SHared automation Operating models for Worldwide adoption

SHOW

Grant Agreement Number: 875530

D10.4: Pilot results based simulations for impact assessment

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Executive Summary

This deliverable is part of *WP10: Operations simulation models platform and tools* and reports the final results of task A10.2 "Vehicle and traffic simulations" and A10.3 "Person, mobility, freight and environment related simulations". Its main focus is set on the simulation-based impact analysis of the ten representative pilot sites of SHOW.

Simulations about the impacts of the CCAV adoption on the overall transport system such as the number of accidents, traffic speed and volume, occupancy, travel times, queue length, vehicle / person kms travelled, average vehicle occupancy, cost per travelled km as well as driving parameters such as vehicle dynamics comfort, times to collision and braking events are the key essence of this deliverable *D10.4 Pilot results based simulations for impact assessment*. For this purpose, a set of key performance indicators KPIs has been defined in consultation with WP13 that works on impact assessment, which were evaluated for the respective pilot sites using simulation methods. In addition, environmental aspects such as emissions of particulate matter and greenhouse gases have been simulated for all pilot sites.

A significant part of this document is the presentation of objectives and enhancements (OE) made to the simulation sites since release of deliverable D10.3. A condensed summary including partners, tools, and key findings (KF) can be seen in the following:

Brainport (TNO, macro simulation using *Urban Strategy*)
OE: City-level simulations of the impact of an automated DRT service have been performed involving the results of the street-level simulations and pilot data.
KF: Automated DRT service can lead to a modal share of 2.6%. However, the vehicles loss hours (congestion) increases by 3% as a consequence of 57% of DRT vehicle kilometers running empty (i.e. without passengers). Additionally, the introduction of DRT leads to a decrease in bike and public transport usage.

Graz (VIF, micro simulation using *Autoware* and *SUMO*)
OE: After extensive VRU simulations (reported within D10.3), the simulation landscape had to be extended by SUMO to perform the required impact analysis. Using OpenStreetMap data and pilot site data a realistic traffic simulation of the Graz pilot site was generated.
KF: Impact of AV service on existing traffic is marginal (average speed reduced by 0.7%) because the AV is operating most of the time on a separate bus lane.

Karlsruhe (FZI, micro simulation using *Carla* and *ROS*)
OE: A Carla simulation environment for testing and validation of the developed automated driving function implemented in ROS has been created.
KF: The automated driving function is able to navigate all scenarios with random traffic without collision or conflict with other road users.

Klagenfurt (AIT, micro simulation using *SUMO*)
OE: Based on the simulations performed for D10.3 new analysis algorithms have been added to extract additional KPIs.
KF: No discernable impacts of the AVs on overall traffic flow of other vehicles on the main roads of Klagenfurt can be detected using simulations.

Linköping (DLR, micro simulation using *SUMO*)
OE: Three different aspects were investigated in more detail: (i) reflecting the reality in the simulation with the focus on the shared space, (ii) understanding possible impacts on the surrounding traffic with scenario analysis and (iii) model development and implementation to deal with charging issues in simulations.
KF: Impact of the on-site AV operations on existing traffic is small (average car speed reduction by < 2 %). At a higher frequency (10 min), average car speed is reduced by

5%. However, when increasing AV speed to 30 km/h, the impact of AV becomes marginal. The low impact of AV is mainly due to the site and route characteristics.

Madrid - Carabanchel (NTUA, micro simulation using *Aimsun* and *SSAM*)
OE: Simulations for Carabanchel were already advanced, from the previous deliverable, incorporating realistic data for both prevailing traffic and the SHOW AD shuttles. The additional work was focused on estimating KPIs and aligning units at the aggregation level.
KF: The analysis indicates that AVs slightly decrease vehicle speeds, slightly increase travel time delays, and road conflicts, while emissions remain stable across all scenarios.

Madrid - Villaverde (NTUA, micro simulation using *Aimsun* and *SSAM*)
OE: Simulations for Villaverde were adjusted representing the real world, shorter route and were enhanced by integrating field pilot data. Moreover, an additional scenario was simulated including an additional AD shuttle. Significant attention was also given for estimating the KPIs required by WP13.
KF: The analysis indicates that AVs slightly affect vehicle speeds, slightly increase travel time delays, and road conflicts, while emissions remain stable across all scenarios, offering crucial insights for traffic, safety, and environmental assessments.

Trikala (CERTH, micro simulation using *SUMO*)
OE: Assessments of the traffic and environmental impacts of automated shuttles on a peri-urban route have been conducted.
KF: Minor impacts of the automated shuttles on conventional traffic and the environment (3.78% reduction on average vehicle speed and 2.63% increase on CO_2 emissions per kilometer) were found.

Monheim (DLR, micro simulation using *SUMO*)
OE: Investigating possible impact of AVs on the existing traffic system; reflecting the reality in the simulation with the focus on the shared space.
KF: Depending on the vehicle class, minor impacts (average car speed reduced by 0.6%, average bus speed reduced by 1.2%) of the AVs on surrounding traffic and were found.

Rome (CTLup, micro simulation using *AnyLogic* and *TransCAD*)
OE: The Rome Simulation Site has a completely different take on the topic, as goods rather than passengers are transported. Therefore, the issues, circumstances and consequently the KPIs are completely different. Focus has been set especially on the optimization of dynamic routing algorithms, the strategic placement of transfer points and the demand forecasting.
KF: The simulation generated highly optimized routes for 5 vehicles, strategically sequencing transit points to minimize travel distance and maximize delivery efficiency.

Brainport (AIT, macro simulation using *MATSim*)
OE: Additional simulations were performed to introduce the faster AV Shuttles as well as a switch to automated PT for all lines and resulting shorter interval times for PT.
KF: A shift from car to automated services could be seen for both, automated PT with shorter intervals as well as automated DRT last mile services. However, car remained the dominant mode for the region.

Overall, it can be summarized that as long as the shuttles and AVs only supplement the existing public transport and do not replace it, the net result is a slightly higher volume of traffic in the area under consideration, with all the accompanying drawbacks. The electric shuttles themselves are largely neutral in terms of environmental pollution. Only indirectly they lead to slightly higher exhaust emission levels due to congestion effects. The specific figures vary slightly, depending on the pilot site, but can be estimated at less than 1%. In order to achieve considerable improvements in modal split, there is a need for a relatively large number of automated vehicles.

After a general introduction in Chapter 1, Chapter 2 deals with the fulfillment of the topics outlined in the Grant Agreement. For each topic, a short paragraph is devoted on what has been done, who has done it, what the results are and where further details can be found.

Chapter 3 presents the individual pilot sites with their characteristics and results. Three main aspects are discussed for each pilot site: (i) What improvements have been made to the pilot site and the associated simulation models during the report period, (ii) how has the data from the real pilot site been used to make the simulations more realistic in order to (iii) answer the overall question as to how the AVs influence their environment – the so-called impact analysis.

A comparison of the KPIs of the individual pilot sites is discussed in Chapter 4. This also reveals a fundamental difference in the outcomes at different levels of abstraction. At low levels that target safety of vulnerable road users (VRUs) and/or operate on the level of single streets, the introduction of additional vehicles tends to create the impression of being disadvantageous. However, at a higher level of abstraction, it becomes clear, that the shift in mobility has benefits for both traffic and environment.

Chapter 5 concludes this deliverable, where the key findings of the simulation are summarized once again.

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Abbreviation List

Abbreviation	Definition
ACC	Adaptive Cruise Control
AD	Automated Driving
AS	Automated Shuttles
AV	Automated Vehicle
CACC	Cooperative Adaptive Cruise Control
CAV	Connected Automated Vehicle
CCAV	Cooperative Connected Automated Vehicle
CV	Conventional Vehicle
D	Deliverable
DRT	Demand Responsive Transport
DVRP	Dynamic Vehicle Routing Problem
KPI	Key Performance Indicator
Lidar	Light Detection And Ranging
MFD	Macroscopic Fundamental Diagram
MPR	Market Penetration Rate
MRM	Minimum Risk Manoeuvres
O-D/OD	Origin-destination
OSM	Open Street Map
PCU	Passenger Car Units
PM	Particulate Matter
PT	Public Transport
ROS	Robot Operating System
SUMP	Sustainable Urban Mobility Plans
TMC	Traffic Management Center
TOC	Transitions Of Control
VRU	Vulnerable Road Users
VTTS	Value of travel time savings
WP	Work Package

1 Introduction

1.1 Purpose and structure of the document

This document summarises the simulations carried out within the framework of the project SHOW. This document is intended for public and open access and builds upon the work in D10.1 [2], D10.2 [3] and D10.3 [4] which described the first simulation iterations, scenarios, relevant KPIs, and use cases and chosen simulation tools that are going to be utilized in SHOW. While previous simulation activities were based mainly on vehicle performance characteristics and assumptions about the pilot site, the present document also incorporates data-feedback from the real-life demonstration and the analysis of impact on existing traffic. The simulations focus on three distinct simulation scenarios (street-level, city-level, and local Vulnerable Road Users (VRUs) simulations) implemented by ten (10) pilot sites: Graz, Karlsruhe, Klagenfurt, Monheim am Rhein, Linköping, Madrid, Rome, Salzburg, Tampere and Trikala. Particular attention is paid to energy usage and environmental impacts of the shared CCAV services developed within SHOW.

Within this document the third and final iteration of simulation results is demonstrated, which exploits data acquired from the running pilot sites, so that the simulations are more accurate. The overall aim of these simulations it to support and guide the real-life SHOW demonstration with special emphasis on traffic- and safety-impacts as well as concluding these impacts with the support of WP13 (Impact assessment). For all the simulation sites and developed scenarios presented in the current deliverable, the final results are given in order to fulfil the project requirements with regards to the use cases and to deliver the KPIs for safety and impact assessment of automated driving applications.

The deliverable is structured as follows: This introductory chapter provides the purpose, structure, intended audience and the interrelationships of this document in regard to the entire project. Chapter 2 deals with the broader objectives of this work package in accordance with the Grant Agreement of SHOW and briefly describes how the individual aspects were addressed, what results have been achieved and where more details can be found. Chapter 3 presents the final iteration and improvements of the ten SHOW pilot site simulations which were improved using real-world data from the corresponding pilot sites. Emphasis is placed on the impact analysis, i.e. how the operation of the SHOW AVs influences the surrounding traffic, safety and environment. A discussion of the results including comparisons between pilot sites is the content of chapter 4. Essentially, findings and experiences are described, which appear relevant after the SHOW project and could be useful for the development of new, future pilot sites. Finally, conclusions are drawn in chapter 5.

1.2 Intended Audience

As WP10 works closely with WP13, which aims at assessing the SHOW use cases with regards to the safety and impact of automated driving services, partners involved in the safety, environmental and impact assessment are anticipated to be closely monitoring the progress of the work described in this document, especially the results of the impact analysis simulations.

From the “open-access nature of this document” point of view, it serves as an informative document describing the simulation approaches and efforts for external stakeholders and enabling them to understand how the simulations of SHOW sites have been improved using real-data and how the results were combined and integrated. In this context it is also worth mentioning the project’s deliverable D10.5:

Simulation Suite, where experiences from all pilot sites and from all SHOW WP10 partners work are currently collected to build an interactive information platform.

1.3 Interrelations

As mentioned in the previous section, this deliverable builds upon the results of D10.1, D10.2 and D10.3 and is related to activities A10.2 and A10.3 of WP10. Furthermore, WP10 is closely cooperating with WP13 by providing inputs to the impact assessment framework (and its outputs). The considered and presented KPIs were developed in close collaboration with WP13 (Impact assessment) and its related activities. Also, WP12 (Real-life demonstrations) is inevitably interrelated, since the real-world data collected at the pilot sites has been incorporated into the simulation in order to improve the simulations and align them with the real-world measurements.

2 Task summary

Over the course of the SHOW project, the role of the simulations changed notably. In the initial phases of the project, the focus was set on the general functionality of the SHOW AVs, estimation of passenger numbers and capacities as well as creation of realistic timetables. In later phases of the project, the issues covered by simulations changed more to the direction of impact assessment of AVs on the surrounding traffic and up-scaling the results to larger coverage areas and/or the use of multiple AVs on the corresponding pilot-sites.

2.1 Vehicle and traffic simulations (A10.2)

Assessment of Traffic safety is one of the earliest and most important aspects to be investigated using simulations. This topic has been covered in D10.2, chapter 3.9.3, for the Tampere site, where safety margins for the shuttle have been validated using simulations. At the Carabanchel pilot site the speed limits of the shuttles for the 19 sections have been determined by means of simulations (see D10.3, chapter 4.7.3.2). In Madrid, among other KPIs, the number of conflicts between shuttles and other road users has been estimated using simulations for both pilots in Carabanchel and Villaverde (refer to D10.3, chapters 4.7.2 and 4.7.3). The impact on conflicts was estimated based on the operation of three SHOW AD shuttles, varying operational speeds of the shuttles, and changes in the mix of automated vehicle fleets (by increasing the AV Market Penetration Rate (MPR)). In Graz the safe passage of the shuttle through the crowded bus terminal Puntigam has been validated by simulations (D10.3, chapter 4.3.2.6). FZI used simulation methods to verify their diagnostic approach for localization system malfunction in D10.3, chapter 4.4.1.3 for the Karlsruhe pilot site. Furthermore, the verification of PTS4 (AV is capable of adapting its speed, depending on environmental conditions) was also confirmed by simulations and reported in D10.3 – chapter 4.4.2.5.

Simulations are often the only possible way to **assess traffic changes** caused by the introduction of automated shuttles. For Madrid the influence of the shuttles on existing traffic has been investigated (see D10.2, chapter 3.7.3), but no noticeable influence of the shuttles in terms of speeds, delay times and travel times was found. Subsequently, traffic changes at network level (e.g. distances traveled), were also examined and reported in D10.3, chapter 4.7.2.3. Similar simulations were made for Karlsruhe, where the traffic with and without AVs was simulated and compared (see D10.2, chapter 3.5.3). A decrease of the average speed of approx. 2 km/h in average was reported there, because of traffic queues forming behind the shuttles. For the Linköping campus site, analyses were carried out to provide an impression about the traffic impact on the surrounding vehicles and cyclists occurring from the introduction of automated shuttles. When bikes, buses and other vehicles run just after automated shuttles, the respective travel duration increases slightly, as reported in D10.3, chapter 4.6.3. The same simulation approach leading to similar results is reported for Monheim in D10.3, chapter 4.8.3. In Trikala, multiple simulation scenarios were analyzed to assess the impacts of the introduction of the automated shuttles on traffic flow (average vehicle travel time, throughput, spatial-temporal change of speed) along the peri-urban route (see D10.2, chapter 3.10). Due to the changes of the pilot site (operation of the automated shuttle shifted to a new peri-urban route) the simulation analysis had to be repeated for the changed pilot site and the new results are reported in D10.3, chapter 4.12. For the Klagenfurt pilot site, the simulations show that there is no significant influence of the automated shuttles on the overall traffic performance. Because of the two-lane infrastructure, there is always a chance to overtake the rather slow automated shuttles (cp. D10.3, chapter 4.5.3). For the Graz pilot site, the simulation was expanded as part of the impact analysis at a later stage and the relevant statistics were collected.

Although the AVs are driving on a separate bus lane most of the time, the average traffic speed of all vehicles in all analysed simulation scenarios is reduced by 0.7%, because the ‘intelligent’ traffic light prioritizes the lane of the AV (see chapter 3.2.3).

Likewise, the **assessment of energy and environmental changes** was primarily done using simulations. In Madrid for Villaverde site and the Carabanchel site both CO_2 and NO_x emissions have been simulated at network level. With increasing shuttle penetration rate replacing the public buses, the emissions decrease due to the electric drive (see D10.2, chapter 3.7.3). For D10.3, chapter 4.7.2, these simulations have been improved and concluded that the electrification of CAV fleet significantly improved the environmental conditions at network level when operating at 30 km/h or 45 km/h. However, lower operational speed resulted in higher CO_2 and NO_x traffic emissions because of congestion effects. As part of the impact analysis, **environmental changes** and the effects of the AVs on the environment were simulated for several other pilot sites as well like Graz (see chapter 3.2.3) or Trikala (see chapter 3.10.2)

TNO has provided a network service for **energy use** of all SHOW AVs. Initially, the method was aimed to analyze real vehicle data, but with some adjustments the method has been applied to the simulation site data of SHOW. More details about this method and how it is applied in the context of the simulations as well as the actual results are reported in deliverable D13.2 that focuses on the traffic efficiency and energy impact assessment.

Simulations were also conducted to further **examine existing driving functions**. SUMO’s Transition of Control (ToC) and Minimum Risk Manoeuvre (MRM) models have been used in the simulation analysis of the Trikala pilot site to assess the impacts of ToCs/MRMs on the performance of the automated shuttles and the traffic flow (see chapter 3.10.1). Additionally, the simulation analysis encompassed scenarios with priority for automated shuttles at signalized intersections. Pertinent simulation results indicated that signal priority significantly enhanced the performance of automated shuttles without adversely impacting traffic operations on the network level.

CCAV driving behavior and the corresponding **lane-changing and car-following models** have been an important issue for practically all SHOW pilot sites. At the German Aerospace Center (DLR) – the inventors and developers of SUMO – model development and testing for shared space simulation was done, regarding lane-changing, car-following, and the interactions between different types of road users. Cyclists’ lane-changing behaviors and road users’ space usage situation were investigated with the collected data as well (see D10.3, chapter 4.6 and chapter 4.8). Moreover, improvements on the simulation models, related to vehicular road alignment and deceleration when approaching a pre-defined stop, as well as the interactions between vehicles, cyclists and pedestrians have been carried out. For more details on the mathematical background of vehicle following and lane changing, please refer to the level 2 documentation of the Simulation Suite, D10.5.

Other project partners have been mainly focusing on the selection, use and **parameterization** of existing models for **lane-change and car-following** for their AVs. For Linköping the examination, the selection, the calibration and the validation of the car-following model based on real data collected from the automated shuttles is described in D10.2, chapter 3.6. For the Trikala pilot site, characteristics of the automated vehicle type that affect the longitudinal motion of the automated shuttle and its car-following behavior have been selected based on empirical evidence collected from the pilot operation of the automated shuttles (see chapter 3.10.1). Lane-changing and car-following model selection and configuration of other pilot sites such as Graz or Madrid are also covered in detail in the Simulation Suite documentation (D10.5).

Dynamic route planning and dynamic changes in infrastructure is a topic that the Graz pilot location requires for regular operation. Static routing is not possible there; the CAV must decide autonomously the best way to travel through the bus terminal based on availability of bus bays. In case no route can be found, a takeover request (TOR) needs to be triggered. This aspect of the Graz pilot site has been implemented and tested using simulations before it was incorporated into the CAV. Details can be found in D10.3, chapter 4.3.3.

SUMO's **models related to charging stations and charging behavior** have been continuously improved and extended throughout the project by DLR, and the respective parameters were examined and adjusted. Furthermore, the **model for vehicle charging has been enhanced** within SUMO. The concept of the recharging model together with charging station search has been developed and a simulation prototype with the consideration of more factors is under development (see chapter 3.5.1).

In the aim of realistic simulations, the SHOW pilot sites have been re-created within the simulations as **virtual environments built with real-world data**. Especially on low abstraction levels, the simulations and the real world are highly interchangeable. This applies particularly for the Tampere site, where a busy intersection has been modelled in detail using aerial images. This virtual environment includes drivable areas, marked lanes, priority lanes, traffic lights and even roadwork cones. Based on real world behavior, various pedestrians, cyclists, buses, trams, vehicles with trailers and passenger vehicles are interacting with the AV in this virtual world. More details can be found in D10.2, chapter 3.9.2. A digital twin of the test sites in Karlsruhe has been created in a similar way for virtual testing using Unreal Engine and lanelet maps. Even the FZI shuttle was modelled for Unreal Engine, based on a 3D model of the real shuttle to mimic its appearance and geometric properties (see D10.2, chapter 3.5.2). For the Graz pilot site, a SUMO simulation based on real world driving experiences has been created in a highly automated way, using OpenStreetMap information and tuned with the characteristic of the real-world AVs (see chapter 3.2.1).

