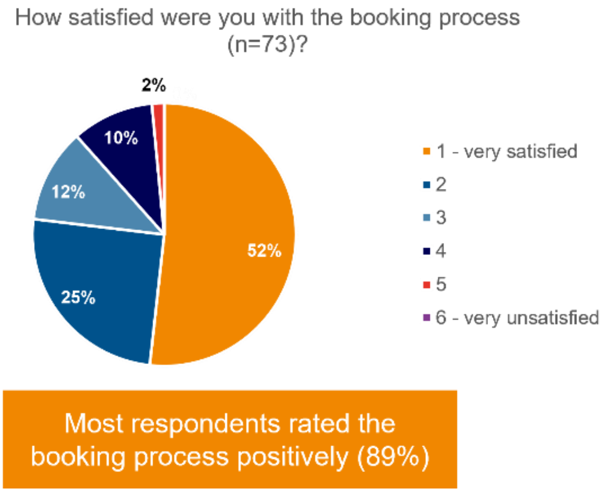
Challenge	**Type** (Operational, Technical, Business, Other)	**Mitigation**	**Mitigation outcome**
Connection between on-demand software and automated shuttles involves many challenges. For example, pick-up points and waiting positions after completing a task.	Technical, Operational	Optical marking of the exact pick-up points and programming of a fixed waiting position for the shuttle after completing a task.	Passengers were able to find the exact pick-up point more easily and the operation worked smoothly.
Addressing the elderly residents who represent a large proportion of the neighbourhood.	Operational	Explaining the complex product in a simple and visual way. Communicate with target groups on site to gain valuable feedback.	The service has been very well received by residents, particularly by elderly people.
Smooth behaviour of the shuttle (and followers), despite the challenges of the site.	Technical	Adaptation of the programmed route before start of operation: speed, position of the track, safety procedures.	The performance of the shuttle was mostly smooth on the track due to the adaptations.

5.10.3 Key incidents and impacts

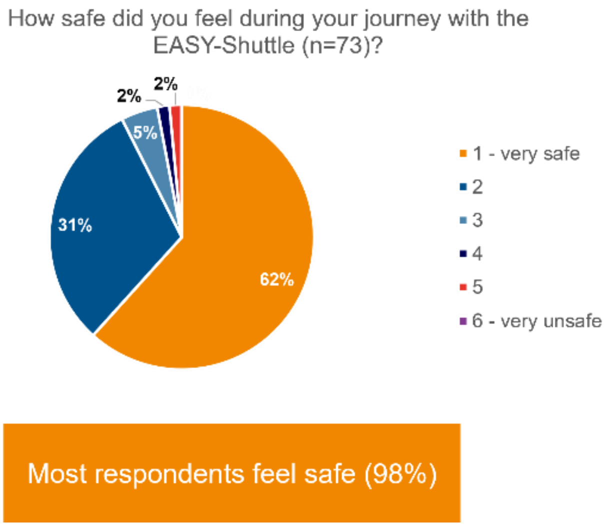
During the commercial phase, there were not many difficulties on site. Some operational and technical adaptations helped to improve the quality of service. The main impact was caused by technical failures of the shuttles, so that often only one of the two shuttles was in operation instead of both.

5.10.4 The passengers' point of view

According to the first analysis result in Figure 11 (the final verified results follow in D13.5), satisfaction with the booking process and the feeling of safety during the journey was high. Further, the passengers rated the service in the booking-app with 4.8 out of five possible stars (665 ratings). In general, passengers' feedback was very positive, where the innovative character and mobility benefits were highly appreciated, and people felt safe and were very satisfied with the service.



(a)



(b)

Figure 11: Passengers point of view: (a) booking process; (b) safety (source: rms)

5.10.5 The safety drivers' point of view

The safety drivers were very committed and interested in developing a better technical understanding. Operationally, they have taken on important roles, particularly in supporting elderly passengers. Due to the novelty of the technology, they were an important factor in explaining automated driving and creating a better sense of safety among passenger. More elaborate results follow on D13.5.

5.10.6 The stakeholders' point of view

The project was the next step in several years of cooperation with the local partners. All partners, and especially the operator, were highly satisfied with the service and the lessons learnt from the project. Intensive discussions are underway on lessons learnt for future automated operations in the region. Even if this service is not continued, follow-up projects or services for the region are being discussed. The need for a more advanced technology is one of the main requirements for future-services. During the MAMCA-workshop with all German pilot sites, the stakeholders were able to contribute and discuss their different perspectives and insights.

5.11 Key local demonstration events

Information for residents at start of operation

What: Information counters for residents at start of operation

Who: residents of the neighbourhood

When: November 2022

Objective: Possibility for direct residents of the site to ask questions, get information on the booking process and to anticipate possible fears

Outcome: Participants asked questions about the vehicle technique and the planned service – they were very interested and gave mostly positive feedback

Event with elderly people

What: Event with elderly people in the neighbourhood, as shown in Figure 12

Who: Elderly People living around the test site - Support of district management and the pensioners' residence

When: March 2023

Objective: Engaging the elderly residents with an information event about the project and presentation of the vehicles with test ride - Focus mainly on the use of the shuttles, especially the booking process

Outcome: Input from participants for a more senior-friendly service

Figure 12: Event in Frankfurt Riederwald (source: VGF)

Online Riddle

What: Online Riddle, where the flyer is shown in Figure 13

Who: RMV-customers

When: June – July 2023

Objective: Competition with a riddle to support the use of the AI-Voicebot in the shuttle

Outcome: More customers used the AI-Voicebot + Test-users came to the site to try out the service

Figure 13: Flyer for online-riddle (source: rms)

5.12 Lessons learned & Recommendations

The operation of automated on-demand shuttles in Frankfurt as part of SHOW has provided valuable insights for future operations as well as recommendations for the various stakeholders involved. From a technical perspective, the connection between the DRT-software and the shuttle has worked well from the outset and offers promising future prospects for implementation in regular operations. This should be further proofed with different providers of both software. Nevertheless, for future projects and especially for real operations, the communication for route adaptations between the two software parts should function more smoothly. In addition, the algorithms for route selection must be further improved and adapted for automated operations. On the vehicle site, there is far too much maintenance work for technical issues, which must be handled more conveniently in the future.

Focussing on the operations, adaptational learnings for the routing and virtual stops of automated DRT-services was gained. Firstly, the adaptation of virtual stops is required, especially if no physical stops are in place for the service. Compared to driver-based DRT-services, where the virtual stops can easily be selected on the map, the stops for automated services need to be selected more precisely. This is mainly due to the fact that the system stops at a specific point and is not able to adjust this waiting position if, for example, a parking car blocks access to the shuttle. This is particularly the case with the barrier-free virtual stops, where more space is required to access the shuttle with a wheelchair via the ramp. Secondly, the routing software must always send the shuttle to a waiting position if there is no next task to be solved. Otherwise, the shuttle would stay at the drop-off point of the fulfilled task and might block the street. This is another special feature of automated operation compared to driver-based DRT-services.

Two important recommendations for operators of automated PT-services are:

1. communicate with the local community constantly and already in advance of the service launch, as this is key to prevent misinformation or a pessimistic view. In this way, a successful launch of the service is more likely as fears and doubts can be allayed in advance.
2. due to the current high cost and time expense of vehicle maintenance, operators should plan for a higher number of shuttles than they would normally do for driver-based services. In this way, the planned service can be guaranteed.

Overall, an important insight is that future driverless operation will lead to a more economical implementation of DRT services, but to achieve this, the next step in autonomous technology must be taken on the vehicle side. In addition, the interface issues with the implementation of the control center are one example of the urgent need for standardization of the different software interfaces.

5.13 Roadmap beyond SHOW and replicability

RMV – as the regional PTA in the Rhine-Main-Region – has been working on automated PT systems together with its wholly owned consulting subsidiary rms since 2019. The SHOW site was an important step towards driverless on-demand services in the region. The next steps will focus primarily on expanding technical expertise and integration into the existing (still driver-based) on-demand services.

As part of the nationally funded “KIRA project”, RMV will take this new step together with Deutsche Bahn in 2024. Autonomous vehicles are planned to be integrated into existing DRT services. From June 2024, Level 4 vehicles are being tested in the city of Darmstadt and the district of Offenbach as part of the KIRA project. Six Nio ES8 vehicles with a retrofitted autonomous driving system from Mobileye are travelling in traffic at normal speeds of up to 80 km/h. The focus is on testing the next step in autonomous driving technology, with a more flexible driving system that should be able to operate without a safety driver in the long term. The next steps are the integration of ioki’s DRT-software, which is already tested, and the transport of passengers within a closed user group.

6 Aachen operation (Part of Frankfurt Pilot site)

6.1 The ecosystem

The information about the ecosystem for the Aachen operation is shown in Table 12.

Table 12: Pilot site ecosystem during the Aachen operation

Participating Entity	Internal to the Consortium (√)	External to the Consortium (√)	Role
FEV/FEV.io	√		Energy application demo Test Management
ATC Proving Ground Holder		√	Providing proving ground
T-Systems international GmbH	√		Communication, Connectivity “Low Carbon Mobility Management” (LCMM) real-world measurements

In addition to the stakeholders listed in the table above, data measured during the operations at the Frankfurt pilot site was collected and reused as a starting point for the operation in Aachen. This data formed the starting point for the use case carried out in Aachen.