Simulations about the impacts of the CCAV adoption on the overall transport system such as the **number of accidents, traffic speed and volume, occupancy, travel times, queue length, vehicle / person kms travelled, average vehicle occupancy, cost per travelled km** as well as driving parameters such as **vehicle dynamics comfort, times to collision and braking events** are the key essence of this deliverable *D10.4 Pilot results based simulations for impact assessment*. Some pilot site simulations have already anticipated this issue and have addressed it – at least in parts – in earlier deliverables like Madrid (D10.2, chapter 3.7), Linköping (D10.2, chapter 3.6), Trikala (D10.2, chapter 3.10 and D10.3, chapter 4.12) or Monheim (D.10.3, chapter 4.8).

2.2 Person, mobility, freight, and environment related simulations (A10.3)

Behavioral **differences between vehicles with different automation levels and conventional vehicles** are one of the central issues addressed in this simulation task. For the Trikala pilot site traffic simulations including passenger cars, public buses, pedestrians and the automated shuttles have been conducted. The initial parameterization of driver models, which determine the behavior of the AVs, has been hypothesized based on literature review findings (see D10.3, chapter 4.12.4). Later, empirical evidence from the Trikala site has been used to improve the behavior of the simulated AVs to reflect reality even better (chapter 3.10.1). Many shuttles, like in Linköping or in Klagenfurt, operate on a virtual rail (see D10.3, chapter 4.6.2.4) and therefore do not have many degrees of freedom compared to manually driven vehicles.

In this case the virtual driver is reduced to an adaptive cruise control – in real world as in simulations. To model the behavior of AVs at the Madrid sites, parameters of the LEVITATE project have been reused (see D10.3, chapter 4.7.3.5). In particular at the Villaverde site, naturalistic traffic volumes were simulated and the interaction between AVs and human-driven vehicles was simulated and reported. More specifically, 11 different scenarios ranging from 0% Automated Driving (AD) Market Penetration Rate (MPR) to 100% MPR simulating fully automated traffic were simulated. A type of co-simulation between CARLA and SUMO was created for the Karlsruhe pilot site in order to reproduce the shuttle's driving behaviour in public traffic as accurate as possible. Using CARLA, the behaviour of the shuttle is simulated with all its details – a so-called digital twin – for the predefined route. SUMO is used to randomly generate a realistic surrounding traffic. By temporally combining both simulators, the driving behaviour of the shuttle is modelled as accurately as possible (see D10.2, chapter 3.5.3). For the Graz pilot site, a similar approach has been chosen, but instead of coupling the simulators temporally, a spatial coupling has been chosen there (see chapter 3.2.1).

Passengers' safety and the **interactions between vulnerable road users (VRUs) and CCAVs** has been a key concern of the entire simulation work package WP10. Microscopic simulation tools (SUMO, Simulate) were used to model the reactions and interactions of automated vehicles with VRUs. For the Graz pilot site, AIT carried out an extensive pedestrian simulation and derived recommendations as to where the AVs should preferably pass through the bus terminal (see D10.2 – chapter 3.4.4) to avoid as many potential conflicts as possible. For the pilot site Linköping video and traffic-data were collected to capture the traffic situation and to investigate cyclists' overtaking behaviours and the interactions between shuttles and other road users within the shared space and examine if any critical issues exist. A SUMO simulation was applied by the DLR for enhancing the simulation and for developing shared space simulation. In particular, the replication of overtaking manoeuvres of AVs for bikes and pedestrians within SUMO was improved to replicate the real-world behaviour better. Information on the simulation setup can be found in D10.3, chapter 6.6.1.3.

For the Carabanchel site in Madrid, NTUA simulated naturalistic VRUs volumes and the interaction with different automated shuttles inside the bus depot. The extracted results included flow and safety KPIs such as pedestrian speed, stop time, travel time as well as conflicts. (D10.3, chapter 4.7.3.6, Figure 63(c)). In D10.4, chapter 3.6.2 further scenarios are described. Also, VTT performed simulations of the interactions between pedestrians and automated shuttles to find appropriate behavior of the shuttle at busy pedestrian crossings, focusing on both, the safety of pedestrians as well as the possibilities of the AV to pass (See D10.2, chapter 3.9.3).

In addition, the simulation of **detections of VRUs** through the on-board sensors and the **reactions of automated vehicles to VRU users** was studied in several simulations. For instance, the Autoware-based vehicle software has been validated to insert slow-down passages and full stops when pedestrians walk close to the planned trajectory (details and videos can be found in D10.5 Simulation Suite Level 1). Similarly, for the Karlsruhe site, FZI simulated the proposed driving functions and resulting interaction of automated shuttles with a pedestrian (VRU) according to STS02 scenario. In particular, the breaking behaviour of AVs as a reaction of the sensing of pedestrians was studied using simulations before applying it in the real shuttle. The setup and the results can be seen in D10.3, chapters 6.4.2.3.1 and 6.4.3.2.

For the question of improved **accessibility**, the Salzburg simulation site was used to study changes in traffic behaviour for vulnerable groups (elderly, young people, people with no driving license) to determine changes in accessibility for those groups. The results are included in chapter 3.9.3.

The impacts of CCAV adoption and shared mobility on mobility are studied in the project's city-wide simulations. In particular, for the Salzburg site, changes in mode choice were studied for different scenarios of introducing automated vehicles. Information from literature was applied to develop demand models for different subsets of the population for being used in MATSim simulations. Modal split results for different scenarios can be found in D10.3, chapter 6.10.3. In addition, several resulting KPIs were studied, including total distance of automated vehicles, total empty kilometers, the ratio of empty rides and occupancy rates. Further KPIs, like total network delay and the amount of travel can be found in chapter 3.9.3**.** In addition, the Brainport site included a city-wide simulation. Results for several DRT fleet sizes are reported in chapter 3.1.3.

Finally, **Take over Requests** were simulated for the site in Karlsruhe. The information will be included in D10.5 because the behavior can be described much better by means of video sequences than in the form of KPIs. Here, the implementation of V2X communication protocols to exchange information with the shuttle about the traffic lights status and additional obstacles in the environment was added to the simulation. The additional information is passed to the planning pipeline for decision making for TOR.

3 Simulation activities per pilot site

Following the simulation work carried out in D10.3, the availability and quality of the real shuttle data and the available resource, the simulation work for the pilot sites at Brainport, Graz, Karlsruhe, Klagenfurt, Linköping, Madrid, Rome, Salzburg and Trikala were further executed as explained below.

3.1 Brainport

3.1.1 Enhanced Simulation

Until now, the focus of the Brainport simulation activities was estimating the street-level impact of automated Demand Responsive Vehicles (DRT) for passengers. The pilot data and accompanying Software-In-The-Loop simulator was used to verify the functioning of the simulated DRT, whereas the microscopic simulations provided the ability to introduce automated DRT in the city center of Eindhoven, including the estimation of their impact on junction delays (for both automated and conventional vehicles).

In the last phase of Work package 10, the focus was on running city-level macroscopic simulations using the Urban Strategy environment. The microscopic simulation results were used to create several scenarios of giving priority to DRT at junctions, and combined with several scenarios within the mode choice module 'New Mobility Modeller' to assess the impact of different costs, fleet sizes and user acceptance rates. In this way, the impact of the introduction of automated DRT on city-level could be computed. Besides the computation of the new modal split, further modules were used to compute the congestion on the road (and accompanying travel times) as well as the optimal DRT fleet dispatching service (which vehicle serves which passenger request).

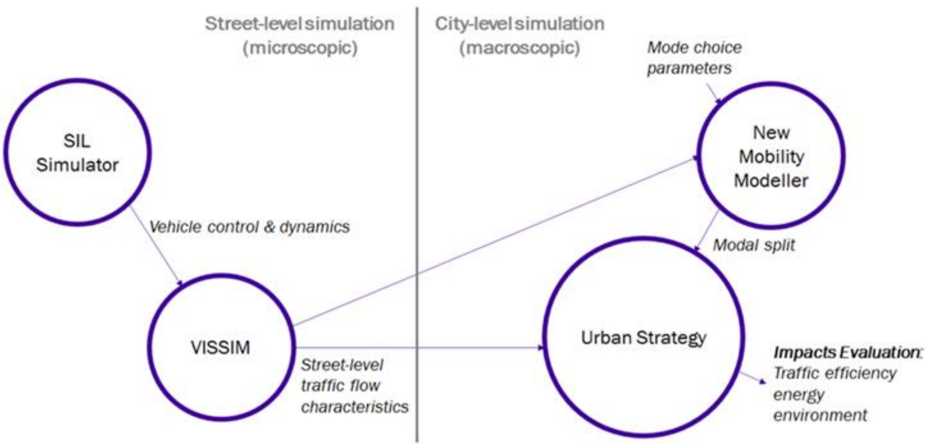


Figure 1: Overview of Brainport simulation architecture

For the city-level simulations, the simulation area including the city of Eindhoven and its surrounding towns was chosen. In this area, one airport and eleven train stations are included. The chosen year to model is 2030 due to the availability of this model year in the chosen transport model, and the morning peak period (7.00-9.00) of an average weekday was modelled. The simulation network consists of 3611 traffic analysis zones, 90,596 roads and 302 transit lines. The transit lines in the area are shown in Figure 2.

Figure 2: Overview of transit lines (green: bus, yellow: train) in the simulation environment

The DRT vehicles were evenly distributed among five starting locations around the city centre of Eindhoven as shown in Figure 3. Each DRT vehicle starts and ends the day at one of these locations.

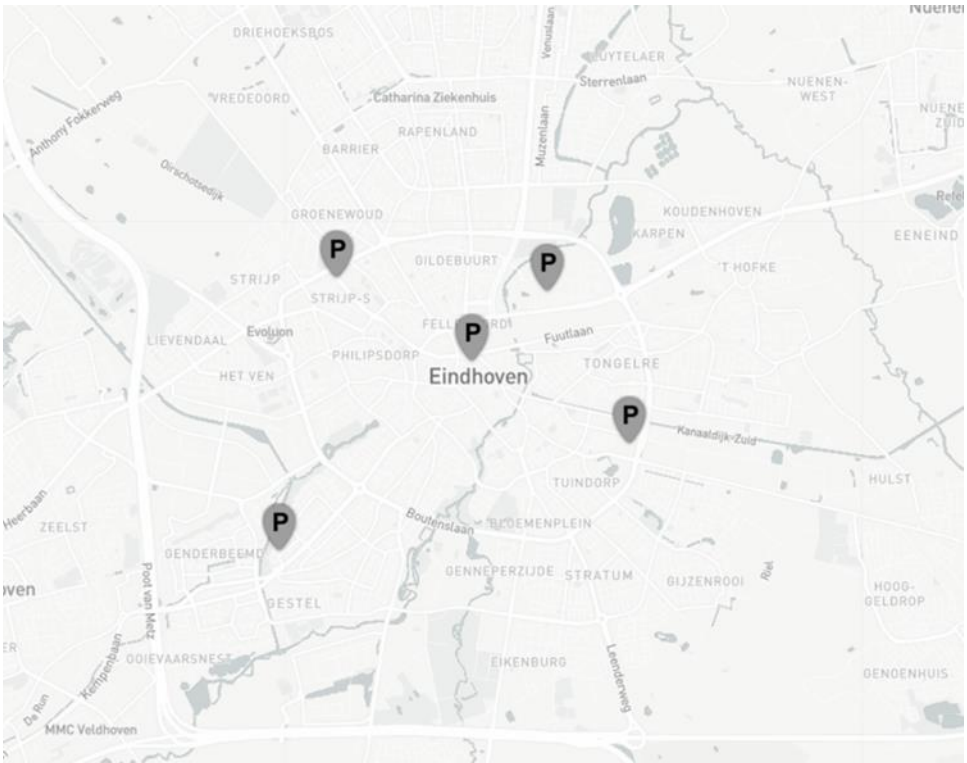


Figure 3: Overview of starting locations (marked with P) of the DRT

In total, 34 scenarios are run on the Eindhoven network, in which each traveller could reconsider its choice between the several modes of transport (car, bike, public transport, DRT). Consequently, the DRT schedule was updated, the route choice was recomputed and the resulting travel times per mode were updated and used again in a new iteration of the mode choice model. The several modules are run in a loop, until an equilibrium in modal split is found.

The 34 scenarios consist of a base situation and several variations. The base situation does not have any active DRT service. The other scenarios vary in the associated junction delays (do DRT vehicles get priority over other vehicles?), the fleet size (between 40 or ‘unlimited’ at each starting location), the costs per trip (cheap, expensive, special pricing to discourage long trips), and the user acceptance rate (low, medium, high).

3.1.2 Feedback of pilot site data

The pilot data of the automated passenger cars running on the test tracks was used to verify the functioning of the microscopic model. The microscopic VISSIM model was used to scale up to several street-level situations where multiple automated DRT vehicles were running on the streets, crossing junctions, etc. This was used as an input for the city-level simulations. This has been reported in the previous deliverables D10.3 and D10.2.

On city-level, no pilot site data could be gathered and therefore this could not be verified.

3.1.3 Simulation-based impact analysis

The resulting modal split for the city of Eindhoven for several DRT fleet sizes is shown in Table 1. It can be seen that in a scenario with an “unlimited” amount of DRT available, 2.6% of the trips will use a DRT vehicle. This entails about 10.000 trips during the morning peak rush hour. At the same time, this results in additional congestion on the road, as measured in vehicle loss hours. The overall vehicle loss hours increase by 3% compared to the base scenario. The congestion increases because travelers use a DRT as a replacement of their bike (-0.9%), car (-0.9%) or public transport (-0.7%) trip, as opposed to only replacing car trips.

This effect is in essence undesirable in terms of usual city goals nowadays, where preferably cities are turning toward sustainable, environment-friendly, car-low areas. As stated in D10.3, the automation of DRTs results in a negative impact on street-level. The used CACC vehicles are keeping larger following distances for safety reasons as compared to the normal non-automated vehicles. Additionally, the automated DRT vehicles are slower in accelerating than conventional vehicles. The effect is that the service would be more efficient if it is offered with non-automated cars, although that would mean that more personnel costs are involved. Efficiency could be gained if the penetration rate of automated DRTs becomes higher and thereby communication between vehicles might lead to shorter lead-follower distances. In this study, only automated DRTs were modelled. Results might slightly differ if a non-automated DRT service was modelled instead.

Table 1: Statistics on the impacts of DRT vehicles on the mobility system with several fleet sizes

DRT fleet size per scenario	0	200	400	600	800	1000	"Unlimited"
Modal split: Car	54.0%	53.7%	53.6%	53.4%	53.2%	53.1%	53.1%
Modal split: Bike	38.5%	38.3%	38.1%	37.9%	37.7%	37.6%	37.6%
Modal split: PT	7.5%	7.1%	6.9%	6.8%	6.8%	6.8%	6.8%
Modal split: DRT	0.0%	1.0%	1.4%	1.9%	2.3%	2.5%	2.6%
Vehicle loss hours Car + DRT [h]	8170	8249	8317	8348	8372	8389	8413
Vehicle Kms Travelled Car + DRT [km x 1000]	3099	3114	3127	3132	3137	3141	3147

Several other scenarios have been investigated to mitigate the effects of having less bike and public transport trips due to the introduction of DRT. The full results are reported in the simulation suite documents, but main conclusions are:

- Automated DRT is used as a mode for mainly shorter trips (on average less than 4 km!). It is thought that this is caused by relatively long waiting times before the DRT arrives if travelling toward the outskirts of the model, which makes it unattractive.
- On average, automated DRT drive 40% of their time with a passenger inside. The remainder is seen as “empty kilometers”. Optimizing the fleet size to the number of requests help increase this number up to 60%, which results in less congestion on a city level.
- The effect of green light priority for automated DRT results in a 0.1% modal split increase (e.g. 2.4% if no priority is given, 2.5% if DRT gets priority at all signalized junctions). The impact is thereby limited.
- The effect of user acceptance or attractiveness of the automated DRT results in a 0.8% modal split increase (e.g. 2.5% with a high acceptance rate, 1.7% with a low acceptance rate).
- The effect of pricing for the automated DRT is high, and can result in 2.3% modal split increase (e.g. 1.2% with a high price, 3.5% with a low price).
- The scenario with the highest automated DRT usage has 3.8% of travelers using the DRT. In this scenario, the prices are the lowest ones (€1.50 start costs + €0.50 per km), DRT gets green priority, the acceptance is the highest and the fleet size is set to 1000 or more vehicles.
- The impact on bike and public transport usage is least in scenarios where cars are suffering additional delays due to green light priority for automated DRT or high penetration rates of DRT – impacting the travel time for cars the most.
- In terms of environmental impacts, if assuming the DRT vehicles are fully electric, as it is the case in the vast majority of automated vehicles, the outcome is always positive, since the car kilometers for vehicles with an ignition combustion engine (ICE) are being replaced by electric DRT kilometers. On a city scale, this results in a 0.3% reduction for a basic scenario with a resulting 2.5% modal split for DRT, but may increase up to 0.7% reduction in green house gases in the scenario where most DRT are being used.

From a city perspective, part of the result is undesirable. Although it is a nice achievement that the vehicle kilometers driven by conventional cars decrease, this is at a cost of less kilometers travelled by bike and public transport. Additionally, the congestion levels in the city increase in every scenario. Most importantly, simulations show that DRT trips are usually very short trips, with an average trip distance of just under 4 km and an average trip time of 9 minutes. Investing in more sustainable friendly solutions – such as shared (electric) bikes or increasing public transport on popular DRT-routes – might be more beneficial than the introduction of DRT in the city center, especially since effects like parking and dwelling around have not been accounted for in this study.

For comparison with other simulation scenarios, the overall KPIs are shown in Table 2. This comparison has been made for the scenario with a normal attractiveness, no green light priority for DRT, normal costs and a fleet size of 1000 DRT vehicles. For DRT, all numbers are reported excluding empty vehicle kilometers driven.

Table 2: Impact analysis related KPIs simulated for the Brainport pilot site

KPI	Baseline – without DRT operation	With DRT operation	Impact	Units
Total network travel time per vehicle type	59069 car 45787 bike 59244 PT	58832 car 45380 bike 57494 PT 1585 DRT	-0.4% car -0.9% bike -3.0% PT	h
The share of each mode choice (in number of trips)	53.98% car 38.47% bike 7.55% PT 0% DRT	53.13% car 37.61% bike 6.76% PT 2.49% DRT	-0.84% car -0.87% bike -0.78% PT +2.49% DRT	%
The share of each mode choice (in distance covered)	70.72% car 16.51% bike 12.75% PT	70.36% car 16.33% bike 12.42% PT 0.89% DRT	-0.37% car -0.18% bike -0.34% PT 0.89% DRT	%
Total number of kilometres travelled in a network, per mode of transport and/or trip purpose	2803619 car 654756 bike 505584 PT	2799291 car 649839 bike 494032 PT 35253 DRT	-0.2% car -0.8% bike -2.3% PT	km
Average travel time delay over the entire network	2.178	2.159	-0.86%	Min/vehicle
Average vehicle speed in a network	47.5 car 14.3 bike 8.5 PT	47.5 car 14.3 bike 8.5 PT 22.2 DRT	0%	km/h
Number of trips in the network, per mode and/or trip purpose	225041 car 160402 bike 31464 PT	222639 car 157570 bike 28345 PT 10453 DRT	-0.84% car -0.87% bike -0.78% PT +2.49% DRT	#
Percentage of vehicle-km of DRT run empty	-	57%		%
Percentage of total vehicle-kms run empty	-	0.71%		%

3.2 Graz

In the previous deliverables, the focus of the Graz pilot site simulation activities was set on Autoware and the simulation environment that comes with it. It is as close to reality as one can get, but there are a few major downsides of this approach: Firstly, the entire scene and all traffic participants must be modelled in 3D – a huge effort for a large track. Secondly, Autoware does not offer an elaborated traffic simulation which provides a random variety in the simulation scenarios. Thirdly, because of the complexity and simulation details, a simulation run takes potentially a long time to finish.

3.2.1 Expansion of simulation capabilities

Therefore, a major part of the Graz test track was modelled and simulated additionally in SUMO, to determine the required KPIs for the impact analysis, such as lap-times and to ascertain the influence of various factors, such as vehicle speed under realistic yet randomized traffic conditions. Only in the area of the bus terminal the detailed Autoware simulation is still used, because VRUs can be handled better this way, and the environment is too complex and unstructured for a meaningful SUMO simulation (cp. Figure 4).

Figure 4: Section definition for SUMO (green) and Autoware (red) co-simulation

The main motivation of having an additional SUMO simulation was the generation of realistic traffic loads around the pilot site area for the automated vehicle to interact with. With a few assumptions about the intentions of drivers, it is relatively straightforward to generate reasonable traffic using SUMO. Most of the traffic on *B67a* is passing through from east to west and vice versa. A small fraction of the traffic enters the shopping mall, both north and south. Likewise, the parking lots and underground garages within the shopping centre can be seen as a source of traffic. The majority of vehicles starting their journey there want to leave the shopping centre. Some traffic is potentially coming from and going to the north. Very important for the traffic simulation is bus line 65, which is using partially the same restricted roads as our AV service (see Figure 5).

Figure 5: SUMO simulation of the major intersection within the pilot site.

Currently there is no direct way to combine SUMO and Autoware simulators, as they are different simulation tools for different purposes. SUMO is a traffic simulator that models road networks and vehicle movements, while Autoware Simulator is a scene simulator for autonomous driving that models vehicle dynamics, sensors and the configuration of the environment. Thus, we have chosen an approach for SHOW where both simulators are spatially coupled loosely at predefined handover points. This means, the current vehicle state (speed, acceleration) at this location is taken from one simulator and fed into the other simulator and vice versa. This way, the advantage of SUMO traffic simulation and Autoware simulator environment can be combined easily and effectively.

Highlighted in green and red are the roads used by the AV (cp. Figure 4). The green road segments to and within the shopping center are modelled and simulated using SUMO. The roads and walkways within the bus terminal are painted in red. This is the part of the track, where the lane-based simulation of SUMO is not adequate to handle the pedestrians roaming around in various directions. Here the simulator of Autoware is used because a lower level of abstraction is needed. Within the Autoware simulator, static obstacles and moving objects can be placed. Based on this 3D scene, sensor data like Lidar point- are generated. By using the processing pipeline and algorithms of the real automated vehicle, the gap between simulation and real world is kept low.

A snapshot of the running SUMO simulation of the major intersection can be seen in Figure 5. For easier inspection, different routes are using different vehicle colours. The colour red is reserved for AVs; busses of the public transport service are always green.

3.2.2 Feedback of data from pilot site operation

The major objectives of the SUMO simulations at the Graz pilot site are the investigation of travel- and waiting-times occurring due to various traffic situations as well as the impact of the AVs on the existing traffic. Based on the data from the real pilot operation, the parameters of the simulation were adapted in accordance to the real conditions. The simplest way to explain this approach is to look at the speed profiles.

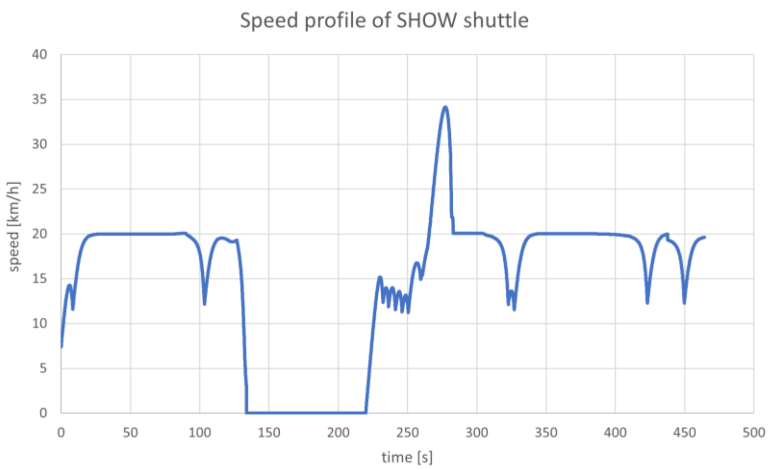


Figure 6: The speed profile of the AV during a trip using SUMO with random traffic

The speed profile of an exemplary simulation run can be seen in Figure 6. The AV enters the section of the track covered by SUMO simulation with a speed of approximately 7 km/h, coming from the bus terminal. It then proceeds along the bus lane toward the shopping centre. At timestamp t = 130s the AV waits at the traffic light to turn green. After the traffic light the AV is on the public road inside the shopping centre. Here the speed is fluctuating because of other traffic participants. At t = 270s the vehicle has clear way inside the shopping centre and accelerates to its max speed (plus speeding factor) before it enters the restricted bus lane again at around t = 300s.

Figure 7 shows in comparison the speed profile of the real AV on a trip through the shopping centre. Because of random traffic – especially in the area of the shopping centre – the speed profile is hard to reproduce. However, the average speed is comparable, and all major stops can be identified clearly in both plots.

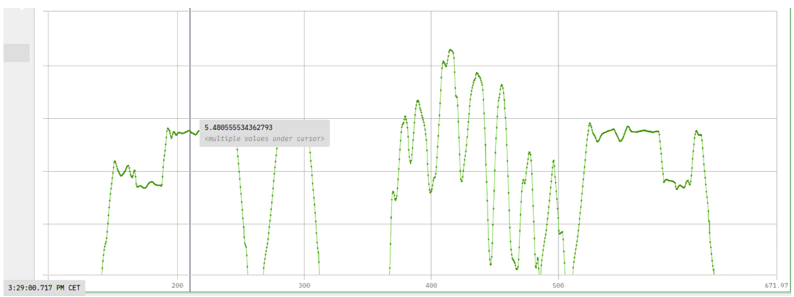


Figure 7: Speed profile of the real AV during a real trip with real traffic

To gather the data presented in the following section, SUMO was run over a hundred times with different random number seeds and the results have been aggregated. The average speed, which is calculated by dividing the track length (~1.8 km) by the trip time is depicted in Figure 8. It can be seen that 16 km/h is the average speed during most simulation runs.

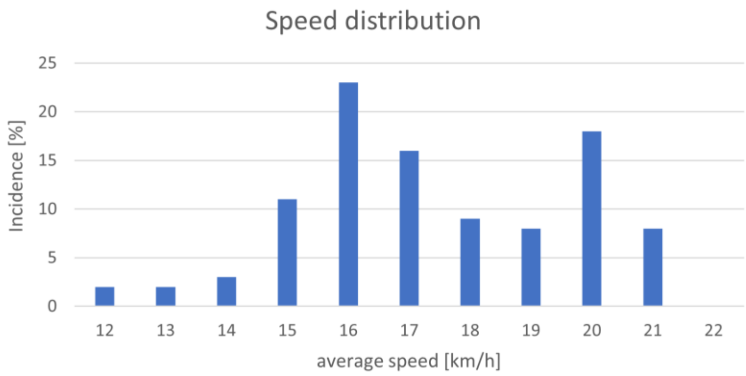


Figure 8: Distribution of average speed over 100 simulation runs using SUMO

As already seen in the average speed histogram, the trip duration (Figure 9) has two peaks as well. The explanation for this is essentially the traffic light in the shopping center. Fortunately, if the light is green, a round trip takes about 340 seconds. On the other hand, if the AV has to wait for green light, the trip time is about 440 seconds. In rare cases (traffic jams, buses impede the AV at the traffic lights), trips of up to 570 seconds are possible.

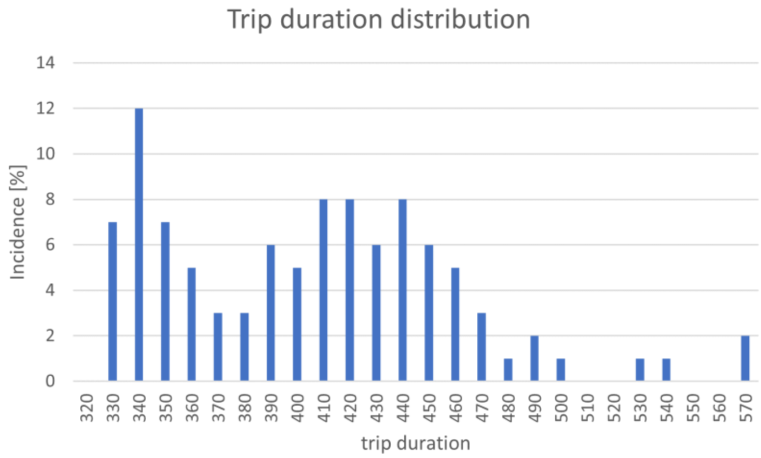


Figure 9: Distribution of trip duration of 100 simulation runs using SUMO

Aside of the speed profile, several other KPIs from the simulation were aligned with the reality of the pilot site. A list of these KPIs is summarized below in Table 3.

Table 3: KPIs of the AVs determined by means of simulations for Graz pilot site

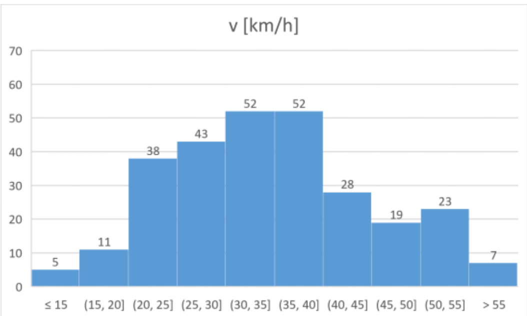
KPI	Simulator	Value	Comment
Collision avoidance	Autoware	0 collisions	Velocity reduction
Conflicts with VRUs	Autoware	0 collisions	Velocity reduction
Time headway	SUMO	≥ 1.1 s	distance headway divided by the vehicle's speed
Proportion of stopping	SUMO	70 s (avg.)	*waitingTime* in tripinfo.xml
Hard breaking	SUMO	0 -2 per trip	deceleration > 2 m/s²
Travel time	SUMO	350 s (avg.)	*duration – waitingTime*
Distance	SUMO	1.8 km + 0.2 km	*routeLength* in tripinfo.xml
Average speed	SUMO	16 km/h (avg.)	*routeLength / duration*
Duration and length of trips	SUMO	450 ± 120 s	*duration* in tripinfo.xml
Low speed due to VRU	Autoware	85 s – 120 s for bus terminal passage	comparison between scenarios with and without pedestrians
Average waiting times	SUMO	120 s (avg.)	derived from jitter of *duration*

3.2.3 Simulation-based impact analysis

SUMO also offers the possibility of a more sophisticated analysis, which real world driving tests cannot provide. In particular, the impact of the AVs on the surrounding traffic can be examined and various influencing factors can be identified this way. For this purpose, 17 representative scenarios have been evaluated in greater depth. Those scenarios vary in traffic density, number of public buses sharing the track and vary the traffic light cycles in order to generate a realistic average behavior.

As on the real pilot site, there is always just one AV simulated on the route (while the other AV is picking up passengers). These 17 scenarios were carried out with and without AVs, as can be seen in Table 4. In addition to the AVs, approximately 5200 vehicles were involved, of which 50 were public buses. For environmental simulations the surrounding traffic was assumed to be a mix of *EURO-IV* and *EURO-V* type cars while the public buses were assumed of being type “*Std GT15-18t Euro VI A-C*”.

For a particular simulation run the distribution of all average speeds of all simulated vehicles is shown in Figure 10. As can be noticed immediately, the presence of our AV has an influence on shape of the histogram. However, when calculating the average speed over all vehicles, the difference is modest: the average speed is reduced from 36.95 km/h to 36.69 km/h in the presence of the AV.



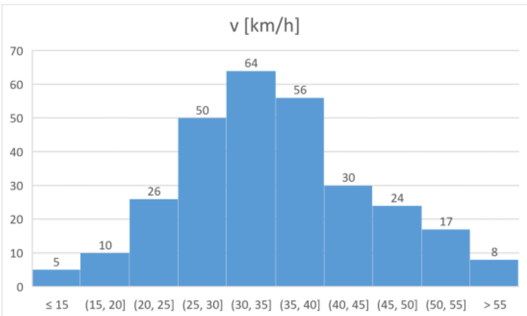


Figure 10: Distribution of average vehicle speed without AV and with AV

The presence of our AV also has a reproducible – albeit small – influence on the average CO_2 emissions of all vehicles in the simulation (see Figure 11). Apparently, outliers of more than 450 mg/km are noticeable. These are public buses, which have significantly higher exhaust emissions.

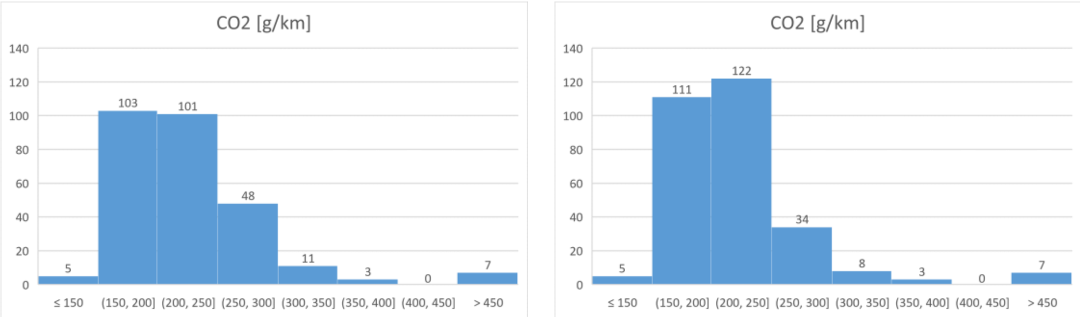


Figure 11: Distribution of CO2 emission per vehicle without AV and with AV

The fine dust emissions were also simulated. Here too, a marginal increase was found across all 17 simulation runs with regard to the presence of the AV (Figure 12).

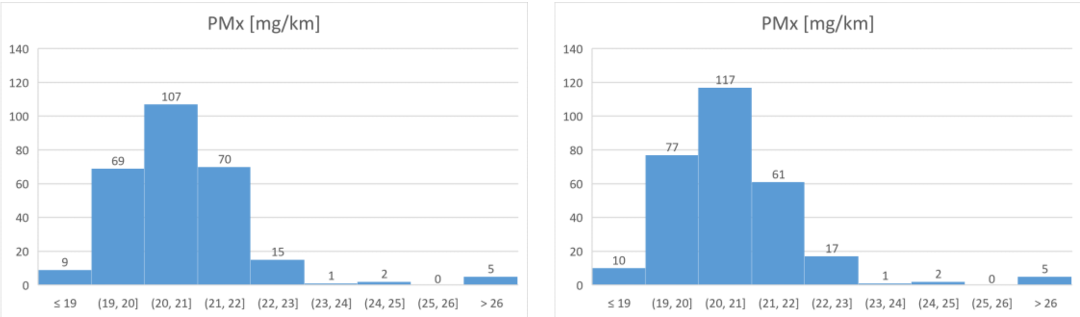


Figure 12: Distribution of fine particle emissions without AV and with AV

In summary, it can be said that the AVs have hardly any influence on traffic in the Puntigam shopping center area of Graz (see also Table 4). On one hand, the AVs operate relatively infrequently and mostly on separate lanes. On the other hand, the general speed limit within the shopping center is 30 km/h – a velocity our AVs can operate under normal conditions without ado. In the end, the traffic light, which prioritizes vehicles on the bus lane and thus causes side effects on the main road, has the biggest influence on the surrounding traffic and causes the reduction of the average speed in the network.

It should be mentioned that the main concern of the responsible authorities in Graz was that the operation of the AVs could lead to chaotic traffic situations on the streets around the shopping center or cause massive disruption to public transport service. This concern can be ruled out based on the simulations results shown in Table 4. Although minor influences are statistically observable, they are negligible for the overall traffic flow.

Table 4: Impact analysis related KPIs simulated for the Graz pilot site

KPI	without AV	with AV	Unit	Impact
Number of vehicles in simulation	5202	5195	-	-
passenger cars	5151	5128	-	-
public buses	51	50	-	-
AVs	0	17	-	-
Simulation duration	1:56	1:56	h:min	-
Number of conflicts with other road users	1.51	1.54	1/km	+2.0%
Average vehicle speed (per vehicle type)	36.95	36.69	km/h	-0.7%
Average travel time delay (per vehicle type)	20.47	21.51	sec	+5.1%
Stops per vehicle for all vehicle types	0.82	0.84	-	+2.6%
Total vehicle delays in an intersection	37.99	39.33	sec	+3.5%
Total travel time in network per vehicle type	123.66	125.22	sec	+1.3%
Avg. energy use per kilometer per vehicle	70.9	71.5	mg/km	+0.8%
Emissions of a vehicle – CO_2	218	220	mg/km	+0.8%
Emissions of a vehicle – CO	1.73	1.72	mg/km	-0.5%
Emissions of a vehicle – NO_x	38.24	38.81	mg/km	+1,5%
Emissions of a vehicle – HC	10.2	10.2	mg/km	0.0%
Emissions of a vehicle – PM_x	22.72	22.79	mg/km	+0.4%

3.3 Karlsruhe

3.3.1 Enhanced simulation

The test site Karlsruhe represents one of the German mega pilot sites in the SHOW project. Developing safe and integrated autonomous mobility and transportation services for passengers and cargo is the main focus of the test site. A microscopic simulation framework has been deployed to investigate the pilot operation impacts on traffic and the safety of other road users. The Carla simulator was adopted as a framework for simulating our microscopic simulations. Carla is a high-fidelity simulator with support for different sensors, providing a test bed for the different perception, localization, and planning modules developed throughout the project. Additionally, ROS and Python supports are available in Carla.

In this work, the focus is dedicated to building a digital twin of “Weiherfeld-Dammerstock” test site, which is an urban part of Karlsruhe in which the shuttle is tested in open traffic. A map of “Weiherfeld-Dammerstock” is created based on a High Definition (HD) map in lanelet format, as illustrated in Figure 13. Re-simulating such HD maps helps identify bottlenecks (e.g., critical intersections) and provides a flexible simulation for stress testing of the developed driving functions. Additionally, random open traffic such as vehicles, cyclists, and pedestrians are used to evaluate the automated driving function safety and its interaction with Vulnerable Road Users (VRUs).