6.2 Operation setting

The road, traffic and weather conditions during the Aachen operation are indicated in Table 13.

Table 13: Road, traffic and weather conditions during the Aachen operation

Variable	Site
Weather	Mixed weather conditions, test drives mainly in fall and summer
Sight conditions	Mainly good sight condition with rain sometimes
Road type	Normal 2 lane urban roads with intersection on proven testing ground ATC
Road works	No road works
Incidents	No
Traffic conditions	No traffic due to restricted proven testing ground
Traffic composition	No other vehicles on the road
Traffic control	Traffic lights available
Area type	ATC proving ground

6.3 Services and use cases

- Energy sustainable automated passengers' mobility in cities (UC1.4)

The use cases were carried out in Aachen at the Aldenhoven Test Center (ATC), a test site that is well suited to simulating City-like environments.

As a baseline, the previous use cases covered the collaborative, coordinated movement of multiple vehicles in a platoon, where a preceding vehicle is followed by a follower vehicle. The coordination of the follower vehicle was performed by a central controlling algorithm, which was executed in a manoeuvre lead vehicle that has bi-directional information exchange with the follower vehicle via V2V networking. On top of that, the controlling algorithm implemented an optimization process for the velocity trajectories to minimize the energy consumption by ensuring the smoothest possible operation of the vehicles concerned. This algorithm, called Centralized Cooperative Adaptive Cruise Control (C-CACC), has already been investigated in simulations and tested on test sites. With a given velocity profile of the preceding vehicle, the benefit of C-CACC compared to state-of-the-art adaptive cruise control (ACC) in a city-like environment was shown to be 29% in terms of energy consumption in the simulation and 21% in the real driving test [2].

Based on this baseline described above, the following use case UC1.4 was set up to cover the automated merge-in/-out manoeuvre of a shuttle into flowing traffic, as it can typically occur at bus stops. The bus stop was simulated using ATC capabilities. The use case should be performed with 2 automated vehicles and another non-automated vehicle as follows: the first automated vehicle served to simulate a preceding car as well as the manoeuvre leader, that centrally controlled the follower vehicles by receiving information about their status and sending commands to them. The non-automated vehicle followed the manoeuvre leader, and both formed a traffic flow. The non-automated vehicle was controlled by a driver, who received and followed commands from the manoeuvre leader as indicated on the HMI. The second automated vehicle acted as a shuttle bus merging into flowing traffic. The coordination of all three vehicles was performed by the manoeuvre leader.

In addition to the functional aspect described above, the potential to reduce energy consumption through coordinated, collaborative merge-in/-out manoeuvre was also investigated using a simulative approach. To make the simulations as realistic as possible, real measurement data of the velocity trajectories of the shuttle operation, as recorded by the LCMM during the shuttle operation at Frankfurt pilot site, were reused as input data for the simulation of the preceding vehicle. The main goals were the following:

- Increase algorithm maturity
- Check real vehicle behaviour on test track
- Estimate energy consumption benefit potential

As a summary, the following sub-steps were necessary for the demonstration:

- Build-up of 2 automated vehicles and one non-automated vehicle
- Development and implementation of the C-ITS V2V functionality for predictive and collaborative driving manoeuvres
- Demonstration of vehicle merge-in/-out manoeuvre in flowing traffic at ATC
- Objective evaluation

- Subjective evaluation in a dedicated experience survey among students and co-workers
- Simulative investigation of the potential reduction in energy consumption using real recorded velocity trajectories from the Frankfurt pilot site as input for the simulation optimization and representation of the real energy consumption with several vehicles

6.4 Site-specific test cases

The site-specific test cases are divided into two parts. The first part dealt with the integration and demonstration of the merge-in/-out algorithm in real automated vehicles at ATC. The second part dealt with simulation-based approaches to investigate the functional capabilities of the algorithm and the energy saving potential.

Implementation and demonstration of vehicle merge-in/-out algorithm at ATC

As a first step, the two automated vehicles used for the test cases were equipped to run the coordination controlling algorithm and V2V communication. After the allocation of FEV's automated vehicles, the first simplified test was conducted to test the collaborative driving function at ATC, using one automated vehicle to simulate the preceding vehicle.

Afterwards, the testing and debugging were extended to test drive-offs at ATC with two automated vehicles. Drive-offs in collaborative driving, using V2V communication with data input from the LCMM data collected at the Frankfurt pilot site, were successful. The algorithm capabilities to coordinate and control velocity trajectories for two automated vehicles and one non-automated follower vehicle to allow the merge-in/-out manoeuvre of a vehicle into the flowing traffic were implemented and verified.

Simulative investigation of algorithm capability and estimation of energy consumption benefit

A simulative approach was chosen to investigate the algorithm's capabilities and effectiveness under specific, realistic boundary conditions. Especially in the context of safety relevant algorithms, simulations are performed to test and validate each algorithm in a virtual environment before it is used in real vehicles for testing purpose. In addition, the simulative approach allows the investigation of more complicated test cases than on the test site with reasonable effort. While the entire development process considers both simulations and real-world tests to analyse the algorithm's suitability for different scenarios, the focus below is on the simulation use cases for vehicle merge-in and merge-out manoeuvres and the energy benefits that can be achieved with the C-CACC function compared to a conventional ACC.

For the energy consumption benefit, LCMM data such as velocity trajectories of a real shuttle cycle recorded during the shuttle operation at the Frankfurt pilot site, were used as an input for the preceding vehicle simulation.

6.5 The fleet

The fleet consisted of 2 automated vehicles, one is suited to simulate a preceding vehicle and the other to simulate the shuttle bus. As indicated in Table 14, 2 modified BMW i3 were used as automated vehicles. The modification was meant to enable V2V functionality and the controller algorithm to perform the coordinated, automated driving manoeuvres. Therefore, both vehicles were equipped with Micro Autobox (MABX) for the prototype controller and Cohda MK5 V2V communication units, as depicted in Figure 14.

Table 14: Fleet characteristics during the Aachen operation

Test/Use Case	Deployed fleet characteristics								
	Vehicle brand & model	**Vehicle type (shuttle, …)**	**SAE Level reached for the field trials [1-5]**	**TRL level reached for the field trials [1-9]**	**Summary of upgrades held during the project (in consistency with D7.2)**	**HMI and Hand-over strategies (in consistency with D7.2)**	**Maximum speed reached during the trials (km/h)**	**Average speed during the trials (km/h)**	**Maximum capacity of vehicle**
Aachen / UC1.4	2x Modified BMW i3	Passenger car	3	7	Build in MABX and Cohda MK5	NA	68 km/h	29 km/h	3

Figure 14: Two automated vehicles equipped with Micro Autobox and Cohda MK5 communication units (source: FEV)

6.6 The Infrastructure

Aldenhoven Test Center (ATC)

The use cases were performed at ATC in Aachen, a proving ground well suited for simulating city-like environments. By using movable buildings, road crossings, traffic lights and much more, an environment could be created that fitted well with the use case requirements. An overview of the test area is depicted in Figure 15.

The dedicated city area was configurable and consisted of at least the following entities:

- Road crossings / intersections
- Traffic lights
- Sidewalks
- Multi-functional and parking area: simulated as bus stop

The available physical and digital infrastructure included GPS, WiFis / 5G, charging station and work shop/garage.

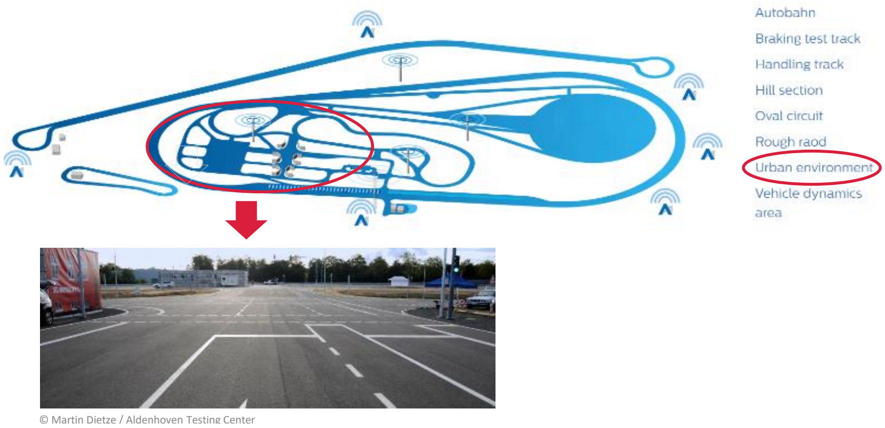


Figure 15: Aldenhoven Test Center (ATC) proving ground map and test area (source: FEV)

In addition, the Vehicle-to-Vehicle (V2V) infrastructure architecture was used during the test drives at ATC. Within the system, vehicles, control modules and communication modules interact directly via V2V communication. Different communication entities play specific roles in manoeuvre cooperation: the preceding vehicle initiates the manoeuvre request, the manoeuvre lead takes over coordination and control, and the follower vehicles are centrally controlled by the manoeuvre lead as platoon members (see Figure 16). It is noteworthy that, in this setup, the manoeuvre lead and the platoon lead refer to the same vehicle, and the manoeuvre lead host the C-CACC software module.

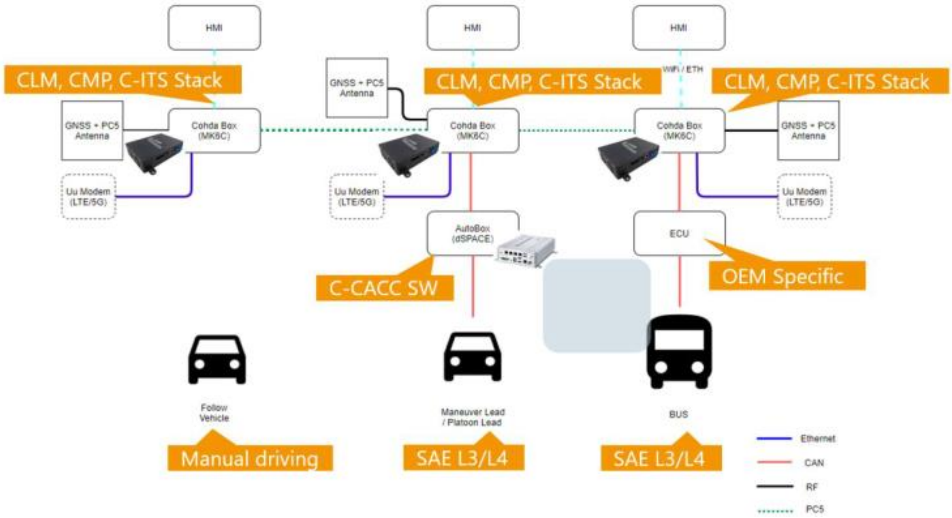


Figure 16: V2V system architecture (source: FEV)

In the context of communication infrastructure, each entity implements the "Cooperative Lane Merge" (CLM) service and the underlying "Cooperative Manoeuvre Protocol" (CMP). Both CLM and CMP were designed and implemented by FEV.io GmbH, based on the proposals from 5GAA. The adjusted C-ITS communication protocol stack to realize cooperative manoeuvre use case and V2X communication (see Figure 17) includes the lower layers Access, Geo Networking, and Basic Transport Protocol (BTP), provided by the Cohda Wireless V2X Module (MK5). These layers comply with the C-ITS standards. The standard services of the Facility Layer and Application Layer are augmented by FEV.io's proprietary services: "CMP" at the Facility Layer level and "CLM" at the Application Layer level.

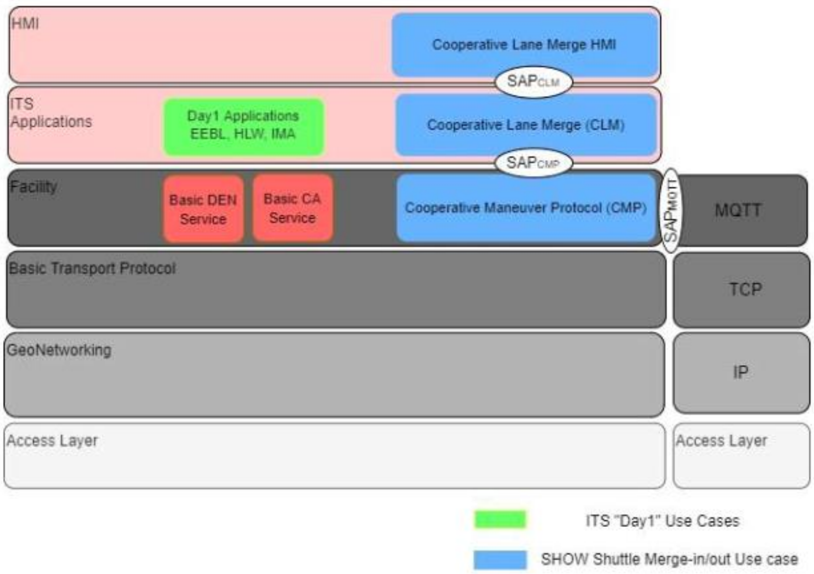


Figure 17: Adjusted C-ITS Protocol Stack (source: FEV)

6.7 Passengers

Co-workers and students acted as the main passengers of the test drives and participated in the dedicated survey afterwards. Some of the employees and students came from the development team and the associated departments. In addition, management employees were also selected to participate in the test drives to include a broader range of experience and age distribution in the feedback. The feedback/survey should not only include an evaluation of the drivability of the developed algorithms, but also reflect a general assessment of electric CCAVs. The survey result is elaborated in Section 6.10.4.

6.8 Total number of passengers

The total number of passengers was 20 in the test drive demonstration at ATC in Aachen.

6.9 Data Collection

The speed profiles of Frankfurt's shuttles, collected through the LCMM system, served as valuable data for investigating the actual energy-saving potential. In the multi-vehicle C-CACC simulation environment, the above-mentioned data was utilized to model the driving profiles of preceding vehicles. The novel approach involved centralized and cooperative optimized driving functions, leveraging linear MPC (Model Predictive Control), which balanced the trade-offs between minimizing energy consumption and maximizing traffic flow under ideal communication conditions. A segment of these driving profiles is illustrated in Figure 18.

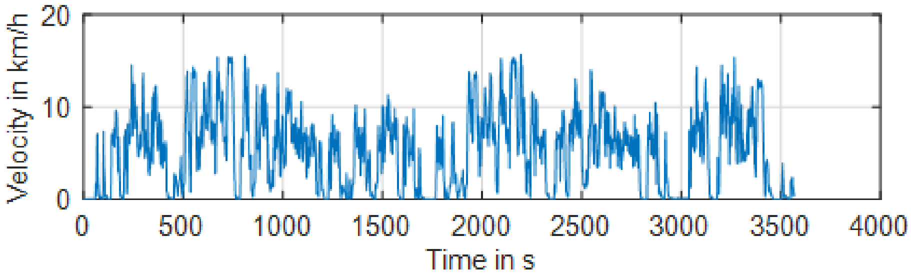


Figure 18: A segment of the Frankfurt shuttle driving profiles (source: FEV)

6.10 Pilot operation key findings

6.10.1 Key findings per Use Case

The high-level findings during the Aachen operation are indicated in Table 15.

Table 15: High level findings per Use Case during the Aachen operation

High level findings per Use Case		
Use Case	**Overall qualitative performance score (1-3[8])**	**Justification**
(UC1.4): Energy sustainable automated passengers/cargo mobility in Cities	**3**	Energy-saving potential of 21% during the real vehicle test with the predefined velocity profile of the preceding vehicle (bus) was achieved and in stop and go sections savings up to 34% could be shown.

The first simplified test results show the algorithm's output for the test case where two automated vehicles accelerated, the first as the platoon leader, and the second as follower vehicle, as depicted in Figure 19. After the platoon leader accelerated and then maintained a constant speed, the follower vehicle started to accelerate smoothly at a lower level to catch up with the platoon leader's velocity. As the distance between the platoon leader and the follower vehicle decreased, the follower vehicle reduced the acceleration. Finally, both vehicles travelled constantly with zero acceleration and were in a stationary relation to each other.

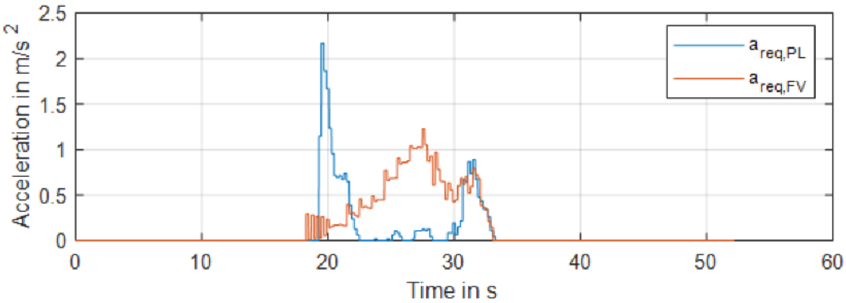


Figure 19: Qualitative example of algorithm output for vehicle coordination (source: FEV)

The final simulation with the real LCMM data from the shuttles at the Frankfurt pilot site, after the behaviour testing at the ATC, shows energy saving potentials of 4,8% in the following manoeuvre. This difference in energy saving potential can be due to the different driving profile of the preceding vehicle. The LCMM driving profile used has a lower average speed with a maximum running speed of about 15 km/h. Therefore, the optimization potential remains lower than with a faster preceding vehicle.

The setup of a more complex merging manoeuvre simulation is shown in Figure 20 with a merge-in and merge-out of a platoon of a FV (Following Vehicle), where a shuttle is merging (MV) into the flowing traffic consisting of a preceding vehicle (PV) and 3 follower vehicles, whereas the first following vehicle is the manoeuvre leader controlling the process using the novel FEV algorithms and the PV drives with the velocity profile of the Frankfurt shuttles.