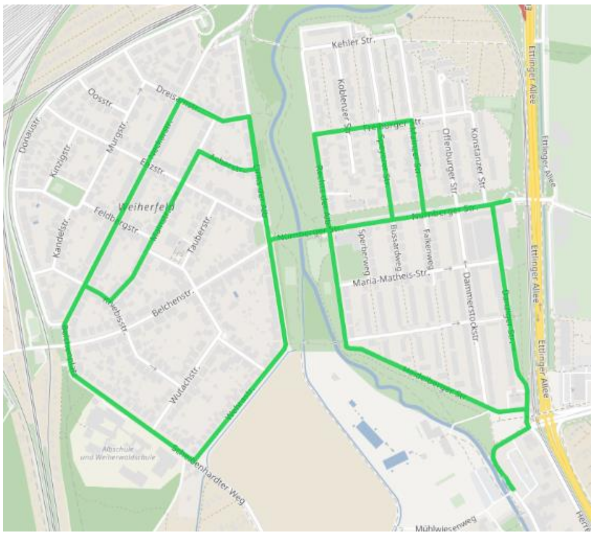


Figure 13: Map of "Weiherfeld-Dammerstock"

Figure 14: Physical shuttle and blender model of the EasyMile EZGen2 shuttle

A digital twin of EasyMile EZGen2 Shuttle was developed in blender (3D software) during this work and imported to Carla using Unreal Engine extensions. Figure 14 demonstrates the physical shuttle on the left and the simulated shuttle in Carla on the right.

a. HAD functions integration:

To ensure the safety and reliability of the developed ROS-based highly automated driving (HAD) functions for the physical demo site, we focused on integrating HAD functions into Carla simulation. Additionally, we supported an extended list of sensor modalities and implemented car-to-everything (C2X) protocols. The proposed driving functions utilize a modular pipeline to plan a future trajectory with a defined time horizon given the current driving scenario. The modular pipeline utilizes HD maps to capture road topology and traffic rules, and a high-level planner is used to find a reference route from a start point to the next stop. A localization algorithm is used to estimate the current pose of the shuttle on the map relative to the reference route, with a perception algorithm detecting and tracking static and dynamic obstacles. A planner then utilizes the output from these algorithms to estimate a future trajectory. In order to achieve a flexible and extendable integration of HAD functions with Carla, a Carla-ROS bridge is utilized and modified. The Carla-ROS bridge is modified to connect and synchronize various sensors and actors in Carla via ROS messages and services. The bridge provides information about the environmental parameters, e.g. weather, list of active actors in the simulation, and sensors. In addition, services for spawning and removing sensors, pedestrians, and vehicles are established to help generate diverse traffic scenarios for testing.

b. Carla-ROS bridge utilization and extension:

Carla ROS bridge is modified to connect and synchronize various sensor modalities and actors in Carla via ROS messages and services. The bridge can provide information about the world state, such as the weather, as well as a list of active actors and sensors. In addition, services for spawning and removing sensors, pedestrians, and vehicles are established to help generate diverse traffic scenarios for testing. Furthermore, sensor data processing steps have been implemented to provide better support for perception algorithms, testing, and data structures used in C2X standards. This work focused mainly on the instance segmentation camera and semantic LiDAR sensor modalities in Carla.

c. Instance segmentation camera.

Carla's instance segmentation camera captures a semantic annotation of the current field of view (FOV) with a pixel label in the red channel and a unique ID of the actor in the remaining two channels. This sensor modality is supported with two additional ROS messages. First, a 2D axis-aligned bounding box message is extracted by grouping pixels for each unique actor. Similarly, the 2D contours message of each actor can be extracted using the OpenCV framework, where the contours represent a closed polygon of pixels belonging to the actor. Custom ROS messages are implemented to support publishing a list of bounding boxes and contours, as these are not standard ROS messages. In addition, the counters or bounding boxes can be projected into a geo-referenced 3D space using a camera calibration matrix and GNSS sensor data. This geo-referenced information about all actors in the sensor's FOV can be published as a Cooperative Perception Message (CPM), a standard message in V2X communication.

d. Semantic Lidar:

Further processing is applied to semantic LiDAR data. A point cloud can be extracted from Carla's semantic LiDAR in which each point is defined by its (x, y, z) coordinates, a unique ID, and the semantic class of the actor from which the point is reflected. Each actor captured in the point cloud is extracted as an object by grouping the points assigned to it based on the semantic label, the unique ID. A bounding box is fitted to the object, and the box center is the mean coordinates of all points. Further, all objects in the point cloud are published as a list on a custom ROS message. Additional information about the objects, such as detection age, heading, and speed, can be calculated using the Carla ground truth information or using tracking algorithms.

e. Road Side Unit (RSU):

A roadside unit, typically mounted on a traffic light, is implemented in Carla to support C2X use cases such as cooperative perception and providing explicit information about traffic light status. The implemented traffic light consists of a camera, LiDAR, GNSS, and a communication module. Additional work is done to allow the RSU to publish different C2X standard messages and an extension of the Carla-ROS bridge is carried out to allow the exchange of these messages with other actors in the driving scenario.

f. Car2x communication:

The Cooperative Awareness Message (CAM) is one of the standard C2X standard messages supported in our work. CAM represents an identifier used by an actor, vehicle, shuttle, or RSU, to provide information about itself and its current state in the driving scenario. This message typically includes the station type, geographic location (longitude and latitude), and specific information about the actor. For vehicles, this CAM message includes information such as current driving direction, speed, vehicle dimensions, acceleration, and steering angle. Carla's vehicle model is updated, such as any vehicle with a GNSS sensor can broadcast CAM messages via ROS with a fixed frequency. On the other hand, RSU CAMs only include the type and geographic location and are published at a constant frequency as well. To further monitor the shuttle driving performance, it is integrated into the control center of the Test Area Autonomous Driving Baden-Württemberg (TAF-BW). The control center of (TAF-BW) serves as a central interface for monitoring different test fields and enables the analysis and visualization of traffic flow at intelligent and connected intersections. We used a ROS recording of the aforementioned CAM to visualize the CARLA-simulated shuttle in the control center by replaying the recording on the TAF-BW backend server. Figure 15 illustrates a screenshot of the shuttle (highlighted in red) visualized in the control center.

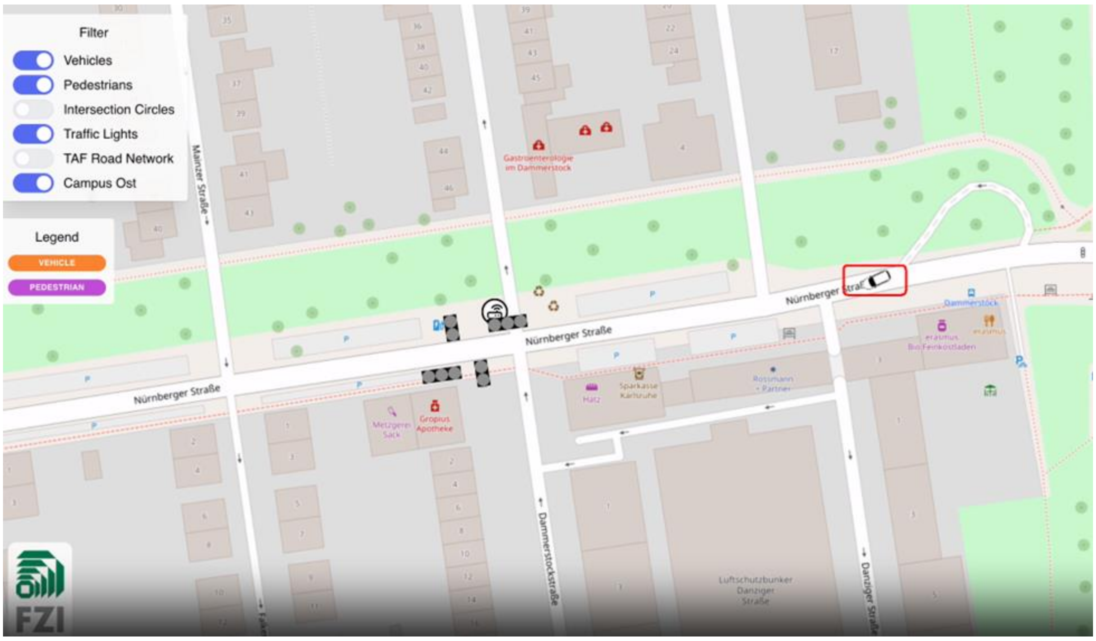


Figure 15: Screenshot of the shuttle (highlighted in red) visualized in the control center

Cooperative Perception Message (CPM) is another C2X message integrated into this work. As discussed earlier, additional development is carried out to publish object lists from both semantic segmentation cameras and semantic LiDAR. In order to publish CPMs a converter is implemented to convert object list messages from both sources to the desired format. CPM can be subscribed to by any actor in the driving environment including the shuttle to enhance its perception information, augment blind spots with more information, and enhance safety.

Detecting traffic light status is a challenging task in autonomous driving due to the diverse traffic light shapes, visibility in the perception sensors' field of view (FOV), and locations relevant to road topology. However, wrong or missed detection of traffic lights can yield catastrophic events such as collisions with other vehicles and Vulnerable Road Users (VRUs). Signal Phase and Timing (SPaT) messages can be an alternative to explicit detection of the traffic light status via perception modules by broadcasting the current status of the traffic light in a C2X message. SPaT message provides both the traffic light status (red, yellow, green, unknown) and the remaining time till the status changes. In addition, a visualization plugin is implemented in RVIZ to render the SPaT messages and visualize the current state of every traffic light in the HD map.

This plugin facilitates the monitoring and debugging of the current vehicle and traffic light states.

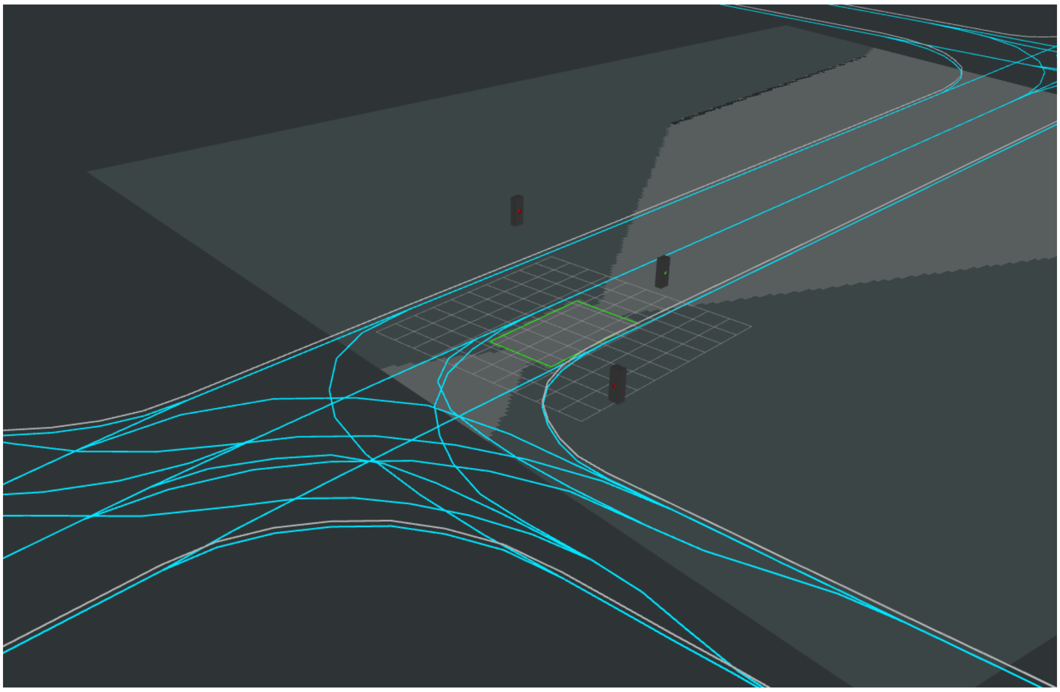


Figure 16: RVIZ used to visualize the current state of every traffic light

All the aforementioned C2X messages are exchanged, can be published or subscribed to, using ROS topics, and can be received regardless of the distance between the publisher and subscriber, which is unrealistic. To enhance the realism of these communication messages, we implement a probabilistic dropout of messages based on the squared distance between the publisher and subscriber as formulated in Equation 1 and illustrated in Figure 17, where the distance threshold represents the maximum distance between a publisher and subscriber such that a message can be received and is set to 100 meters in the figure. The threshold value is chosen on the hardware limitation of the available hardware.

$$Dropout\ probability = \frac{1}{(Distance\ threshold)^2} * max(0, Distance\ threshold - current\ distance)^2$$

Equation 1: dropout probability

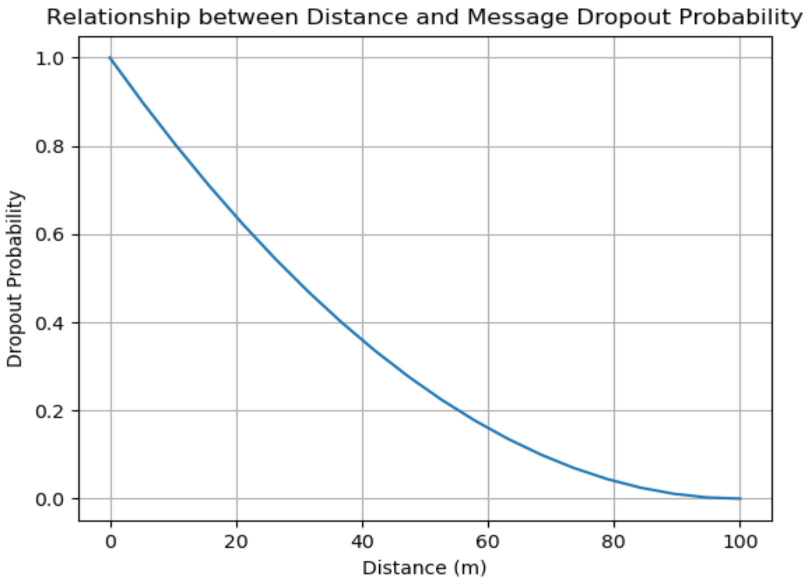


Figure 17: Probabilistic dropout of messages

g. Additional support for autonomous trip monitoring

A custom message is implemented to support energy management. This message extracts information about the shuttle's current weight, as it can vary with the number of passengers, velocity, and distance travelled from the start of the operation in the current simulation time step. An approximate remaining percentage of charge (state of charge) is calculated as a linear function inversely proportional to the total distance travelled. Additionally, the ROS diagnostics system is supported by different modules of automated driving functions such as perception, localization, and planning for troubleshooting and logging. Each module publishes a DiagnosticArray with its current status, name, and any additional information provided.

In addition, all messages from all system components are recorded in a Ros-Bag file, allowing the simulation scenario to be replayed and the sensor data to be visualized. The recorded data can be further used to test additional algorithms, such as tracking without starting an expensive simulation environment like Carla.

3.3.2 Feedback of pilot site data

After the driving function testing and verification in the pre-demo phase at the pilot site, several parameters of the shuttle operation in the physical pilot site were adopted in the simulation digital twin to enhance the simulation usability and realism. In the following table, several key parameters adopted are discussed. First, we modified the 3D shuttle model used in Carla to mirror the same dimensions as the physical shuttle. Additional parameters relevant to the vehicle kinematics and dynamics model, such as the desired velocity, acceleration, and curvature, are mimicked in Carla. Particularly, the desired velocity is adapted to be the same as the average velocity achieved by the shuttle in its operation during the pre-demo phase in the test site. Finally, the planner settings for finding the optimal path are copied over to ensure the ability of the driving function to find similar trajectories in simulation as well.

Further parameters such as the PID controller converting the trajectories to the shuttle control input are not adapted from the real test site, as the underlying physics and dynamics of the simulated shuttle model still diverge from the physical one and need to be tuned better for a stable operation in the Carla simulator.

Table 5: Pilot site data used in simulation

Parameter - Setting	Values from the pilot site	Description
Vehicle Length	4.0 (m)	The shuttle dimension along the longitudinal direction
Vehicle Width	2.0 (m)	The shuttle dimension along the lateral direction
Desired Velocity	20.0 (km/h)	The desired velocity to be maintained by the planner in its trajectories
Maximum Acceleration	3.5 (m/s^2)	The maximum acceleration that the vehicle can achieve during its operation
Maximum Curvature	0.2 (1/m)	The maximum curvature between two consecutive poses in a planned trajectory
Planner trajectory size	20	The number of sequential poses estimated by the planner in each trajectory.
Planner population size	96	The size of the initial population initialized by the planner.

Based on the adapted parameters, KPIs are calculated from shuttle trajectories recorded in ten different runs with random target stops and traffic. An overview of the calculated KPIs can be found in Table 6. No Take over Requests have been registered in the simulation as the driving functions developed have avoided conflicts with other agents and never required manual take over.

Table 6: KPIs calculated from shuttle trajectories

KPI	Simulator	Value	Comment
Collision avoidance	Carla	0 collisions	Based on Carla's collision sensor data
Conflicts with VRUs	Carla	0 collisions	Based on Carla's collision sensor data
Hard braking	Carla	0 events	Deceleration > 3 m/s^2
Travel Distance of AV	Carla	0.6 km + 0.1 km	The distance travelled by shuttle. Since the shuttle can reach any stop on the road network. This distance was chosen with a 0.1 km random deviation and can be increased or decreased based on design
Average Speed of AV	Carla	3.4 m/s (12.24 km/h)	The mean velocity achieved by the shuttle during its operation
Acceleration Variance of AV	Carla	1.467 m/s^2	The acceleration variance during the shuttle operation

3.3.3 Simulation-based impact analysis

We compare three different simulation scenarios in SUMO to analyse the impact of the automated shuttle on the traffic flow. We simulate traffic scenarios with only the automated shuttle, only traffic participants (other vehicles) whose behaviour is generated by SUMO, and both the shuttle and the traffic participants.

Table 7: Impact analysis results for Karlsruhe

KPI	Shuttle-only	Sumo traffic-only	Shuttle and SUMO
Number of agents	1 (1 shuttle)	399 (399 cars)	210 (1 shuttle, 209 cars)
Elapsed time	190.69 minutes	157.23 minutes	81.04 minutes
Number of conflicts	0	4 (2 SUMO vehicles too close to each other)	1 (2 SUMO vehicles too close to each other)
Speed per vehicle type	Shuttle: 2.6 m/s (9.36 km/h)	Other vehicles: 8.19 m/s (29.50 km/h)	Shuttle: 2.63 m/s (9.48 km/h), Car: 7.64 m/s (27.50 km/h)
Number of vehicle stops	7 (planned stops)	122	shuttle: 4 planned stops, other vehicles: 74
Number of hard braking events	0	0	0

The shuttle-only simulations illustrate that the shuttle can drive on the simulated road network without any conflicts, off-road driving, and with an average speed of 9.36 km/h successfully stopping at planned stops. For the traffic-only simulation, a total of 399 agents are simulated in the same road network. In this scenario, vehicles had to stop 122 times to give way to other vehicles and avoid conflicts. The average speed was 29.50 km/h, which was very close to the desired speed of 30 km/h. 4 Conflicts occurred caused by SUMO traffic being too close to each other. However, no collisions happened. In the combined simulation with the shuttle and additional vehicles from SUMO, the shuttle and the other vehicles correctly gave way, and again, the shuttle was able to drive within the simulated world without any conflicts. One conflict occurred; however, it was caused by two SUMO agents which drove too close to each other and the shuttle was not involved. The average speed of the shuttle was very close to the first case (9.36 km/h), but the average speed of the other cars decreased by 2 km/h and was only 27.50 km/h. This reduction of the average speed is linked to the existence of the shuttle in the simulation, the other vehicles were not allowed to overtake, and in turn, there was a queue behind the shuttle. The traffic congestion due to the shuttle presence in the street is illustrated in Figure 18.

Figure 18: Traffic congestion due to the shuttle presence

3.4 Klagenfurt

Due to the Klagenfurt site not running a vehicle up to date, no real live data was included in the simulations. The vehicle variables for the automated shuttle were taken according to specifications of the real vehicle used in the Pörtschach part of the Austrian mega site and were already included in the simulations for D10.3, so no new simulations were run. They are again included for clarity in Table 8.