[8] 1 [Low] – 2 [Medium] – 3 [High]; success qualitative score, considering all aspects (technical, user acceptance).

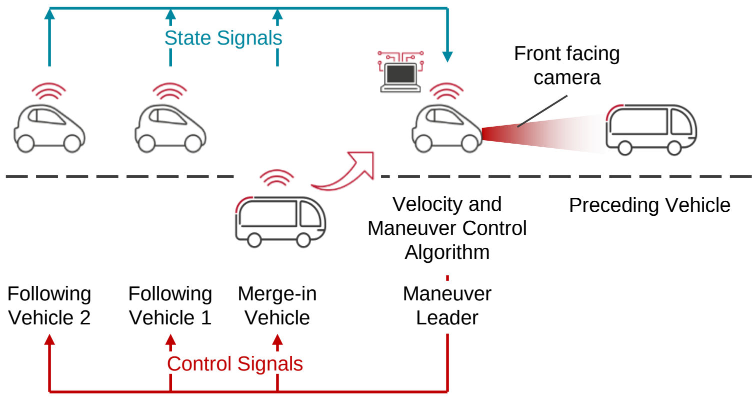


Figure 20: Algorithm simulation shows the shuttle merge-in in a platoon (source: FEV)

When a merge-in vehicle (MV), such as a shuttle, departs from a bus station and aims to join a platoon, it can send a merge request to the lead vehicle (PL or ML) using vehicle-to-vehicle (V2V) communication. Upon receiving this request, the ML's manoeuvre controller algorithm becomes active. The manoeuvre controller employs optimization-based calculations to determine an energy-efficient merging position for the MV. Simultaneously, the ML assumes control over the MV's velocity. Once a sufficient gap between two vehicles is identified—providing enough space for the MV to merge while maintaining safety — the ML sends a merging clearance signal to the MV. Upon receiving this signal, the MV is authorized to execute the lane change and complete the merging manoeuvre. In Figure 21 the graphs show the simulated positions, velocities and accelerations during the merge-in manoeuvre.

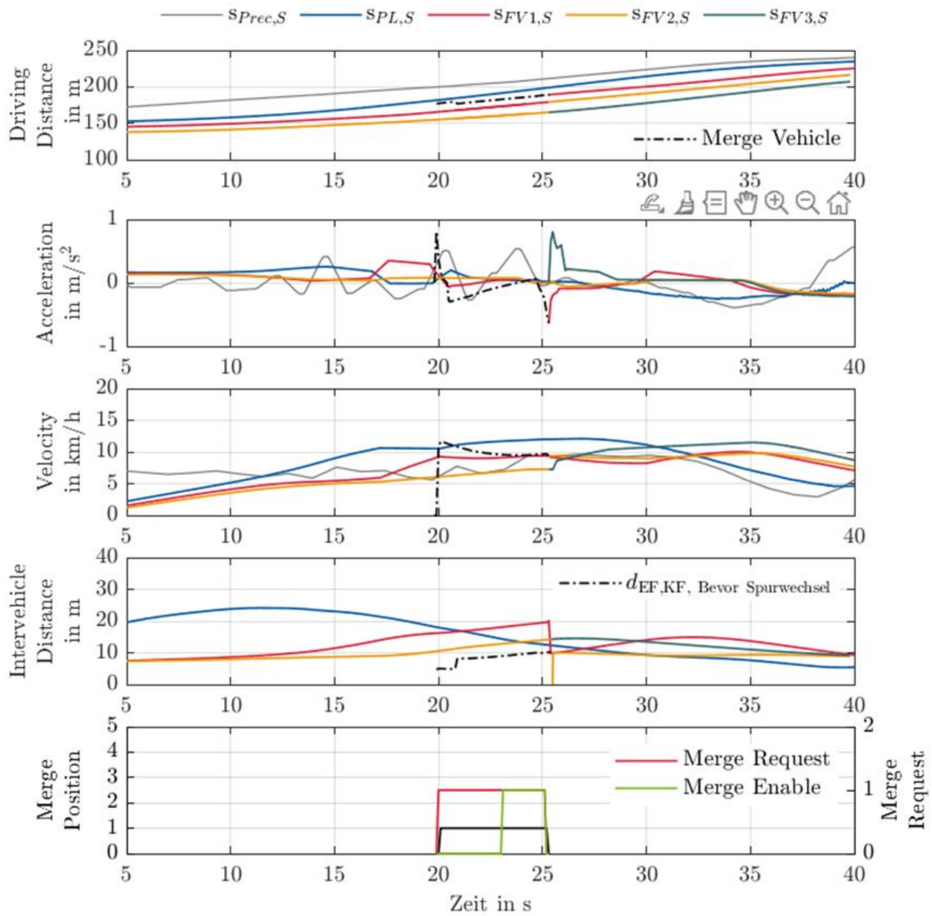


Figure 21: Merge-in manoeuvre simulation with real LCMM data from Frankfurt site (source: FEV)

The goal was to optimize the velocity trajectories of all platoon vehicles involved and reduce unnecessary acceleration and deceleration even during merging manoeuvres to minimize the overall energy consumption. For this purpose, a linear model predictive control (MPC) algorithm was employed to formulate and solve the optimal control problem.

A comparative analysis was conducted to analyse the potential energy savings between the C-CACC and a state-of-the-art adaptive cruise control (ACC) in an urban environment using real LCMM data as a preceding CCAV shuttle. The study included a simulation where a platoon consisted of one manoeuvre or platoon leader (ML or PL) and four following vehicles (FV1-4), all following a preceding vehicle (PV) with a real velocity profile form the Frankfurt shuttles (see Figure 22).

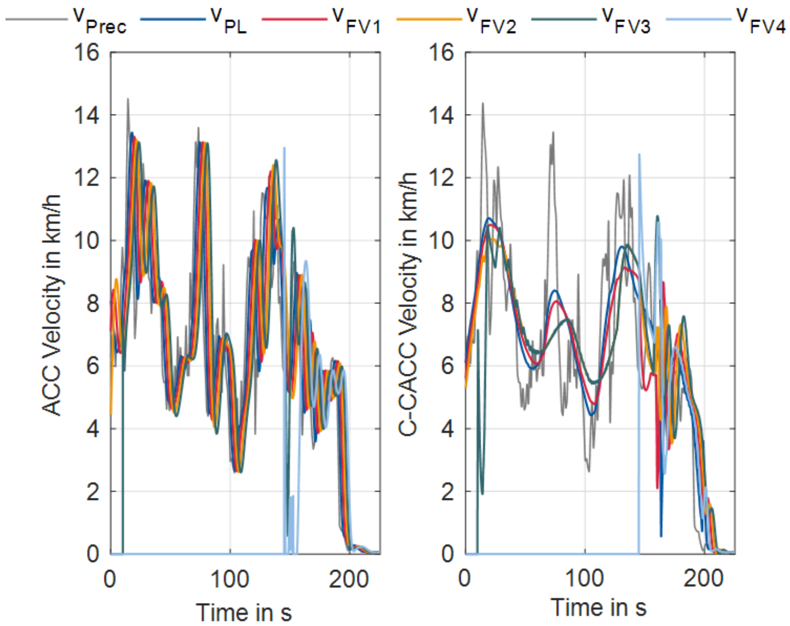


Figure 22: Platoon simulation with real LCMM data from Frankfurt side (source: FEV)

To evaluate the energy consumption, a battery electric vehicle plant model was used. In the reference simulation, all vehicles used a state-of-the-art ACC algorithm.

By comparing the velocity trajectories of all platoon vehicles using both C-CACC and ACC during a merge-in manoeuvre, it becomes evident that the amplitude of these profiles is lower with C-CACC than with ACC. This indicates that C-CACC effectively reduces unnecessary acceleration and deceleration, even in scenarios where the preceding vehicle (shuttle) frequently changed its velocity and merging manoeuvres were carried out. This reduced the total energy demand for traction, resulting in an **energy-saving potential of 9.9%** during two merge-in manoeuvres.

6.10.2 Key challenges

The key challenges have been identified and shown in Table 16.

Table 16: Key challenges during the Aachen operation

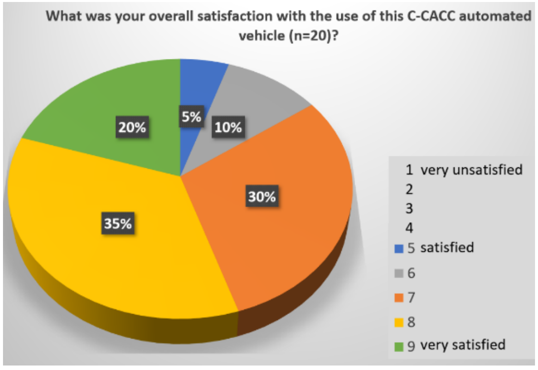
Challenge	**Type** (Operational, Technical, Business, Other)	**Mitigation**	**Mitigation outcome**
Aachen: Improvement of energy consumption & driving comfort by platooning and merge in of shuttles and followers	Technical	Algorithm development for Cooperative, Coordinated Driving Manoeuvres, delivering smooth operation	Energy savings of ~20% at normal urban driving speeds and ~10% at merging manoeuvres and a 7.8 out of 9 rating for driving comfort in the dedicated survey
Automated vehicle availability, modification and build up	Technical	Build-up of 2nd automated w/o extra budget	Restricted access and availability of 2nd automated vehicle
Stable V2V communication	Technical	Use Cohda MK5 instead of MK6 due to communication problems with MABX	V2V communication was established.
Underestimated additional effort due to bug fixing, vehicles position accuracy, new safety functions for ATC testing	Technical	Bugs were fixed, but new safety features were needed to ensure safe and usable vehicle-to-vehicle positioning that could not be developed and implemented due to limited vehicle access and project constraints.	Open optimizations can be part of a later follow-up project.
Computational power restriction	Technical	Could not be solved because a MABX change was not possible within the project frame	The build-up of automated vehicles with more computational power can be part of a later follow-up project.
Energy consumption optimization with more than 2 following vehicles	Technical	Upgrade the simulation to 4 following vehicles	In real urban start stop traffic, energy savings can exceed 30%.