Table 8: Navya shuttle SUMO vehicle model values Klagenfurt pilot

Shuttle name	max. speed	σ	τ	Accel.	Decel.	Actionsteplength	vClass	carFollowModel
Navya_neu	13.8 m/s	0.6	1.0	1.2 m/s^2	5 m/s^2	0.1 s	evehicle	ACC

New analyzes were run on the simulation outputs of the simulations of a scenario in which three shuttles are running on three different routes (see Figure 19).

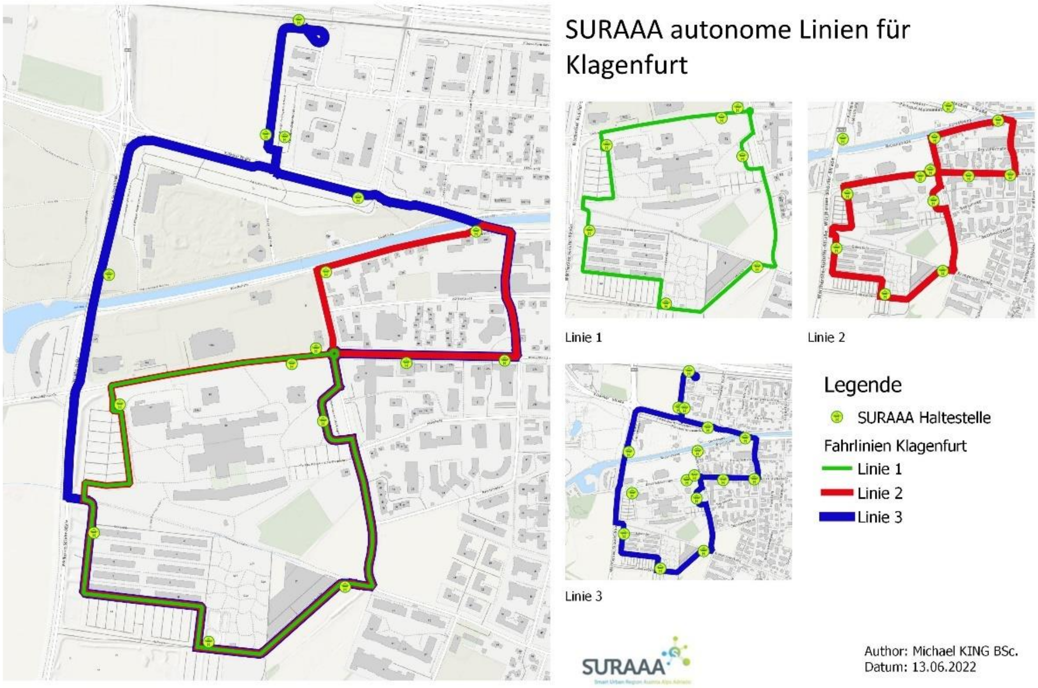


Figure 19: Routes of the shuttle in the simulation.

3.4.1 Simulation-based impact analysis

The analysis of the simulation runs for baseline scenario and scenario 4 can be seen in Table 9. The results show that there is little impact from operating the shuttles on public roads. The average speeds of the different vehicle cohorts even increase slightly, but the changes are small. Also, there are very few conflict situations, with the shuttle adding only a fraction of conflicts per km. This is all in line with the results presented in D10.3.

Table 9: KPIs for the base line scenario and the scenario 4 with shuttles operating on three lines

KPI	without AV	with AV	Unit	Impact
Number of Agents				
cars	20093	20095	1	-
light trucks	703	703	1	-
trucks	988	988	1	-
busses	404	404	1	-
shuttle	-	3	1	-
Number of conflicts with other road users	0.594	0.597	1/km	+0.5%
Average vehicle speed of				
cars	7.34	7.35	m/s	+0.1%
light trucks	7.03	7.08	m/s	+0.7%
trucks	6.75	6.82	m/s	+1.0%

KPI	without AV	with AV	Unit	Impact
busses	4.45	4.46	m/s	+0.2%
shuttle	-	4.03	m/s	-
Average travel time delay of				
cars	40.4	39.5	s	-2.2%
light trucks	45.0	43.0	s	-4.4%
trucks	49.8	45.1	s	-9,4%
Total travel time in network of				
cars	141.3	140.4	s/km	-0.6%
light trucks	147.7	145.6	s/km	-1.4%
trucks	155.0	150.4	s/km	-3.0%
The share of each mode choice (in distance travelled)				
cars	97.5	97.3	%	-0,2%
public transport	2.5	2.7	%	+8,0%
Total number of kilometers travelled in the network, per mode of transport				
cars	36280	35843	km	-1.2%
public transport	941	993	km	+5.5%
Number of trips in the network, per mode				
cars	21784	21786	1	+0.0%
public transport	465	495	1	+6.5%
Avg travel time delay over the network	45.05	43.09	s/km	-4.5%
Average vehicle speed in the network	7.43	7.86	m/s	+5.8%
Avg. energy use per kilometer per vehicle	124	123	g/km	-0.8%
Emissions of a vehicle – CO_2	390	387	g/km	-0.8%
Emissions of a vehicle – CO	8.7	8.6	g/km	-1.1%
Emissions of a vehicle – NO_x	909	895	mg/km	-1.5%
Emissions of a vehicle – HC	114	112	mg/km	-1.8%
Emissions of a vehicle – PM_x	29	28	mg/km	-3.4%

3.5 Linköping

3.5.1 Enhanced simulation

The main special character at the Linköping test site is the shared corridor, where the AS and cyclists share the bike path that can additionally be freely crossed by pedestrians. In general, commercial or open source microscopic traffic simulation tools cannot yet fully account for shared space situations. This is mainly due to the limitation that each edge (road) in a simulation is designated to one direction and involved users only consider the movements of other road users on the same edge before approaching an intersection. In addition, complex interactions between road users occur in shared spaces.

To close the gap of road users not considering the movements of other road users in the opposite direction, the concept of bidirectional roads was proposed and implemented in SUMO version 1.15.0 as a part of the sublane road user simulation model. The concept and the usage of bidirectional edges were already explained and reported in D10.3. The respective modelling enhancements have been carried out further since then with the focus on overcoming unrealistic interactions, conflicts and waiting situations to better reflect the reality. While running on a bidirectional edge, swerving to the right is favoured, but it can also be done to the left. If swerving is not possible, the opponents will brake to avoid a collision. This awareness by road users in the opposite direction extends at least to a comfortable braking distance in the downstream direction and may include several successive edges and junctions along the route of the road user in question. If necessary, road users will prefer to overtake other road users from the right-hand side on bidirectional edges. A probability factor can be used to define the preference for overtaking on the right-hand side. In addition, it is possible to have multiple lanes on a bidirectional edge and the road users allowed on each lane can be further specified, e.g. bicycles and/or vehicles sharing a two-way lane and pedestrians walk on either side of the two-way lane. The development of the bidirectional-edge concept for road traffic is though still in the experimental phase. More data is needed for testing, improvement and validation to properly account for various interactions between road users. So far, the traffic data collected on the shuttle route, reported in D10.3, and from the test site was used to enhance the simulation results (see section 3.5.2). SUMO's sub-second simulation was used for simulating the road users' interactions more accurately. The respective enhancements on the Intelligent Driving Model (IDM) and the pedestrian model were carried out as well [1]. Such enhancement work on modelling has been continuously carried out.

In addition, the modelling concept of charging behaviour in SUMO was developed in order to be able to deal with charging issues in simulations. The necessary attributes for charging stations and electric vehicles, e.g. charging type, speed and capacities, were examined, adjusted and added. Several functional tests were executed and run together with SUMO's other functional tests daily. In addition to charging at predefined charging stations, an abstract simulation concept, shown in Figure 20, was proposed to consider situations where needs for charging can be fulfilled on the way to a given destination. Such a charging requirement may, for example, be related to the pre-defined charging threshold of an EV, the remaining distance to the specified destination that cannot be reached with the current state of charge (SoC), or/and the perception of the respective driver. The whole process is explained as follows: the state of charge (SoC) of each electric vehicle is monitored to check (1) the minimum SoC requirement of the vehicle and (2) the battery required to reach the respective destination, which is an estimate based on the shortest distance from the current position to the destination and a buffer factor to consider uncertain traffic situation. If case (1) is not met, the corresponding vehicle can remain on a road for a certain period, be removed from the network or be taken to the nearest charging station by a roadside assistance service, represented by additional user-specified penalty time. If a vehicle does not have enough power in its battery to reach its destination, i.e. in case (2), the action to search for a suitable charging station is activated. The search is performed in the direction towards the given destination, and a travel-time based search radius is used. The selection indices of the charging station alternatives are then calculated and decided according to the detour duration, the charging time and the number of charging piles at each charging station candidate. If the vehicle has no battery on the way to the appointed charging station, one of the options mentioned in case (1), will be selected. When the vehicle arrives at the appointed charging station, a check is made to see if a free charging pile is available. In this case, the vehicle will be charged until the wished SoC is reached, whereby the default setting is the SoC required to reach the destination. If all charging piles are occupied and the waiting time is greater than a predefined threshold time, the vehicle will give up and continue driving while simultaneously searching for the next suitable charging station. The respective prototype is already implemented and can be used with the SUMO version 1.20.0 onwards. Some feature tests are also available in the SUMO repository. During the demonstration phase, (re)-charging was not an issue at all pilot sites, mainly due to the limited service area at each site. Accordingly, no respective research questions need to be addressed with the use of simulation. This implementation is still important for addressing the energy issue of electric vehicles and can benefit other projects.

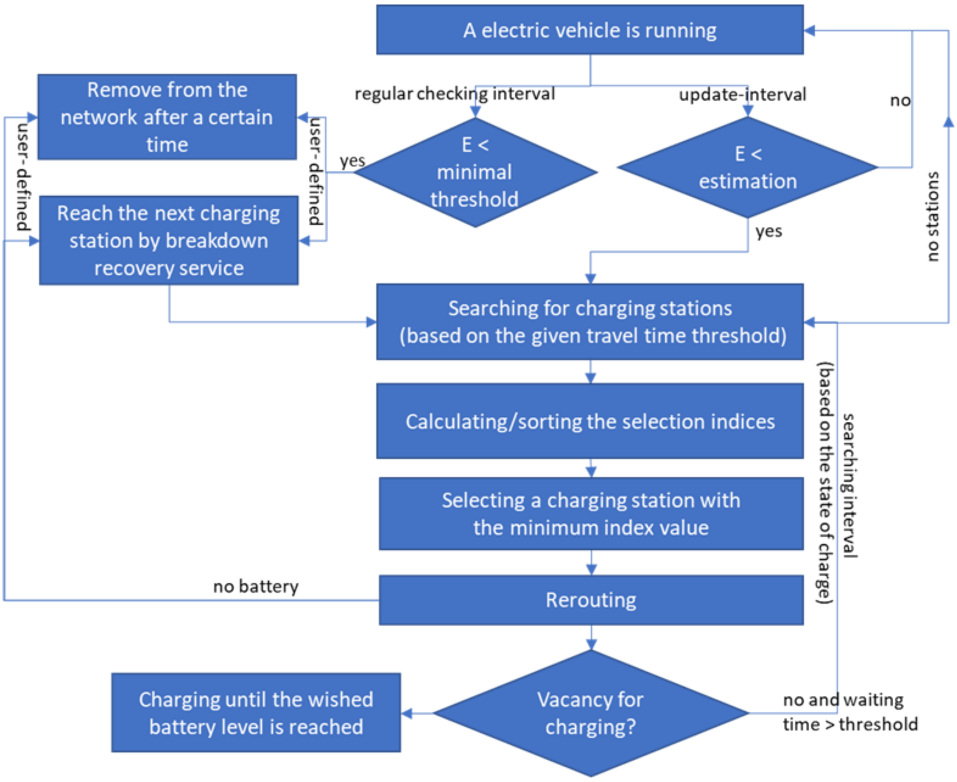


Figure 20: The sketch of the proposed concept to model charging activities on the way

3.5.2 Feedback of pilot site data

Following the technical and modelling extensions mentioned above and described in D10.2 and D10.3, the data collected at the test site was used to enhance the reproducibility of the simulation. The focus was on reproducing the site traffic situation in the simulation. Mean travel speed and its standard deviation were chosen as indicators to examine to what extent the respective measurements in the shared corridor can be reflected in the simulation after calibration. Considering the speed distribution, both the speed factor and the speed deviation were defined to be the main parameters for the calibration. The results in Table 10 show that the mean speed difference between the real and simulated data for the southbound bicycles is about 4% and the other mean speed differences are less than 1% when applying the following parameter values: speed deviation = 0.08 m/s and speed factor = 1.05 for AS, and speed deviation = 0.4 m/s and speed factor = 1.45 for bikes. The standard deviations of the simulated speeds were generally slightly higher than the real ones for both, AS and bikes, especially for the latter one. The introduction of additional cyclist types to represent the heterogeneity of cyclists could help to better reflect the measured standard deviation. However, more parameters need to be calibrated for additional cyclist types.

Table 10: Measured and simulated velocities in the shared corridor

Direction	Southbound				Northbound	
Road user	Cyclist		AS		Cyclist	
Data type	measured	simulated	measured	simulated	measured	simulated
Mean speed (m/s)	3.98	4.14	2.06	2.08	3.90	3.95
Standard deviation	0.88	0.98	0.55	0.68	0.78	1.09

Furthermore, the traffic data collected was also used to adjust the traffic density at the site. Across the whole network, there were 1296 vehicles, 353 pedestrians, 618 bicycles during the afternoon peak period. 517 vehicles, 434 bicycles, 228 pedestrians and 72 buses travelled on the shuttle route and on the adjacent roads. To reflect the movement flexibility of cyclists and pedestrians in the reality, they could adapt their routes on the way according to the traffic conditions they faced. The key traffic performance is summarised in Table 11. The average waiting counts and waiting time are the number of times and the time during which the speeds of the vehicles was below or equal to 0.1 m/s. The results show that the road users travelled within a reasonable speed range on the site under the maximum speed limit of 30 km/h. The AS travelled at an average speed of 9.5 km/h below the specified speed limit of 14 km/h, and had no significant negative influence on other road users. This is mainly due to the relatively low traffic density on the site and because about 50% of the AS route was in the space shared with free-moving bicycles, or on an exclusive bus lane. In addition, both the buses and the AS had longer waiting times. This is mainly because they waited for the green light at the signalised intersections, whilst most other vehicles entered and left from the other parts of the site, where the intersections were prioritised. According to the planned routes and the observation, the buses and the AS passed the signalised intersections twice and three times per run respectively, and the places where they often waited were at the intersections.

Table 11: The simulated traffic performance on the shuttle route with the introduction of AS at the Linköping site

Type	Average speed [km/h]	Average duration [min]	Average waiting time [sec]	Average waiting counts [#]	Average/planned route length [km]
Vehicle	22.8	6.5	11.7	1.4	0.8
Bicycle	9.7	5.1	8.6	1.6	0.8
Bus	14.1	6.2	57.4	2.4	1.4
AS	9.5	24.3	71.6	5.0	3.9

According to the reported driving speed data of AS, the general speed was around 7-8 km/h for the whole route. The difference between the simulated and real AS speeds should be due to unexpected obstacles and technical issues on the route, which is in line with the reports of the safety operators. Such unexpected issues can also influence other road users, and are difficult to address in the simulation due to their low probabilities compared to incident-free time.

3.5.3 Simulation-based impact analysis

In terms of the traffic system, the primary concern with the introduction of AS is the extent to which they would affect their surrounding traffic and environment. Currently, for safety reasons, AS have to operate at a lower speed than the regular road speed limit. Flexible scheduling should ensure efficient operation in the long term. At the same time, however, passenger demand must also be met. Accordingly, the focus was put on speed and operation frequency to further analyse the influences on the traffic system performance. In addition to the base scenario without AS (Scenario 0), six scenarios were developed as listed and explained in Table 12.

Table 12: Overview of the scenarios at the Linköping site

Scenario	Content
Scenario 0 (base)	The current traffic situation without AS as the baseline scenario
Scenario 1	It is based on Scenario 0 with 2 AS, running every 10 minutes at a maximum speed of 15 km/h, and serving at the pre-defined stops.
Scenario 2 (current)	It is based on Scenario 0 with 2 AS, running every 20 minutes at a maximum speed 15 km/h, and serving at the pre-defined stops.
Scenario 3	As Scenario 2, but only 50% of the stops were served.
Scenario 4	As Scenario 2, but the maximum travelling speed was increased to 30 km/h, i.e. the speed limit in this area, and the AS run every 10 minutes.
Scenario 5	As Scenario 4, but the AS run every 20 minutes.
Scenario 6	As Scenario 5, but only 50% of the stops were served.

Figure 21 clearly shows that the AS speed increased when the number of served stops was reduced, and that the higher speed limit significantly contributes to the higher AS speed, as expected. For the other users, there were no apparent speed differences between the scenarios. When further examining the speed difference for other users, Figure 22 shows that the AS, running at a lower speed and higher operation frequency (scenario 1), have a relatively greater impact (around 5%) on the average speed of the vehicles, some of which left the parking lots and some of which entered, left or traveled through the campus. When the operation frequency of AS increased (scenario 2) or the number of served stops decreased (scenario 3), the respective impact declined. With the speed limit of 30 km/h, the AS had very little influence on other users' travelling speeds. Overall, the speed changes for other road users are quite small, within 5%. This limited impact is mainly due to the lower traffic density in the case study area, and part of the AS route was located in the shared space and on the bus-only lane.

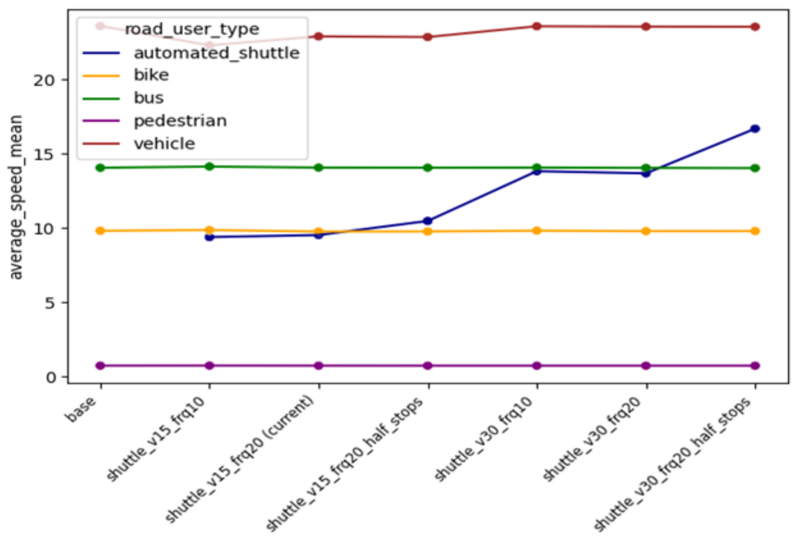


Figure 21: Comparison of the average speeds (km/h) between the scenarios at the Linköping site

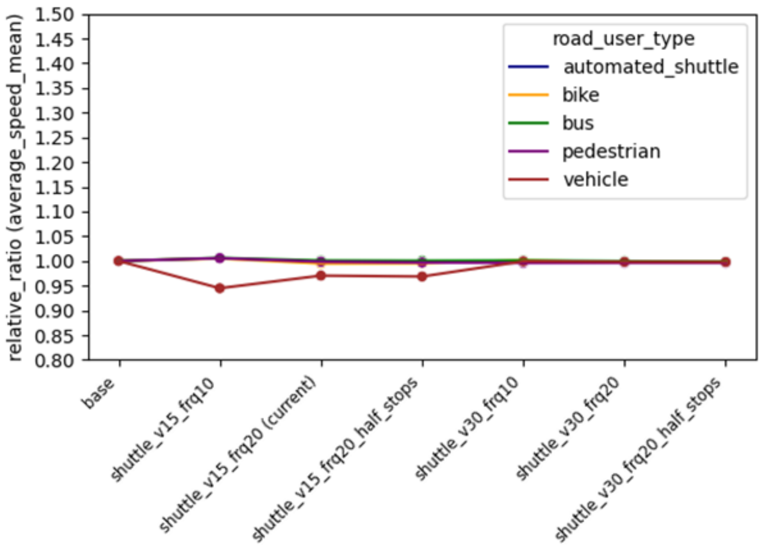


Figure 22: Comparison of the relative ratios of the average speeds between the scenarios at the Linköping site

Moreover, Figure 23 shows the relative ratios of the travel times between the scenarios. The situations for other road users generally correspond to those based on the average travel speeds mentioned above. The changes in travel times for the majority of scenarios are below 1% - except for scenario 1. When the AS operated at a low speed, but from every 20 min to every 10 min, the average travel durations of the bikes and pedestrians declined. This could be because some of them adapted their routes, which made the respective route lengths shorter. Due to the network structure, the route adaptation of the vehicles was limited. This increased the corresponding travel time under the situation where more AS were travelling at a low speed. An overview of the traffic performance in each scenario is indicated in Table 13. It can be seen that the difference in the traffic performance between the scenarios is limited. The average waiting time of the AS in the scenario 5 is higher than the others. As mentioned before, waiting times mainly occurred at the intersections. Due to the different operation frequency, scenarios 1 and 4 had more AS than the others. In addition, the AS in the scenarios 4-6 travelled faster than those in the other scenarios.