6.10.3 Key incidents and impacts

No incidents or impacts were recorded during the tests on ATC.

6.10.4 The testers' point of view (Aachen)

According to the analysis result in Figure 23, the users and co-drivers of the automated vehicles rated the overall satisfaction with 7.6 out of nine (very satisfied) possible points (20 ratings). In general, the users' and co-drivers' feedback was very positive: around 70% found the driving experience during the test drive with automated functions to be very comfortable and smooth.



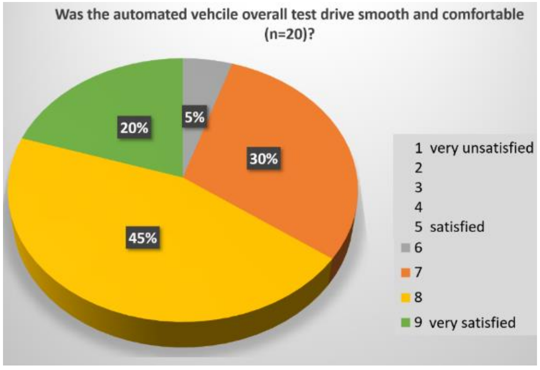


Figure 23: Users' point of view (Aachen) (source: FEV)

6.10.5 The stakeholders' point of view

During the MAMCA-workshop with all German pilot site partners, the stakeholders were able to contribute and discuss their different perspectives and insights. The most important requirements for electric CCAV platoons in urban PT from the dedicated survey are shown in Figure 24.

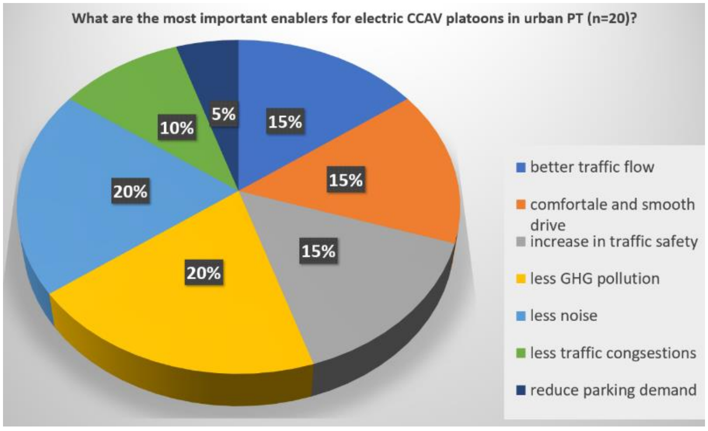


Figure 24: Stakeholders' point of view (source: FEV)

6.11 Lessons learned & Recommendations

The energy saving potential in stop-and-go urban traffic is up to 30%.

Along with this, the results can also contribute to other KPIs e.g. CO_2 reduction through energy savings, noise level reduction through use of electric CAV, increased safety through secure V2V communication and surrounding detections, improved traffic flow

/reduced traffic congestion through higher average speed, and increased driving comfort through optimization of vehicular acceleration and deceleration.

The main barriers and challenges for electric CCAV platoons in urban PT are revealed from the dedicated survey and presented in Figure 25. All obstacles must therefore be overcome to integrate more V2X platforms into urban PT.

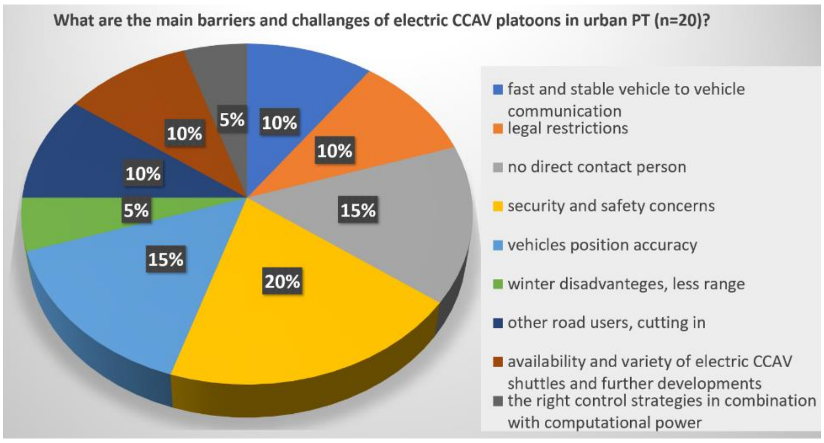


Figure 25: Barriers and challenges of electric CCAV platoons in urban PT (source: FEV)

6.12 Roadmap beyond SHOW and replicability

As a continuation of the European Program “Horizon 2020”, the Hi-Drive[9] project is one of the successors to SHOW. FEV.io GmbH is a project member of the Hi-Drive project.

The communication technology (i.e. protocol stack code libraries) from SHOW will be reused and enhanced for the Hi-Drive context. The results of the investigations will also be used/expanded in Hi-Drive, which has comparable challenges (merge in manoeuvre on freeway ramps). After adaptation and further development, both the simulation environment and the novel development process approach can be used in various projects at FEV.

[9] Hi-Drive Deployment of Higher Automation Hi-Drive

7 Monheim Pilot site

7.1 The ecosystem

An overview of the pilot site ecosystem in Monheim is shown in Table 17.

Table 17: Pilot site ecosystem in Monheim

Participating Entity	Internal to the Consortium (√)	External to the Consortium (√)	Role
DLR	√		German Mega Site leader
BSM	√		Leader
EasyMile	√		Vehicle provider (OEM)
T-Systems	√		Software provider (LCMM)
City of Monheim		√	Mother company of BSM
TÜV Rheinland		√	Technical Supervisory Association
Bezirksregierung Düsseldorf		√	District government
MUNV NRW		√	Ministry of transport for the federal state North Rhine-Westphalia

7.2 Operation setting

The operation condition in Monheim is summarized in Table 18.

Table 18: Road, traffic and weather conditions at the Monheim site

Variable	Site
Weather	Mixed weather (Central European), operation all-year round
Sight conditions	Restricted in unexceptional rain, snow or fog (very rare)
Road type	Peri-urban roads, pedestrian zone, cobblestones
Road works	Due to road works driving a diversion until 11/2022
Incidents	No accidents
Traffic conditions	Traffic conditions varied during the day: More traffic in typical commuting times (from 7am to 9am and from 3pm to 6pm)
Traffic composition	Cars, delivery vehicles, buses, bicycles, no dedicated lanes for AV shuttles
Traffic control	Not applicable
Area type	outside built-up area

7.3 Services and use cases

The most important goal for the shuttle operation in Monheim has been the integration of automated shuttle services into regular PT operation. One of the most important objectives for the operation of the automated shuttle fleet at the Monheim pilot site was to connect the old town, with its narrow streets that are inaccessible to conventional buses, to public transport. Another objective is to address the issue of driver shortage. A study by the Association of German Transport Companies predicted that 74,000 job positions will remain unfilled in Germany by 2030 due to an aging workforce and that an additional 100,000 drivers will be needed. The goal is to expand all forms of public transport in order to minimize private transport, which makes driverless transport indispensable. Finally, increasing safety for all road users is also an important objective. The shuttle route at the Monheim pilot site is illustrated in Figure 26.

Figure 26: Route of the automated shuttles in Monheim (source: City of Monheim)

7.4 Site-specific test cases

- Automated passenger mobility in cities under normal/complex traffic & environmental conditions (UC 1.1 and 1.2)

In the old town, the automated shuttles have been equipped with licence plate recognition so that the bollards automatically lower when the shuttles approached. In terms of parking, the city has either removed some parking facilities or marked the park zones in colour. This is explained in more detail in the next section (UC 1.3).

- Interfacing non-automated vehicles and travellers (UC1.3)

BSM has worked together with the city council to reduce car parking along the route or to mark the park zones with blue paint so that car drivers would respect their allocated parking zones more and park within the lines. As a result, many additional stops of the automated shuttles were avoided.

- Energy sustainable automated passengers mobility in cities (UC1.4)

To charge the shuttles with sustainable energy, a special bus depot for up to 5 automated shuttles was built with solar panels on the roof. Since then, the shuttles have been charged with sustainable energy.

- Actual integration to city traffic management control (UC1.5)

To fully integrate the operation of the shuttles into the control center, additional software (Easy Mile: Site CC) and monitors were installed in the traffic management control centre. Also, the staff (traffic managers) were trained so that they are able to deal with various situations related to the operation of the shuttles.

- Mixed traffic flows (UC1.6)

All shuttles deployed at the pilot site travelled on regular streets, which they shared with other vehicles. In addition, the shuttles travelled in a shared area in the old town, where shuttles, cyclists and pedestrians shared the same street space. Residents and passengers were informed as much as possible about automated driving and the shuttles, e.g. with information campaigns at local festivals and with a specifically created flyer and video about automated shuttles. BSM also initiated an accompanying research on the shuttle operation, which was carried out by the Karlsruhe Institute of Technology (KIT).

- Teleoperation (UC1.7)

The test case could not be performed as the specific generation of the EasyMile shuttles used in Monheim are not technically advanced enough. The aim is to achieve this in the future, but for the duration of SHOW this was not possible in Monheim.

- Big data/AI based added value services for Passengers/ Cargo mobility (UC3.2)

In collaboration with T-Systems smartphones were installed in the shuttles, on which the system LCMM was installed. LCMM recorded the route, the speed and also the stops along the route so that several "profiles" could be created. This data was collected by BSM, where BSM's safety operators initialised LCMM at the beginning of the operation of the respective shuttle and stopped it at the end of the shuttle operation. T-Systems downloaded the data in weekly reports and sent the data to CERTH, who used the data for the dashboard.

- Automated services at bus stops (UC3.4)

A platform for mobile devices was developed for ticketing, i.e. the Bahnen-Monheim-App, as indicated in Figure 27. Customers (non-Monheim residents) can use this app to buy their tickets, while Monheim residents can use PT for free. The platform was not developed as part of SHOW, but it could be used by passengers outside of Monheim.

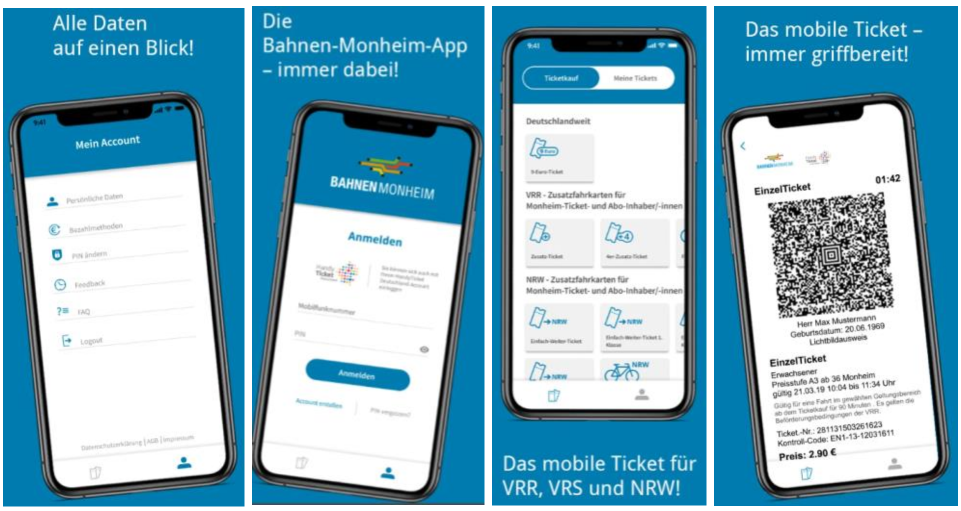


Figure 27: Illustration of the Bahnen-Monheim booking app (source: BSM)

7.5 The fleet

8 automated shuttles, i.e. 5 EasyMile EZ10 Gen2 and 3 EasyMile EZ10 Gen3, were in operation during the demonstration period. The corresponding fleet characteristics at the pilot site are shown in Table 19.

Similar to the Frankfurt Pilot site, the average speed during the trials was calculated by dividing the kilometres travelled by the total travel time per shuttle run. Thus, the stop time spent at each stop was included in the calculation. Due to the technology used, it was not possible to subtract the stop time from the total travel time. So, the calculated average speed is much lower than in reality. On short routes (less than 500 m on the 1.7 km route) the shuttles could reach 16 km/h. The shuttles had to pass by several intersections and roundabouts, and even went through the town tower and a shared space area (500 m), where the shuttles were not allowed to go faster than 10 km/h. In addition, there were several bollards along the route that forced the shuttles to wait until they were lowered to the ground. In general, 3 shuttle runs of 1.7 km were executed in an hour (normally a 1.7 km shuttle run took 16 to 20 minutes). The realistic average speed was therefore between 5 and 6 km/h.

Table 19: Fleet characteristics at the Monheim pilot site

Test/Use Case	**Deployed fleet characteristics**								
	Vehicle brand & model	**Vehicle type (shuttle, …)**	**SAE Level reached for the field trials [1-5][10]**	**TRL level reached for the field trials [1-9]**	**Summary of upgrades held during the project (in consistency with D7.2)**	**HMI and Hand-over strategies (in consistency with D7.2)**	**Maximum speed reached during the trials (km/h) [11]**	**Average speed during the trials (km/h)**	**Maximum capacity of vehicle**
Same for all UCs	*EasyMile EZ10 Gen2/ Gen3*	*Shuttle*	*2 plus*	*9*	*NA*	*NA*	*16 km/h*	*~ 5 km/h*	*11+ safety operator*

[10] The automation level in Germany is restricted by the necessity to have a safety driver on board. Even if the vehicles are technically able to fulfil requirements for a higher SAE level, the grading according to SAE classification can be described as Level 2 plus to 3.

[11] Initial calculations for both maximum and average speeds – perhaps slight differences occur till the end of the project in the context of WP13 analyses.

7.6 The infrastructure

Physical and digital infrastructure at the pilot site includes:

- 5G, LIDARs, GPS, NRTK
- Storage and charging in bus depot which was especially build for that purpose
- Maintenance at demo site (1,5 km away from route – trailer was purchased for that reason)

7.7 Passengers

The end-users are mainly elderly or families with children. Mobility-impaired people also use this service. There are also quite a few tourists who want to experience driving the shuttle.

7.8 Total number of passengers

The automated shuttles in Monheim have been in operation since February 2020. The shuttle operation was started with 5 EasyMile Gen 2, which were co-funded by the regional transport association. These 5 shuttles were purchased by BSM. Since 2023, 3 EasyMile Gen 3 have been leased. These 3 shuttles were mainly used for training on BSM's own premises or for show cases such as the one at Zeche Zollverein in Essen in October 2023.

BSM replaced one of the German pilot sites in January 2022. The period in which passengers were counted for SHOW ranged from May 2022 until December 2023. The total number of passenger rides during SHOW was 32.069. By September 2024, the total number of passenger rides since commissioning in 2020 had reached 81.786.

7.9 Data collection

The vehicle data was collected using the EasyMile software and also via LCMM. Passenger numbers were recorded manually by the safety operators using event diaries. Regarding the survey data, it was collected via the following ways: (1) postcards with QR codes were distributed by the safety operators; (2) A piece of paper with the QR codes were attached to the windshield of each shuttle, which could be immediately scanned with a mobile phone; (3) The Facebook community of BSM was asked to fill out the surveys; (4) BSM colleagues asked friends and acquaintances to fill out the surveys.

7.10 Pilot operation key findings

7.10.1 Key findings per Use Case

The key findings during the pilot period are indicated in Table 20.

Table 20: High level findings per Use Case at the Monheim site

High level findings per Use Case		
Use Case	**Overall qualitative performance score (1-3[12])**	**Justification**
UC 1.1: Automated passengers/cargo mobility in Cities under normal traffic & environmental conditions	**3**	Under normal conditions the AVs performed well.
UC 1.2: Automated passengers/cargo mobility in Cities under complex traffic & environmental conditions	**1**	Under extreme conditions the line could not be operated. Extreme conditions were either heavy rain or heavy snowfall. On average, this happened on less than 10 days per year in Monheim.
UC 1.3: Interfacing non automated vehicles and travellers (including VRUs)	**2**	The shuttles couldn't overtake incorrectly parked vehicles without intervention. Cars overtaking the shuttles would cause them to slow down or stop if they didn't have enough distance when overtaking. This also happened when bicycles overtook the shuttles. They could slow down the shuttles or make them to brake hard if they don't keep enough distance. Even pedestrians walking in front of the shuttles (in the pedestrian zone) slowed down the shuttles. This also applied for dogs walking with their owners.
UC 1.4: Energy sustainable automated passengers/cargo mobility in Cities	**3**	A bus depot with solar panels and battery storage was built and the shuttles have run on 100% green energy. The whole system was self-sustainable.
UC: 1.5: Actual integration to city TMC	**3**	The shuttles have been fully integrated into the TMC. EasyMile's "Site CC" system, which displayed the exact locations and data of the shuttles, was integrated into the PTO's control center. The same employees which monitored the large buses also monitor the shuttles.