These differences affected the arrival times of the AS at the intersections, the traffic situation at/within the intersections they faced and the average values of the traffic performance, especially the waiting times at the intersections.

Vehicle emissions depend heavily on vehicle age, engine performance, type of energy consumption and traffic situation. Due to the lack of corresponding real-world data at the site, all vehicles except AS were assumed to be vehicles that use petroleum-based fuels, and the default emission setting in SUMO was used for the purpose of scenarios comparison. Under these circumstances, Table 14 provides an overview of the simulated emissions in each scenario. In total, the changes in emissions between the scenarios are very limited. Since most of the changes occur below the third decimal place of the emission values, most of the numbers are the same after rounding. It should be noted that the busses in Linköping use either biogas or electricity, where the former one is not completely emission-free, but still CO_2-neutral.

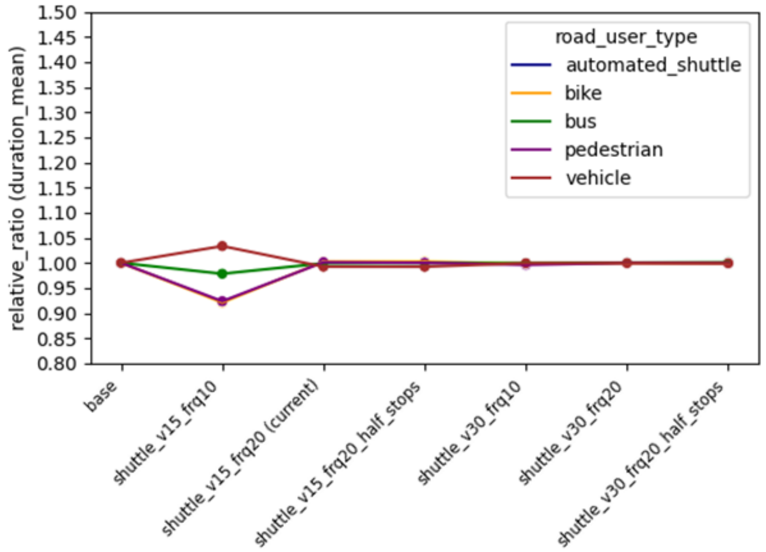


Figure 23: Comparison of the relative ratios of the travel times between the scenarios at the Linköping site

Table 13: The simulated traffic performance on the shuttle route with the introduction of AS at the Linköping site

Scenario	Road user	Average speed [km/h]	Average duration [min]	Average waiting time [sec]	Average waiting counts [#]
Scenario 0 (base)	Vehicle	23.5	6.5	9.4	1.1
	Bicycle	9.8	5.1	7.9	1.5
	Bus	14.1	6.2	57.0	2.3
	AS	-	-	-	-
Scenario 1	Vehicle	22.2	6.7	13.5	1.4
	Bicycle	9.8	4.7	7.4	1.6
	Bus	14.1	6.1	56.6	2.5
	AS	9.3	24.6	94.0	5.0

Scenario	Road user	Average speed [km/h]	Average duration [min]	Average waiting time [sec]	Average waiting counts [#]
Scenario 2 (current)	Vehicle	22.8	6.6	11.7	1.4
	Bicycle	9.7	5.1	8.6	1.6
	Bus	14.1	6.2	57.4	2.4
	AS	9.5	24.3	71.6	5.0
Scenario 3	Vehicle	22.8	6.5	11.7	1.4
	Bicycle	9.7	5.1	8.6	1.6
	Bus	14.1	6.2	57.4	2.4
	AS	10.4	22.1	87.7	3.7
Scenario 4	Vehicle	23.5	6.5	9.4	1.1
	Bicycle	9.8	5.0	7.8	1.6
	Bus	14.1	6.2	56.9	2.4
	AS	13.8	16.8	89.3	4.0
Scenario 5	Vehicle	23.5	6.5	9.5	1.2
	Bicycle	9.8	5.1	7.9	1.5
	Bus	14.0	6.2	57.3	2.4
	AS	23.5	16.9	97.8	4.0
Scenario 6	Vehicle	23.5	6.5	9.5	1.2
	Bicycle	9.8	5.0	7.8	1.5
	Bus	14.0	6.2	57.7	2.4
	AS	16.6	13.9	50.9	2.3

Table 14: The simulated emissions on the shuttle route with the introduction of AS at the Linköping site

Scenario [emission unit: g/km]	0 (base)	1	2 (current)	3	4	5	6
Average CO_2 per vehicle	1066.6	1068.4	1067.3	1067.3	1067.1	1067.2	1067.9
Average CO per vehicle	7.9	8.0	7.9	7.9	7.9	7.9	7.9
Average NO_x per vehicle	8.2	8.2	8.2	8.2	8.2	8.2	8.2
Average HC per vehicle	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Average PM_x per vehicle	0.2	0.2	0.2	0.2	0.2	0.2	0.2

3.6 Madrid

The NTUA simulations within WP10 are conducted for two different pilot sites in Madrid, Spain. The first site is in Villaverde, including a circular automated transit service route within an urban environment. The second site is in Carabanchel, comprising a parking area in the form of a bus terminal for Madrid public buses operated by Empresa Municipal de Transportes de Madrid (EMT Madrid). The microsimulation scenarios aim to investigate and support critical aspects for the operation of the Madrid sites (both Villaverde and Carabanchel). In Section 3.6.1, attention is placed on the Villaverde pilot, where microsimulation results are presented from the Madrid urban environment, focusing on the circular automated transit service route and its impacts on local transportation indicators. Following this analysis, in Section 3.6.2, the results for the Carabanchel pilot are unfolded, revealing insights regarding its microsimulation scenarios, including the dynamics of the parking area and the efficiency of the bus terminal.

Within the following sections (3.6.1 and 3.6.2), various microsimulation scenarios and cases are being showcased for both sites. This subsection follows up on the previous three related deliverables (D10.1, D10.2, D10.3), which serve as the foundation for this document. In this deliverable, efforts have been made to estimate and present Madrid simulation data for both sites consistently, addressing the Key Performance Indicators (KPIs) required by SHOW WP13. Additionally, real data from the conducted naturalistic driving within pilots in the microsimulation for Villaverde have been incorporated.

3.6.1 Villaverde site

3.6.1.1 Enhancement of simulations

As simulations for Villaverde were recently initiated, two months prior to the present deliverable, adjustments were necessary in order to incorporate naturalistic condition data (related efforts are further developed in Section 3.6.1.2 “Feedback of data from pilot site operation”). Since the previous deliverable D10.3, recent efforts have focused on simulating the new route within the Villaverde network. This direction was a necessity as the originally planned AV operation covered a longer route than the actual real-world one. The simulations had followed the original planned longer route. Consequently, simulations had to be adjusted to the new route to match the shorter actual distance rather than the previously simulated longer route.

Additionally, efforts focused on integrating naturalistic, field pilot data into the simulation model for this site as well as adding an extra SHOW vehicle; a shuttle bus operating to the already existing shuttle bus route. In the previous simulation efforts, only one shuttle bus was operating, while in the current deliverable two shuttles are considered, mirroring the real pilot site of Madrid. Furthermore, significant attention was given to estimating KPIs and ensuring alignment in units, aggregation level, and level of detail, as required for WP13, for both Villaverde and the other site in Madrid, Carabanchel. An overview of the Villaverde network is provided below to showcase simulated use cases and to align with the pilot sites. For more detailed information about the network and the incorporated traffic data in the simulation network and model, readers can refer to the previous deliverables D10.2 & D10.3, as developed in those documents.

The key aim of utilizing field pilot data for automated vehicles was to derive results as realistic as possible and to provide further insights that cannot be measured under real conditions through microscopic simulation (e.g., delay time, emissions, conflicts, etc.). These findings are also valuable for the operations of the pilot sites. The steps taken to integrate realistic data into the Villaverde site simulation are outlined below.

The Villaverde network is depicted in Figure 24. The network comprises the detailed network features and parameters previously described and available in D10.2 & D10.3. These details are not reiterated here to avoid repetition, as they represent simulation efforts from the previous period. Specifically, one automated shuttle bus service (utilizing two different SHOW AV shuttles) has been integrated into the study network of the "Aimsun Next" software. This service has been modelled to operate concurrently with existing public transportation. The two SHOW automated shuttle buses, namely the Irizar 12-meter bus and the Gulliver mini-bus (both can reach SAE level 4), run at fixed 10-minute intervals, resulting in six departures every hour. The newly-simulated circular route covers a distance of 0.8 km and includes five bus stops along its path, as illustrated in Figure 25.

Figure 24: Villaverde Network in Aimsun Software

The study network includes a subpart of the Villaverde district in Madrid, Spain. Utilizing Aimsun Next simulation software, the network comprises 365 nodes and 668 road segments, covering a total road length of 23 km and an area of approximately 2 km^2 (see Figure 24). This simulation also incorporates the parallel-running 23 bus lines and 39 public transport stops, along with their respective frequencies and waiting times, sourced from bus operator websites.

Road geometry was sourced from the OpenStreetMap platform and validated against additional maps. Various characteristics, including length, width, number of lanes, directions, free flow speed and capacity were considered for each road segment. Similarly, node characteristics such as allowed movements, lane count per movement, priority, traffic light control plans, free flow speed and capacity were integrated into the model.

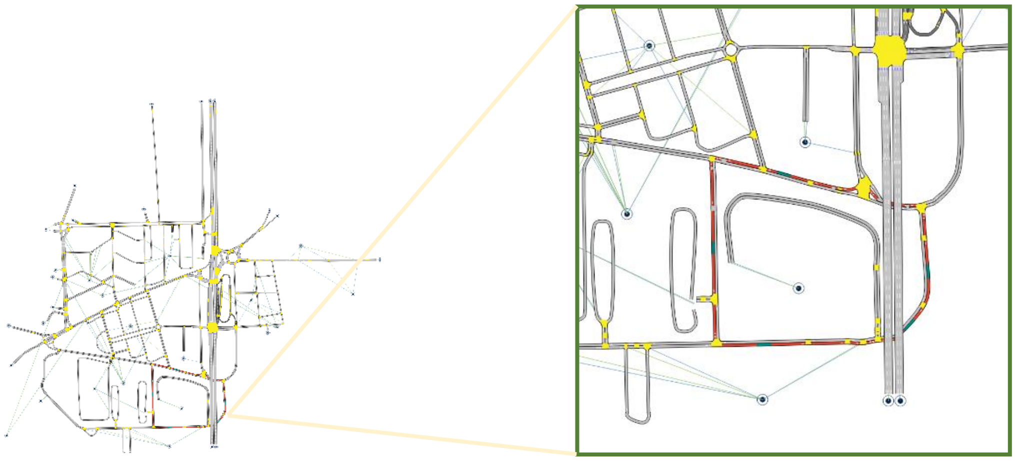


Figure 25: Villaverde network in Aimsun Software with OD centroids (left) and circular route of SHOW automated shuttles, highlighted in red (right).

In addition, the microscopic model included volume data that were collected for the year 2018 from about 80 detectors, as presented in Figure 25. The necessary traffic data as well as AD shuttle bus features were provided by EMT Madrid (Empresa Municipal de Transportes de Madrid - www.emtmadrid.es) which is responsible for planning public urban transport in the city of Madrid, Spain. The detectors recorded traffic volume in vehicles per time. Those data were used to create the travel demand. More specifically, a scenario was simulated and created the routes that will be followed and the respective OD matrices were extracted. The OD matrices encompassed 30 centroids distributed across the study network, with a peak-hour travel demand of 5,784 car trips and 716 truck trips. The network calibration was performed based on real traffic data, ensuring accuracy and reliability.

3.6.1.2 Feedback of data from pilot site operation

The process included the integration of realistic data into the simulation model for the Villaverde site, along with adding an extra SHOW shuttle to the new shorter route. To utilize realistic data for automated shuttle operations, trajectory files were employed to simulate the speed profiles of the two shuttles. Since the Villaverde operation was recently initiated, trajectory files were unavailable, and data from the Carabanchel site in Madrid were utilized (further details on simulating the Carabanchel site are provided in section 3.6.2).

Trajectory data for the three SHOW automated vehicles (Gulliver, Irizar, and Twizy) within the Carabanchel parking depot were provided by TECNALIA & EMT. These trajectory files, recorded every 250 ms, encompassed driving measurements. A sample realistic speed profile from Gulliver, Irizar, and Twizy operations is shown in Figure 31. The objective was to replicate speed profiles by assigning speed limits for each AD vehicle (Gulliver and Irizar which are operating in Villaverde site) in each section of the simulation network, based on the provided field data, to achieve the most realistic results possible (the reader can refer to Figure 30 for the Carabanchel case).

Using the vehicle trajectories, the naturalistic speeds of each vehicle, as well as their X and Y coordinates, were utilized to estimate the maximum speed for each section per vehicle. Furthermore, a general rule was observed from the trajectory data: in curved (turning) segments, 12 km/h and 8 km/h were the upper speed limits for Irizar and Gulliver, respectively, while in straight segments, 15 km/h and 16 km/h were considered realistic speed limits for Irizar and Gulliver, respectively, based on real-world operations.

Three scenarios were considered in the simulations, incorporating field data from the pilot operations. Each of the two AD vehicle operations (Gulliver and Irizar) was represented by two scenarios, alongside a baseline scenario reflecting the existing network without Gulliver and Irizar operations. The simulation duration for all scenarios was 1 hour (peak hour), with a departure frequency of 10 minutes. Therefore, six routes/circle rounds were completed by Gulliver, Irizar during this timeframe.

3.6.1.3 Simulation-based impact analysis

In this subsection, all the possible KPIs from the Madrid site required by WP13 are presented in the following plots and an overview table. Following this presentation, the impacts produced by the SHOW AVs are discussed. Comparative plots were created based on extracted values from the simulation to compare the impacts of different vehicles. Specifically, these KPIs measure the impact on the network level, or within specific vehicle type groups, plots were generated. Insights relating to vehicle-level were provided in the previous deliverables (D10.2 and D10.3).

The analysis of the Villaverde pilot site in Madrid reveals insights into the performance of AV operations, with a particular focus on the Irizar and Gulliver scenarios, as presented in Figure 26. Notably, there are marginal changes in average vehicle speed across different vehicle types. In the Irizar scenario, while the speed of trucks exhibits a negligible increase of 0%, cars and buses experience a marginal decrease of 0.99%. This finding suggests that the presence of slower-moving AVs, compared to conventional traffic, may be contributing to the slight reduction in bus and car speeds. These changes, although marginal, are notable, especially considering the low average speeds during peak hours, similar to AV operations, and could create indirect road safety benefits in real-world operations that stakeholders might wish to consider.

Conversely, in the Gulliver scenario, trucks and cars demonstrate a slight increase in speed by 0.76% and 1.20%, respectively, contrasting with the trend observed in the Irizar scenario. Moreover, the assessment of travel time delay per vehicle type reveals a proportional relationship with variations in average speeds. These findings underscore the performance differences between the Irizar and Gulliver scenarios in terms of average vehicle speed and travel time delay across various vehicle types.

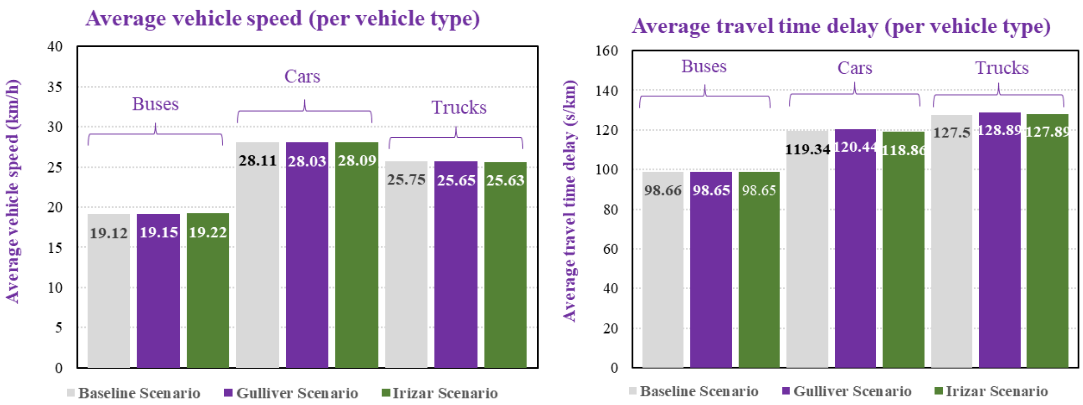


Figure 26: Comparative plots for the investigated traffic-related impacts at a network level.

Figure 27 illustrates an increase in the number of conflicts with other road users per kilometre travelled across various scenarios. While there is a modest rise of 3.81% with the Irizar, the Gulliver scenario experiences a slightly higher increase of 4.24%. Additionally, conflicts involving the SHOW vehicles appear to counter the speed trend. The Irizar, being a 12-meter bus, and the Gulliver being a minibus, operate slower than the rest of the traffic, which can contribute to the slight increase in conflicts, which are occurrences frequently created by speed differences. Moreover, the addition of 5 stops forces the following vehicles to brake more often, further contributing to conflict generation. The impact can be analysed in more detail microscopically, focusing on individual vehicles through road safety assessment, as will be the aim of WP13.

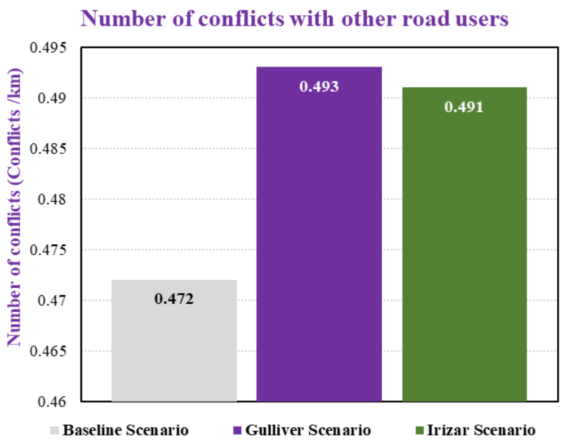


Figure 27: Comparative plots for the investigated road safety-related impacts at a network level.