High level findings per Use Case		
Use Case	**Overall qualitative performance score (1-3[13])**	**Justification**
UC 1.6: Mixed traffic flows	**2**	It was difficult for the shuttles to cope with mixed traffic flow as the speed of the shuttles was relatively too low. Therefore, many overtaking manoeuvres were performed which resulted in an even lower speed of the shuttles due to emergency braking and lower speed.
UC 3.2: Big data/AI based added value services for Passengers/ Cargo mobility	**3**	Mobile phones have installed and data was tracked with LCMM. This data was used to optimise the shuttles' speed, and some bollards were installed to minimize emergency stops. The collected data was used by other partners in SHOW and provided on the dashboard.

7.10.2 Key challenges

The key challenges have been identified and indicated in Table 21.

Table 21: Key challenges at the Monheim pilot site

Challenge	**Type** (Operational, Technical, Business, Other)	**Mitigation**	**Mitigation outcome**
Speed and reliability of the shuttles	Technical	Continuous speed optimisation (where possible through adjustments along the route, i.e. removal of parking spaces, regular felling of trees and bushes)	Speed increased (only slightly, but still), additional operational robustness improved
Maintenance of the shuttles as workshop is far away from route	Operational	Purchase of a trailer	Vehicles could be moved easily.

[12] 1 [Low] – 2 [Medium] – 3 [High]; success qualitative score, considering all aspects (technical, user acceptance).

[13] 1 [Low] – 2 [Medium] – 3 [High]; success qualitative score, considering all aspects (technical, user acceptance).

Challenge	Type (Operational, Technical, Business, Other)	Mitigation	Mitigation outcome
Procurement of the shuttles: purchase versus Leasing	Business	The first shuttles were purchased, but this offers less flexibility	Leasing is better as it is more flexible.

7.10.3 Key incidents and impacts

No major difficulties occurred during the commercial phase. There were no accidents involving with personal injury.

7.10.4 The passengers' point of view

Most of the passengers were satisfied with the service, felt safe and comfortable, and many used the shuttle service frequently.

The passengers were interviewed by Karlsruhe Institute of Technology (KIT) and the report on the results of the accompanying research on automated minibusses in Monheim am Rhein can be found in [3]. According to this report, two rounds of the surveys were conducted. 70 passengers were asked to evaluate the selected characteristics of the shuttles and the respective service. A 5-star rating system was used, while one star and five stars represented very bad and very good respectively. The mean ratings of all evaluated criteria are shown in Figure 28. In general, all criteria of the shuttles are positively appraised. The speed and the de-/acceleration behaviour of the shuttles were rated most negatively. The privacy in the shuttle was also rated worse compared to the other criteria. The seating arrangement and the presence of the safety operator in the middle of the shuttle were given as the reasons for the lack of privacy. According to the second round of surveys, the passengers became more satisfied with regard to all criteria except punctuality. In additions, the passengers found the shuttles useful for elderly and saw the shuttle connection to smaller neighbourhoods as particularly advantageous. Still, SHOW-specific elaborate results follow in D13.5.

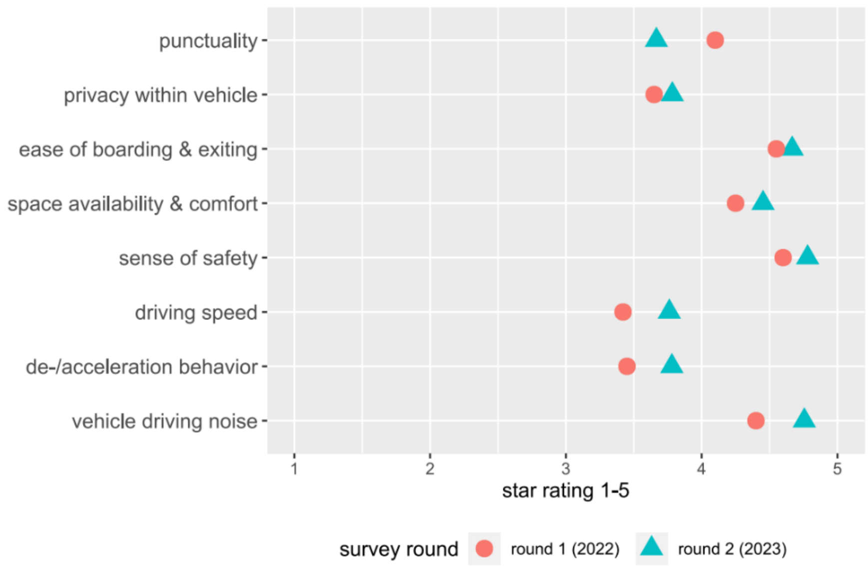


Figure 28: The evaluation of the shuttles from the passengers' perspective (source: [3])

7.10.5 The safety operators’ point of view

Most of the safety operators enjoyed operating the shuttles as it was a change from driving a “normal bus” and they enjoyed the close contact with the passengers.

The safety operators were also interviewed by KIT and the respective results can be found in [3] as well. As indicated in Figure 29, the shuttles encouraged communications among passengers and between safety operators and passengers from the safety operators’ perspective. The comfort and sense of security of the passengers were rated very high by the safety operators, as the passengers themselves reported. The great added value of the safety operators lay in their service and assistance function, while they mainly understood to ensure safety during operation. Still, SHOW-specific elaborate results follow in D13.5.

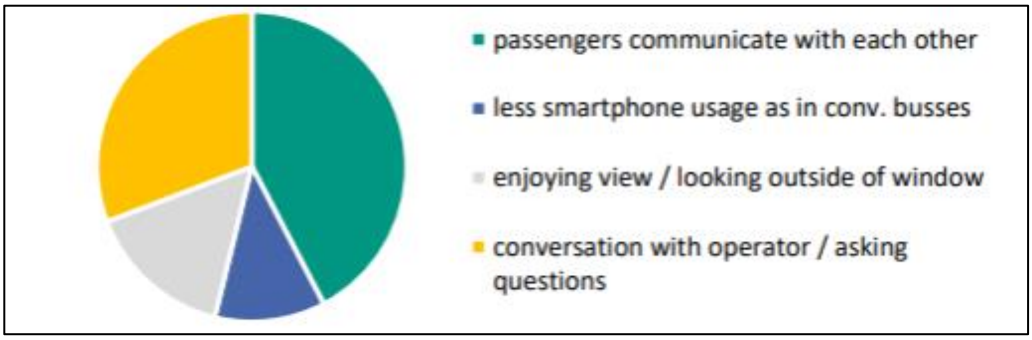


Figure 29: Safety operators’ point of view at the Monheim pilot site (source: [3])

7.10.6 The other road users’ point of view

Car drivers had reservations about the shuttles because they felt they are too slow. However, this has improved over time as people have become accustomed to the shuttles and their speed.

Together with the above-mentioned surveys related to passengers and safety operators, the other road users were also interviewed (through a household survey) by KIT and the respective results can be found in [3] as well. The evaluation result about the dis- and advantages of the shuttles are summarized in Figure 30. The advantages and disadvantages of the shuttles were assessed similarly by users and non-users, while users were somewhat more positive an optimistic overall. Both user groups considered possible interactions between the shuttles and other road users as a disadvantage. However, the shuttles could help reduce pollution, enable mobility for the elderly and people with reduced mobility, and improve the connectivity of the PT system.

The overall result is that residents of Monheim felt safe while using the shuttles and enjoyed their rides. However, they believed that the speed of the shuttles needs to be increased.

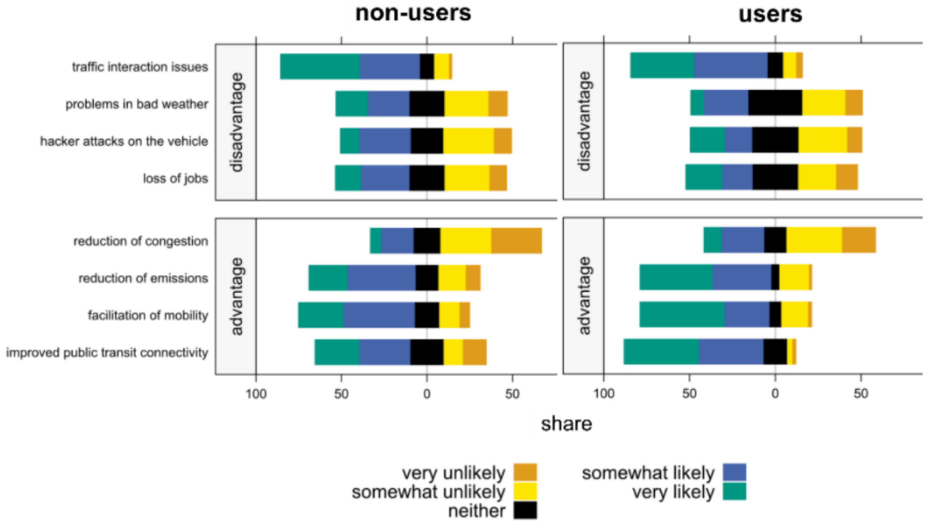


Figure 30: Evaluation of the dis-/advantages of the shuttles from the non-users' and users' perspective at the Monhiem pilot site (source: [3])

7.10.7 The stakeholders' point of view

The city of Monheim is continuously supporting the operation of the shuttles. The mayor and city council started the initiation process of the operation of automated shuttles in the year 2017.

When BSM published the results of the accompanying research, the representatives of all stakeholders attended the event and showed great interest. The city of Monheim, TÜV Rheinland, Bezirksregierung Düsseldorf and MUNV (Ministry of Transport) have strongly supported the shuttle service since its inception and will continue to do so in the future.

7.11 Key local demonstration events

Visit of bus depot for students

What: Visit of BSM bus depot and ride with EZ10 shuttles (see Figure 31)

Who: Students of private university of Cologne: "Fachhochschule des Mittelstands (FHM)"

When: April 18th, 2023

Objective: To give practical guidance for their lecture "Automotive & Mobility Management"

Outcome: Informed students after a day of practical experience

Figure 31: Students visit of bus depot at the Monheim pilot site (source: BSM)

Triennale Monheim Festival

What: Triennale Monheim Festival (see Figure 32)

Who: Various artists / sound specialists

When: June 3rd until July 2nd, 2023

Objective: To install different sound objects in means of transport (standard buses and shuttles) so that Monheim residents and visitors can experience a unique sound experience

Outcome: One month of special experiences in public transport and public spaces (more information about Monheim Triennale can be found in [4])

Figure 32: Triennale Monheim Festival (source: BSM)

Visit of partner project

What: Visit of Cool 4 partner project (see Figure 33)

Who: Japanese delegation of Cool 4

When: November 12th, 2022

Objective: To discuss and compare the experiences from Japan and Europe

Outcome: Exchange of experiences, lessons learned and networking opportunities

Figure 33: Visit of Cool 4 partner project at the Monheim pilot site (source: BSM)

7.12 Lessons learned & Recommendations

The lessons learned and respective recommendations are divided into four aspects: technical, operational, business, and others, and explained as follows.

Technical:

- It is need to constant improvement of the route: self-validation and increase of speed on particular sections of the route.
- It is need to work closely together with OEM (EasyMile) to improve the performance of the shuttles.

Operational:

- Regarding maintenance tasks it is necessary to properly and regularly train technicians to solve non-complex and non-software-related issues.
- The construction of a garage to house and charge the shuttles must be carried out in the immediate vicinity of the shuttle route. This also prevents the vehicles from theft and vandalism and shields them from extreme weather condition (i.e. heat)
- Trailer purchased to drive shuttles to the appointed bus depot where workshop is located. This is advisable. Depending on the situation on site, a field operation concept must be worked out for each location. In Monheim the shuttle depot is too far away from the workshop, so this was necessary as the shuttles need to be serviced and repaired from time to time.
- Special training for safety operators (4-day-course with final exam) should be mandatory. Our safety operators are regular bus drivers and must complete a 4-day-course given either by an EasyMile trainer or by a chief operator (qualified by EasyMile to provide training himself) to be allowed to operate the shuttles. During this course the drivers learn about how to manage the shuttles, such as how to drive and park in manual mode, when to switch from automated mode to manual mode and vice versa. Drivers also learn how to pull dumps, how to validate at intersections, what to do in tricky situations, how brakes and sensors work and so on. Then they take

a practical test related to manual driving on a route with obstacles and a theoretical test related to batteries, brakes, sensor system and so on.

Business:

- Additional costs for special scheduling of operators must be considered. Due to the requirement of the technical supervision authority, more breaks are required for operators. Therefore, a higher number of safety operators is required. The bus drivers of BSM's large buses are legally obliged to take a break after 4.5 hours driving at the latest. The technical supervision authority TÜV required breaks after 40 minutes of shuttle operating at the latest due to the new and unusual conditions (concentration without actually steering or braking). This was later extended to 60 minutes, but is still far less than 4.5 hours. Therefore, BSM needs many more operators to operate the shuttles than large buses.
- Leasing shuttles might be cheaper than purchasing them. Leasing can give PTO more flexibility as technology evolves quickly.

Others:

- Close cooperation with city administration is required, for example to trim trees and bushes along the shuttle route. Otherwise, these might be detected by the shuttles as obstacles and can lead to additional stops and thus a reduction in average speed.
- It is important to get feedbacks from end users on usability, safety, user experience and feedbacks regarding routes or alternative routes. For the Monheim pilot site, this was done by SHOW surveys, KIT accompanying research on automated vehicles and numerous personal conversations with end users conducted by our safety operators and colleagues from BSM's business development department.
- Try to operate shuttles only on routes with lower permitted speeds, e.g. in pedestrian zones or 20 km/h or max. 30 km/h, so that shuttles can flow with the traffic and other VRUs don't perceive them as obstacles.

7.13 Roadmap beyond SHOW and replicability

In Monheim, automated shuttle operation will continue until January 2026, as Monheim has a line concession until that date. There are currently no plans to extend the current route. An additional route would only make sense if the vehicles were to operate completely driverless.

Currently, Monheim is involved in two CCAM-related projects. One is the European project Diversify CCAM (HORIZON-CL5-2023-D6-01-04) [5] and the other is the German national project Safestream [6]. In Safestream, BSM plans establish a technical supervision and assume a role as experience provider, while the city Monheim is one of the test locations. T-Systems and EasyMile are also partners in this project. The project Diversify CCAM aims to develop a CCAM Diversification Tool (CCAM D-Tool) for transportation planners and a CCAM Diversity Observatory for the entire CCAM value chain, both focusing on achieving inclusiveness and equity within the European mobility ecosystem. Both SHOW partners VTI and DLR are also involved in this project.

8 Conclusions

After going through ups and downs, i.e. finding, replacing and re-planning test sites, the lower acceptance of public transport and the vehicle component shortages and waits mainly caused by the coronavirus pandemic, the piloting periods at the German mega site remained at a minimum of 12 months and varied from 12 to 20 months, and the number of automated shuttles was even higher than originally planned. In total, all 12 automated shuttles and one modular vehicle travelled approximately 110,000 km and transported roughly 50,000 passengers and 1,629 cargo deliveries. No critical failures occurred. Passengers' enthusiasm and high acceptance of AVs are noteworthy. The relatively long-term success and positive feedback from passengers and residents regarding the AS operations suggest that expanding DRT services in areas with limited PT access is an important step for achieving comprehensive mobility transformation. Pilot activities have highlighted the critical role of safety operators during the transition to fully automated operations, not only due to complex traffic scenarios but also for handling unexpected events and assisting passengers. Continuous training and education for safety operators are vital, and there is ample room for improvement in the development of AS technology. Engaging passengers and residents, explaining new service offerings, and addressing their feedback are particularly important for automated DRT services. In addition, the approval process for AS is time-consuming, necessitating a review of relevant legislation to facilitate easier implementation and integration into existing PT systems. Currently, the speed limit for AS in Germany is relatively low at 20 km/h; increasing this limit could enhance public acceptance. Ongoing dissemination and communication efforts are also essential for building greater public awareness and acceptance of AS [1].

The integration of AS into the local PT system at the Monheim pilot site has proven the feasibility of AS in practice. The respective AS will continue to offer regular services. To expand PT coverage, the provision of an additional A2 line and/or an DRT service is proposed and under discussion. In the Rhine-Main and Karlsruhe regions, the comprehensive implementation of automated DRT services is expected to be gradually advanced and the implementation of automated driving technology in PT will be further investigated in the future. Regarding vehicle development, FZI continues to develop automated driving functions with the FZI-shuttles focusing on teleoperation and remote fleet-management. Further work on various projects in the U-Shift project landscape is planned. As part of the U-Shift technology transfer project, the aim is to obtain approval for the use of the U-Shift IV on public roads. Besides, various vehicle components will be further developed and the technology transfer to small and medium-sized enterprises (SMEs), medium-sized companies and large companies will be continued.

References

[1] Flötteröd, Y.-P., Karnahl, K., Pavlakis, S., Holdermüller, A., Ochs, S., Zofka, M., Dietl, K., Mook, M. (2024). Real-life automated public transport operations at the SHOW German Mega Site – experiences and lessons learned. In H. Cornet and M. Gkemou (Eds.), Shared Mobility Revolution - Pioneering Autonomous Horizons. Springer Cham. eBook ISBN: 978-3-031-71793-2. https://link.springer.com/book/9783031717925

[2] SHOW (2024). Optimized energy consumption through collaborative driving maneuvers. The insight article of FEV of the Horizon-2020 SHOW project, Grant Agreement No. 875530.

[3] Görgülü, M., Barthelmes, L. and Kagerbauer, M (2024).,Accompanying Research on Automated Minibusses in Monheim am Rhein : Report on Results, research report, Institut für Verkehrswesen (IFV). DOI: 10.5445/IR/1000170289

[4] Monheimer Musikfestival GmbH (2024). Monheim Triennale. https://archiv.monheim-triennale.de/de/mt2/2023/artists. accessed on 2024.09.03.

[5] Diversify – CCAM (2024). Diversify – CCAM, EU Project ID 101147484. https://www.ccam.eu/projects/diversify-ccam/. accessed on 2024.09.03.

[6] Safetream (2024). SAFETREAM. https://safestream.tech/. accessed on 2024.09.05.