Figure 28, which has been plotted based on provided emissions data, indicates marginal fluctuations in CO_2, NOx, and PM emissions per kilometer travelled across different vehicle scenarios. While there are no significant changes in CO_2 emissions, with variations ranging from 0% to +0.18%, the changes in NOx emissions show slight changes ranging from -0.19% to +0.19%. Similarly, PM emissions remain unchanged across all scenarios. These minimal variations suggest limited impact on emissions, as the network spans a wider area covering a total road length of 23 km compared to the route of SHOW shuttles 0.8 km, which may have less influence on general traffic emissions. However, overall, the emissions profile remains relatively stable, indicating consistent environmental performance across the different vehicle scenarios.

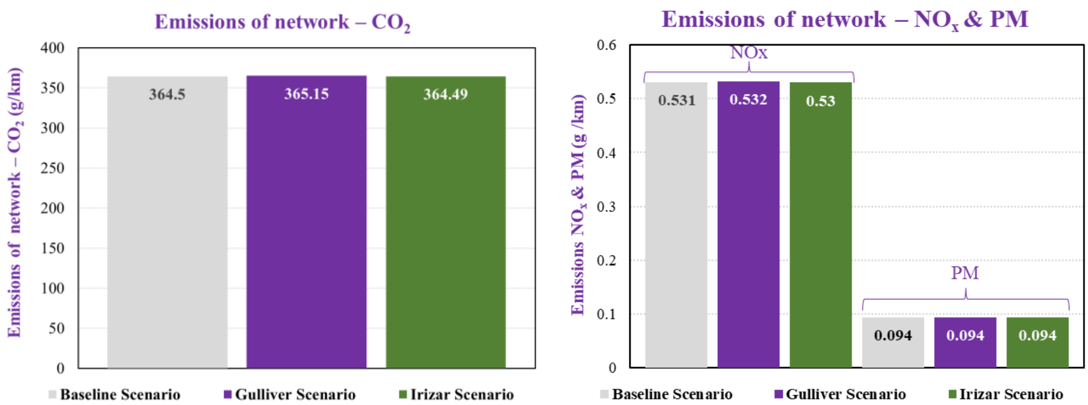


Figure 28: Comparative plots for the investigated environmental-related impacts at a network level.

Table 15 presents the impact analysis related to KPIs simulated for the Villaverde pilot site in Madrid, considering two scenarios: Irizar and Gulliver shuttles. Several noteworthy trends emerge from the data. Firstly, there is an increase in the number of conflicts with other road users across all vehicle types, with Irizar and Gulliver experiencing rises of 3.81% and 4.24%, respectively, per kilometre travelled.

Secondly, in both the Irizar and Gulliver scenarios, similar trends are evident across various vehicle types. Notably, there is a pattern of marginal changes in average vehicle speed, with buses experiencing slight increases while cars and trucks undergo minor decreases. This consistency in trends between the two scenarios suggests a shared impact on vehicle operations, potentially influenced by the leading slower-moving AVs – compared to following conventional traffic – which may be negatively impacting speeds. This effect can be translated as a decrease in speed or proportional increase in travel time delay in both scenarios.

Thirdly, the numbers of stops are constant across all scenarios. Moreover, there is a slight increase in the total vehicle delays in intersections with Irizar to have greater delays. Moreover, the share of each mode choice and the total number of kilometres travelled in the network remain relatively stable across different scenarios. The stability of mode choice share and total kilometres travelled by buses, cars and trucks in the network can be attributed to the consistent experimental parameters utilized in the simulation across various scenarios. Environmental impacts, as measured by CO_2, NOx, and PM emissions, show minimal changes across all vehicle types in both scenarios, as discussed above.

Lastly, the calculation of expected safety enhancement is pending as a WP13 activity, and dependent on the utilization of SSAM files to be provided to NTUA. These forthcoming calculations will further refine our understanding of safety implications associated with the deployment of automated vehicles in the Villaverde pilot site under both Irizar and Gulliver scenarios.

Table 15: Impact analysis related KPIs simulated for the Villaverde pilot site

KPI	Baseline	Irizar	Change	Gulliver	Change	Units
Number of conflicts with other road users	0.472	0.491	+3.81%	0.493	+4.24%	Conflicts /km
Average vehicle speed (per vehicle type) - *Buses*	19.12	19.22	0.52%	19.15	0.16%	km/h
Average vehicle speed (per vehicle type) - *Cars*	28.11	28.09	-0.07%	28.03	-0.28%	km/h
Average vehicle speed (per vehicle type) - *Trucks*	25.75	25.63	-0.47%	25.65	-0.39%	km/h
Average travel time delay (per vehicle type) - *Buses*	98.66	96.99	-1.69%	98.65	-0.01%	s/km
Average travel time delay (per vehicle type) - *Cars*	119.34	118.86	-0.40%	120.44	+0.92%	s/km
Average travel time delay (per vehicle type) - *Trucks*	127.5	127.89	+0.31%	128.89	+1.09%	s/km
Number of vehicle stops per vehicle for all vehicle types	0.05	0.05	0%	0.05	0%	Stops /vehicle /km
Total vehicle delays in an intersection	11487.7	11828.2	+2.96%	11509.2	+0.18%	s
Total travel time in network per vehicle type	119.66	119.18	-0.40%	120.68	+0.84%	s/km
The share of each mode choice (in number of trips or distance	3.05%	3.04%	-0.01%	3.05%	0%	%

KPI	Baseline	Irizar	Change	Gulliver	Change	Units
travelled) – *Buses (Distance travelled by Buses/ Total distance by all means)*						
The share of each mode choice (in number of trips or distance travelled) – *Cars (Distance travelled by Cars/ Total distance by all means)*	90.29%	90.19%	-0.10%	90.20%	-0.09%	%
The share of each mode choice (in number of trips or distance travelled) – *Trucks (Distance travelled by Trucks/ Total distance by all means)*	6.66%	6.66%	0%	6.65%	-0.01%	%
Total number of kilometres travelled in a network, per mode of transport and/or trip purpose – *Buses (Distance travelled by Buses/ Total distance by all means)*	3.05%	3.04%	-0.01%	3.05%	0%	%
Total number of kilometres travelled in a network, per mode of transport and/or trip purpose – *Cars (Distance travelled by Cars/ Total distance by all means)*	90.29%	90.19%	-0.10%	90.20%	-0.09%	%
Total number of kilometres travelled in a network, per mode of transport and/or trip purpose – *Trucks (Distance travelled by Trucks/ Total distance by all means)*	6.66%	6.66%	0%	6.65%	-0.01%	%
Average travel time delay over the entire network – *Delay time over the network*	119.66	119.18	-0.40%	120.68	+0.84%	s/km
Average vehicle speed in a network	27.69	27.64	-0.18%	27.59	-0.36%	km/h
Number of trips in the network, per mode and/or trip purpose	130 & 5,784 & 716	130 & 5,784 & 716	0%	130 & 5,784 & 716	0%	Buses Cars Trucks trips
Emissions of a vehicle – CO_2	364.50	364.49	0%	365.15	+0.18%	g/km
Emissions of a vehicle – NO_x	0.531	0.530	-0.19%	0.532	+0.19%	g/km
Emissions of a vehicle – PM	0.094	0.094	0%	0.094	0%	g/km

3.6.2 Carabanchel site

3.6.2.1 Enhancement of simulations

As the simulations for Carabanchel were at an advanced stage, incorporating naturalistic condition data from the previous deliverable 10.3, recent efforts have concentrated on estimating KPIs and ensuring alignment in units, aggregation level, and level of detail, as required for WP13. Below is an overview of the Carabanchel network provided to highlight the simulated use cases and to align with the rest of the demonstration sites. For more detailed information, the reader can refer to the previous deliverable 10.3.

The key aim of utilizing field pilot data for automated vehicles was to derive results as realistic as possible and to provide insights through microscopic simulation (e.g., delay time, emissions, conflicts, etc.) that cannot be measured under real conditions. These findings are also valuable for the operations of the pilot sites. The steps taken to integrate realistic data into the Carabanchel site simulation are outlined below.

As a first step, a description of the network characteristics is provided. The Carabanchel site, located in the city of Madrid, Spain, was designed using the "Aimsun Next" mobility software. The simulated network, depicted in Figure 29 (left), comprises 30 nodes and 40 sections. The model accounts for prevailing movements, with vehicle origin-destination (OD) matrices consisting of 11×11 centroids, encompassing a total of 34 cars and 126 buses during the morning peak hour. Additionally, the pedestrian OD matrix includes 6 entrances and 7 exits, accommodating a total of 211 pedestrians during the morning peak hour. The circular route with bus stops is showcased in Figure 29 (right). Parking lots are simulated as centroids, as the parking maneuver is not feasible within the simulation software. Consequently, the effect on the network remains consistent due to network calibration. The Carabanchel model was simulated for a single morning hour, incorporating prevailing traffic conditions (vehicle and pedestrian flows) provided by TEC & EMT, which also supplied relevant data to create the OD matrix for buses, cars, and pedestrians.

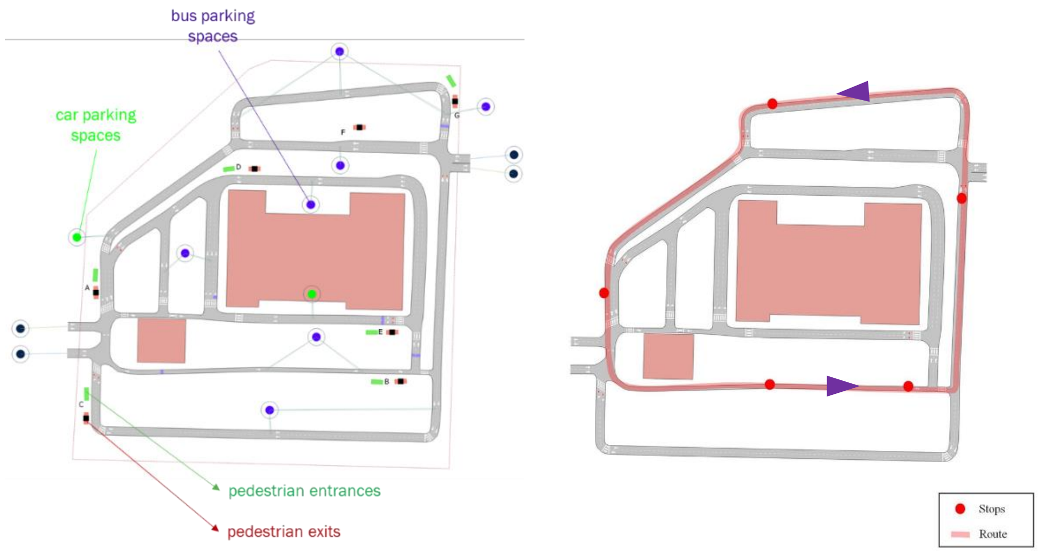


Figure 29: Carabanchel network in Aimsun Software (left) and circular route with bus stops (right).

3.6.2.2 Feedback of data from pilot site operation

After the initiation of the pre-demonstration phase, where SHOW vehicles were tested on-site, TECNALIA & EMT provided trajectory data extracted from all three SHOW automated vehicles (Gulliver, Irizar, and Twizy) operations, with the goal of integrating naturalistic data into the simulation model. This real data was incorporated into the simulation as follows: The autonomous driving (AD) vehicles route encompassed 19 different sections in the Aimsun model. The objective was to replicate speed profiles by assigning a speed limit for each AD vehicle (Gulliver, Irizar, and Twizy) in each of the 19 sections, based on the provided field data, to achieve the most realistic results possible (Figure 30).

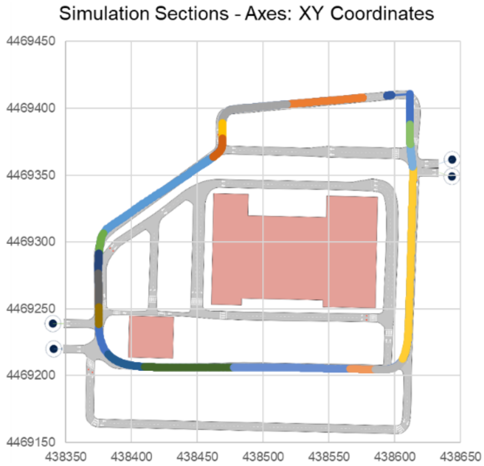


Figure 30: Simulation Sections used for replicating speed profiles.

Using the vehicle trajectories, the actual speeds of each vehicle (Gulliver, Irizar, and Twizy), as well as their respective X and Y coordinates, were utilized to estimate the maximum speed for each section per vehicle. Furthermore, from the trajectory data, bus stops were identified and placed in the simulation model, along with an average waiting time of 14 seconds. The bus stops and route can be observed in Figure 29 (right). However, Twizy, a lightweight passenger vehicle, completes the entire circuit without stopping. The parameters of each vehicle is provided in Table 16.

Table 16: Vehicle Parameters for Simulation.

SHOW Vehicle	Dimensions (Length x Width)	Total Capacity	Seating Capacity	Maximum Desired Speed	Maximum Acceleration (m/s^2)	Maximum Deceleration (m/s^2)	Weight (kg)
Irizar	12m x 2.55m	60	25	60 km/h	1.36	10	15,845
Twizy	2.4m x 1.4m	1	1	80 km/h	1	1	480 (+~120)
Gulliver	5.32m x 2.116m	25	7	32 km/h	2	6	3,000

Four scenarios were considered in the simulations, incorporating field data from the pilot operations. Each of the three AD vehicles operations (Gulliver, Irizar, and Twizy) was represented by three scenarios, alongside a baseline scenario reflecting the existing network without Gulliver, Irizar, and Twizy operations. The simulation duration for all scenarios was 1 hour (morning peak hour), with only one route/round completed by Gulliver, Irizar, and Twizy during this timeframe.

TECNALIA & EMT provided trajectory data from the three SHOW automated vehicles (Gulliver, Irizar, and Twizy) within the parking depot. The trajectory file included measurements taken every 250 ms, encompassing driving measurements. An example of a realistic speed profile from Gulliver, Irizar, and Twizy operations is presented in Figure 31.

Figure 31: Example of realistic speed profile from Gulliver, Irizar and Twizy operations.

3.6.2.3 *Simulation-based impact analysis*

In this subsection, all the possible Key Performance Indicators (KPIs) required by WP13 are presented in the following plots and an overview table. Following this, the impacts produced by the SHOW AVs are discussed. Following the same logic as the results of the Villaverde site, comparative plots were created based on the extracted values from the simulation to compare the impacts of different vehicles. Specifically, the KPIs assess the impact on the network level, or within specific vehicle type groups, plots were generated. Insights relating to vehicle-level and pedestrian metrics were provided in the previous deliverable (D10.3).

The insights provided in Figure 32 reveal trends regarding average vehicle speed and travel time delay for buses and cars. For buses in the Carabanchel network, there is a gradual decrease in average vehicle speed across the different scenarios, ranging from a 0.48% reduction to a more significant decrease of 0.94%. This suggests that the slower-moving AVs (compared to conventional traffic) ahead may be negatively impacting bus speeds. Correspondingly, there is a notable increase in average travel time delay for buses, with percentages ranging from 4.97% to 12.26%. These findings indicate that the slight reduction in speed results in buses experiencing more delays.

Similarly, results are presented for cars, as they are the other included vehicle type in the network. Specifically, there is a consistent decline in average vehicle speed across the different scenarios, with reductions ranging from 0.21% to 1.34%. This decline suggests that factors affecting vehicle speed are consistent across both buses and cars. Similarly with buses, there is a notable increase in average travel time delay for cars, with percentages ranging from 2.77% to a 23.62%.

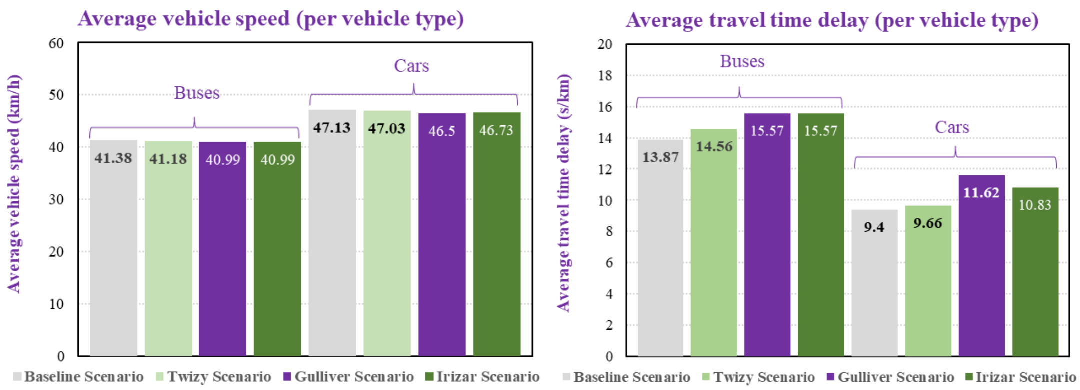


Figure 32: Comparative plots for the investigated traffic-related impacts at a network level.

Figure 33 illustrates a rise in the number of conflicts with other road users per kilometre travelled across various scenarios. While the Twizy exhibits a modest increase of 2.23%, the Irizar and Gulliver experience more significant spikes of 18.99% and 21.86%, respectively. Additionally, conflicts involving the SHOW vehicles seem to counter the speed trend (with the Twizy, as a light passenger car, operating without stops and operating faster than the Gulliver, a minibus, and the Irizar, a 12-meter bus, adapting more readily to overall traffic). This may be attributed to vehicles operating at higher speeds resulting in shorter trip durations and fewer interactions with other vehicles within the bus depot.

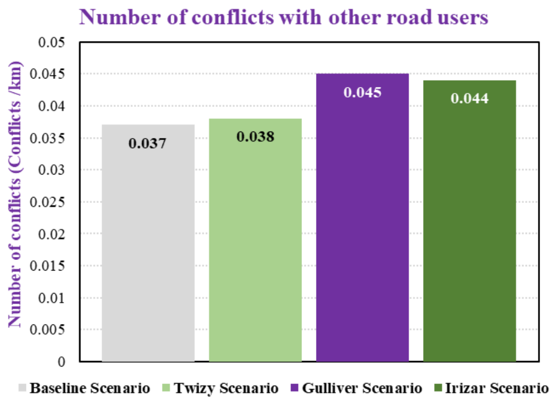


Figure 33: Comparative plots for the investigated road safety-related impacts at a network level.

Figure 34 presents a plot based on emissions data provided indicates marginal fluctuations in CO_2, NO_x, and PM emissions per kilometer traveled across different vehicle scenarios. While there are slight reductions in CO_2 emissions ranging from -0.16% to -0.68%, indicating potential improvements in carbon footprint, the changes in NOx and PM emissions are also minimal, with reductions ranging from -0.30% to -0.84%. These modest reductions could be attributed to the decrease in speeds within the depot caused by slowly moving AVs. The slight reduction in PM emissions can be caused possibly by the slower speeds that AVs impose on traffic, which may reduce tire and brake wear due to less aggressive driving. Additionally, slower vehicle speeds can lead to reduced resuspension of road dust, further contributing to lower PM emissions.

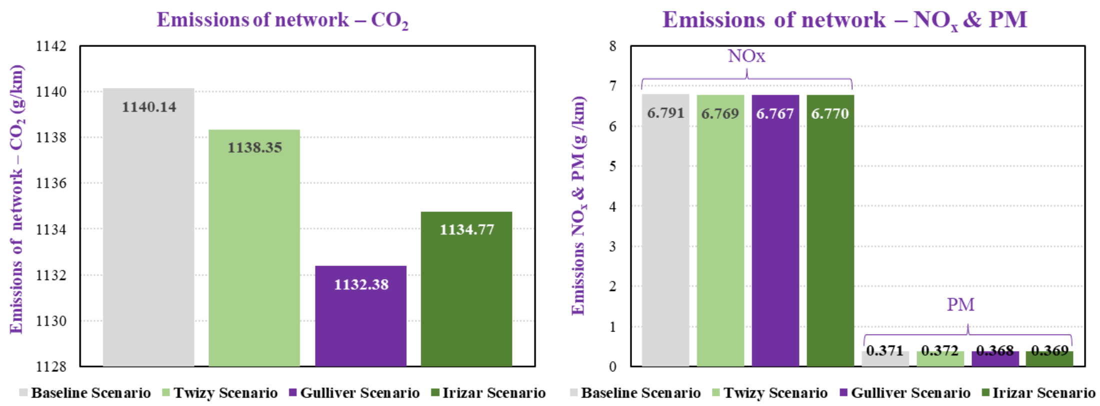


Figure 34: Comparative plots for the investigated environmental-related impacts at a network level.

Table 17 presents the impact related KPIs that are simulated for the Carabanchel pilot site in Madrid.

Table 17: Impact analysis related KPIs simulated for the Carabanchel pilot site

KPI	Base	Twizy	Δ	Irizar	Δ	Gulliver	Δ	Units
Number of conflicts with other road users	0.037	0.038	+2.23	0.044	+18.9%	0.045	+21.8%	Conflict /km
Average vehicle speed (per vehicle type) - *Buses*	41.38	41.18	-0.48%	40.99	-0.94%	40.99	-0.94%	km/h
Average vehicle speed (per vehicle type) - *Cars*	47.13	47.03	-0.21%	46.73	-0.85%	46.50	-1.3%	km/h
Average travel time delay (per vehicle type) - *Buses*	13.87	14.56	+4.97%	15.57	+12.3%	15.57	+12.2%	s/km
Average travel time delay (per vehicle type) - *Cars*	9.40	9.66	+2.77%	10.83	+15.2%	11.62	+23.6%	s/km
Number of vehicle stops per vehicle for all vehicle types	0.04	0.04	0%	0.05	+25%	0.04	0%	Stops /vehicle /km
Total travel time in network per vehicle type	85.83	87.83	+2.33%	89.72	+4.53%	90.30	+ 5.2%	s/km
The share of each mode choice (in number of trips or distance travelled) – *Buses (Distance travelled by Buses/ Total distance by all means)*	71.73%	71.15	-0.80%	71.12%	-0.85%	71.16%	-0.79%	%

KPI	Base	Twizy	Δ	Irizar	Δ	Gulliver	Δ	Units
Total number of kilometres travelled in a network, per mode of transport and/or trip purpose – *Buses (Distance travelled by Buses/ Total distance by all means)*	71.73%	71.15	-0.80%	71.12%	-0.85%	71.16%	-0.79%	%
Total number of kilometres travelled in a network, per mode of transport and/or trip purpose – *Cars (Distance travelled by Cars/ Total distance by all means)*	28.27%	28.85	+2.05	28.88%	+2.23%	28.84%	+2.01%	%
Average travel time delay over the entire network – *Delay time over the network*	12.87	13.84	+7.54	14.64	+13.7%	14.61	+13.5%	s/km
Average vehicle speed in a network	42.67	42.3 0	-0.87%	42.06	-1.43%	42.00	-1.57%	km/h
Number of trips in the network, per mode and/or trip purpose	126 34 211	126 34 211	0%	126 34 211	0%	126 34 211	0%	Buses Cars Pedr. trips
Emissions of a vehicle – CO_2	1140.1	1138.3	-0.16%	1134.7	-0.47%	1132.4	-0.68%	g/km
Emissions of a vehicle – NO_x	6.791	6.769	-0.32%	6.770	-0.30%	6.767	-0.34%	g/km
Emissions of a vehicle – PM	0.371	0.372	+0.27	0.369	-0.50%	0.368	-0.84%	g/km

In light of the provided insights summarized in Table 17, several notable trends can be outlined. Firstly, an increase in conflicts with other road users is observed across all vehicle types, with Twizy experiencing a modest rise, while Irizar and Gulliver encountered more sharp increases, per kilometre travelled, as stated previously. Secondly, although there is a slight decrease in the average vehicle speed for both buses and cars, this reduction does not translate into a proportional decrease in travel time delay. On the contrary, there is a notable increase in travel time delay for all vehicle types, with buses experiencing a rise of 4.97% and cars encountering a surge of 2.77% in delay per kilometre travelled.

Additionally, the total travel time in the network per vehicle type demonstrates an upward trend, which could be attributed to the decrease in speeds within the depot caused by slowly moving AVs. The stability of mode choice share and total kilometres travelled by buses and cars in the network can be attributed to the consistent experimental parameters utilized in the simulation across various scenarios. Moreover, environmental impacts, as measured by CO_2, NO_x, and PM emissions, show marginal reductions across all vehicle types, indicating potential efficiency improvements as stated previously. Finally, the calculation of expected safety enhancement has also received progress, with the SSAM files having been prepared and available to NTUA.

These calculations will be conducted in WP13, which will further refine these observations and explore the associated implications, to be showcased in future deliverables.

3.7 Monheim am Rhein

3.7.1 Initial simulation

The Monheim test site was set up within the SUMO simulation framework to assist the impact assessment performed in WP13. As no information about the real-world demand was available, a synthetic demand was generated using SUMO's tool *randomTrips.py*. The mainly considered road users include bikes, pedestrians, passenger cars, and buses. Two scenarios, with and without AS operation respectively, were established. The simulation period was set to 1 hour and the considered traffic demand includes 590 vehicles, 253 people, 175 bicycles, 104 buses. The initial set-up is described in-depth in D10.3, chapter 4.8.

As already reported in D10.3 and displayed in Figure 35, AS has certain impact on the overall network performance and road users' travel time, especially due to the lower allowed maximum speed and the limitation of road infrastructure, as most roads have only one lane.

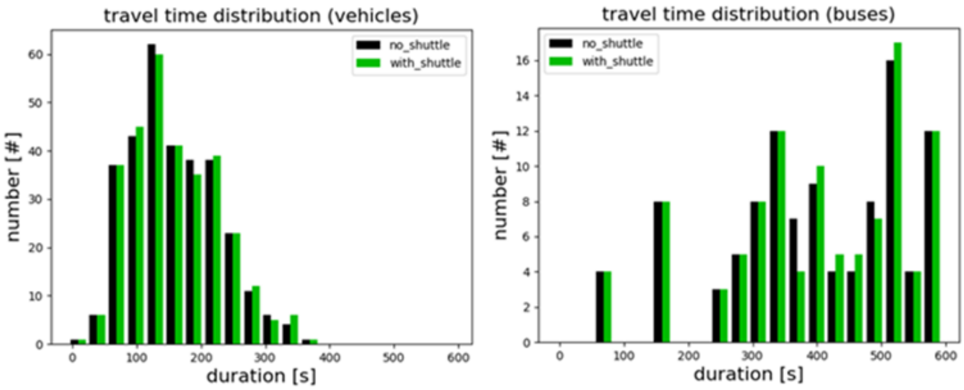


Figure 35: Initial comparison of the travel durations spent by vehicles and buses with and without the AS service at the test site Monheim am Rhein

3.7.2 Extensions after D10.3

SUMO's capabilities to replicate shared spaces have been extensively extended since the release of D10.3.

Though applicable to the Monheim scenario, no parameter validation or calibration could be performed. The Monheim test site supported measures of the vehicle's performance, yet only in an aggregated matter, covering measures aggregated over varying time spans of several hours to several days that did not allow to be mapped to microscopic values such as speed profiles or velocities. As such, no adaptation to the measures collected from the test site could be performed.

3.7.3 Simulation-based impact analysis

Based on the initial simulation result, the impact of AVs was further analysed. No like the other pilot sites, the AS in Monheim have been already integrated into the daily public transport service. Accordingly, the focus was put on the current operation. The average waiting counts and waiting time are the number of times and the time during which the speeds of the vehicles was below or equal to 0.1 m/s. Table 18 shows the simulated traffic performance with and without the AS operation. In the whole network, the average speeds of cars and buses slightly reduced by 0.6% and 1.2%, respectively. The respective waiting times, waiting counts and travel time increased, But the corresponding changes are limited. Due to the small number of values, small changes result in higher impact percentages, which should be interpreted with caution.

Table 18: The simulated traffic performance at the Monheim site

KPI	without AS	with AS	Unit	Impact
Number of agents	405 vehicles, 253 pedestrians and 176 bicycles (whole network)			
Average vehicle speed (car)	35.2	35.0	km/h	-0.6%
Average vehicle speed (bus)	16.4	16.2	km/h	-1.2%
Average waiting time (car)	5.7	6.2	sec	-8.9%
Average waiting time (bus)	49.8	52.7	sec	5.8%
Average waiting counts (car)	0.7	0.7	number	0.0%
Average waiting counts (bus)	2.2	2.3	number	3.7%
Total travel time in network (car)	2.7	2.8	min	3.7%
Total travel time in network (bus)	6,8	6,9	min	1.5%

3.8 Rome

3.8.1 Pilot Site & Simulation Site

The logistics simulation scenario in Rome represents a groundbreaking endeavor within the realm of urban logistics optimization. This innovative project, nestled within the broader framework of the SHOW initiative, endeavors to construct a virtual twin site that faithfully replicates the intricacies of real-world logistics operations within the Rome metropolitan area. By incorporating a spectrum of logistics vehicles, including both conventional and electric options, with the potential for automation, the simulation promises to offer invaluable insights into the dynamics of modern urban logistics.

At its core, the simulation aims to scrutinize the interplay between various factors, such as transfer points, vehicle automation, and routing efficiency, and their impacts on critical metrics like traffic congestion, distance traveled, and delivery time. Leveraging data gleaned from initiatives like the Smart Packaging project of 2019, the simulation stands poised to provide a comprehensive assessment of both the environmental footprint and the operational efficiency of diverse logistics scenarios.

Central to the simulation's methodology is the meticulous examination of energy consumption patterns, travel times, delays, and driving behaviors. Parameters such as vehicle speed, the utilization of automated vehicles, and the strategic placement of transfer points are scrutinized to unravel their implications on the broader logistical landscape.

Moreover, the simulation casts its gaze towards the burgeoning realm of e-commerce, striving to optimize distribution routes to minimize both temporal and spatial inefficiencies. By orchestrating the seamless flow of goods from main distribution hubs to intermediate nodes, and ultimately to end customers, the simulation endeavors to unlock new frontiers in the realm of urban logistics optimization.

To ensure the fidelity and robustness of the simulation, a diverse array of data sources and variables are harnessed. Drawing upon demand data sourced directly from

Rome's burgeoning e-commerce ecosystem, as well as operational insights gleaned from sites like Trikala, encompassing metrics such as velocity, distance, and distribution concepts, the simulation stands as a testament to the convergence of cutting-edge technology and rigorous analytical methodologies.

In essence, the logistics simulation scenario in Rome transcends mere simulation; it represents a paradigm shift in our understanding of urban logistics optimization. By fusing advanced computational techniques with real-world data, this ambitious project holds the promise of reshaping the future of urban logistics, ushering in an era of unprecedented efficiency, sustainability, and resilience.

3.8.2 Simulation scenarios

In an era dominated by e-commerce and rapid urbanization, the logistics industry faces unprecedented challenges and opportunities. Meeting the growing demands of online consumers while minimizing environmental impact requires innovative solutions and strategic planning. This novel logistics simulation introduces a dynamic scenario focusing on direct deliveries to end customers, revolutionizing the traditional supply chain model. Through the integration of advanced technologies such as automated vehicles, predictive analytics, and strategic transfer points, the simulation aims to optimize the delivery process while enhancing efficiency, sustainability, and customer satisfaction. By simulating two distinct scenarios – one representing the conventional baseline and the other incorporating automated vehicles and optimized routing – this simulation provides a glimpse into the future of logistics, where innovation and strategic foresight converge to reshape the way goods are delivered in urban environments. Join us on a journey to explore the possibilities of tomorrow's logistics landscape. Expanding on this innovative logistics simulation idea, let's delve into how advancements in technology and strategic planning can revolutionize the delivery process:

- Dynamic Routing Algorithm: In both scenarios, the key to efficient logistics lies in a dynamic routing algorithm. This algorithm continuously optimizes delivery routes based on real-time data such as traffic conditions, weather, and delivery priorities. By integrating machine learning and predictive analytics, the algorithm can anticipate potential delays and reroute vehicles accordingly, ensuring timely deliveries.
- Integration of Automated Vehicles: In the second scenario, the introduction of automated vehicles marks a significant advancement. These vehicles are equipped with sophisticated sensors and communication systems, allowing them to navigate urban environments with precision and safety. By leveraging autonomous vehicles, the logistics network can achieve greater flexibility and scalability, as these vehicles can operate 24/7 without fatigue or human limitations.
- Strategic Placement of Transfer Points: Transfer points play a crucial role in streamlining the delivery process. By strategically locating these points within urban areas, the logistics network can minimize last-mile distances and reduce congestion in densely populated areas. Additionally, transfer points serve as consolidation hubs where shipments from the main distribution zone are sorted and dispatched to secondary hubs efficiently.
- Predictive Analytics for Demand Forecasting: Accurately predicting customer demand is essential for optimizing inventory levels and scheduling deliveries. By analyzing historical data, market trends, and seasonal patterns, the simulation can forecast future demand with a high degree of accuracy. This allows the logistics network to proactively adjust inventory levels and allocate resources accordingly, minimizing stockouts and excess inventory costs.
- Environmental Sustainability: Embracing environmentally friendly vehicles and practices is a cornerstone of modern logistics. In both scenarios, a strong

emphasis is placed on reducing carbon emissions and minimizing the ecological footprint of the delivery process. From electric vehicles to route optimization algorithms that prioritize fuel efficiency, every aspect of the logistics network is designed with sustainability in mind.

- Real-Time Monitoring and Feedback: To ensure operational excellence, the simulation incorporates real-time monitoring and feedback mechanisms. Managers have access to dashboards and analytics tools that provide insights into key performance indicators such as delivery times, vehicle utilization, and customer satisfaction. By continuously monitoring performance metrics, the logistics network can identify areas for improvement and implement corrective actions in real-time.
- Scalability and Adaptability: As the demand for e-commerce continues to grow, the logistics network must be scalable and adaptable to meet evolving customer needs. Both scenarios are designed with scalability in mind, allowing the network to expand seamlessly as demand increases. Whether it's adding new delivery routes, integrating emerging technologies, or optimizing warehouse layouts, the simulation provides a platform for testing and refining strategies in a risk-free environment.

By simulating these scenarios, logistics companies can gain valuable insights into the potential benefits of adopting advanced technologies and strategic practices. From improving delivery efficiency to reducing costs and mitigating environmental impact, the possibilities are endless when innovation meets logistics.

3.8.3 Rome Simulation Site Implementation

The simulation site is meticulously designed to replicate the intricate urban landscape of Rome, comprising 15 transit points strategically dispersed across the city's 15 zones. Each zone is meticulously delineated to ensure efficient coverage and accessibility, with a centroid serving as the focal point for transit operations. These centroids are strategically positioned at the heart of their respective zones, taking into account the geographic distribution of delivery destinations and the underlying communication network.

To optimize delivery efficiency, the simulation employs advanced routing algorithms that leverage real-time data on traffic conditions, road networks, and delivery priorities. Each delivery location is meticulously assigned to the closest transit point, minimizing last-mile distances and streamlining the overall delivery process. Moreover, the simulation incorporates a conservative vehicle speed of 5 km/h to accurately model urban traffic dynamics and ensure realistic delivery timelines.

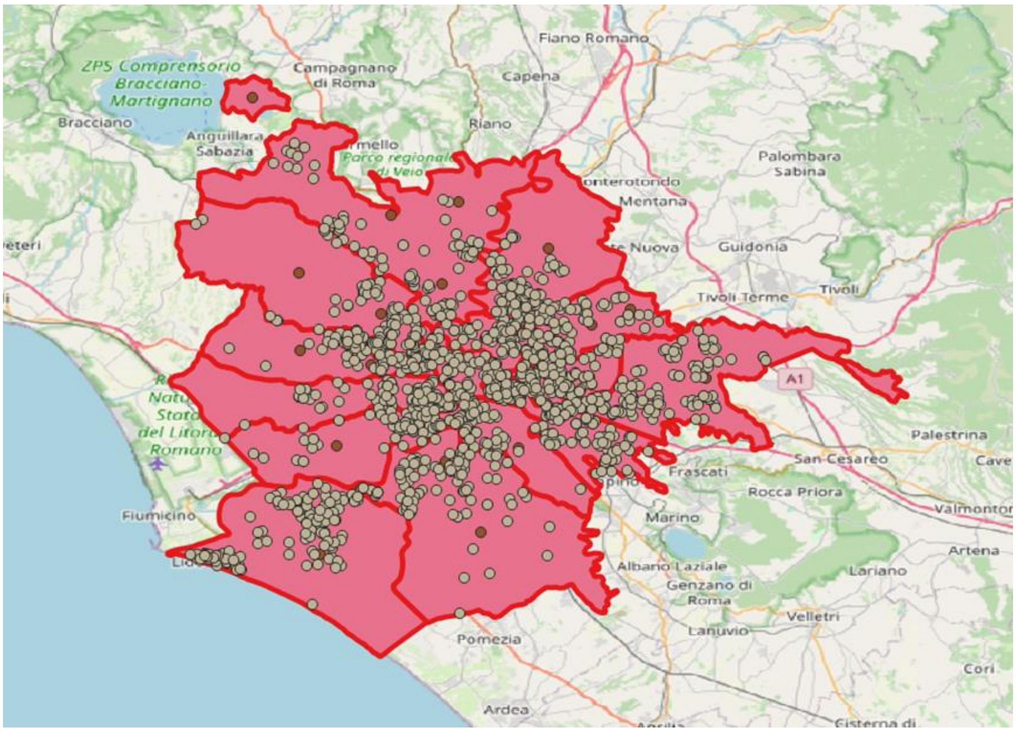


Figure 36: Overview pilot site Rome

In this simulation, we tackled the Vehicle Routing Problem (VRP) using Python, harnessing the power of distance matrices and demand data to optimize the routes for a fleet of 5 vehicles servicing 15 transit points. A single depot served as both the starting and ending point for all routes, providing a centralized hub for logistical operations. To solve the VRP, we employed advanced optimization techniques and algorithms, leveraging Python's robust libraries such as SciPy, NumPy, and OR-Tools. The simulation meticulously considered key parameters including the number of vehicles, vehicle capacity, transit points, and depot location to design efficient and cost-effective routing solutions. Using distance matrices derived from real-world data and demand information from each transit point, we formulated the VRP as a mathematical optimization problem. By minimizing total travel distance while satisfying vehicle capacity constraints and visiting all transit points, the simulation generated optimal routes for each vehicle in the fleet. The objective was to optimize the routes for a fleet of 5 vehicles, each with a capacity of 200 to serve 15 transit points. A single depot was utilized as the starting and ending point for all routes.

To sum up, the logistics simulation deployment has a set of Key Parameters, as listed below:

- Number of Automated Logistics Vehicles: 5
- Vehicle Capacity: 200 units
- Number of Transit Points: 15
- Urban Central Depot: 1

For the simulation, we meticulously prepared input data consisting of a distance matrix and demand data. The distance matrix encapsulates the distances between every pair of transit points within the logistics network, providing essential information for route optimization. Additionally, demand data was collected to indicate the volume of goods to be transported from each transit point, facilitating efficient resource allocation.

To tackle the complexities of route optimization, we selected a vehicle routing algorithm capable of efficiently assigning routes to vehicles while adhering to capacity constraints and minimizing total distance traveled. This algorithm served as the backbone of the simulation, orchestrating the intricate logistics operations with precision and effectiveness.

With the algorithm in place, the simulation embarked on the task of route optimization. Through iterative refinement, the algorithm dynamically adjusted routes to minimize the total distance traveled by the vehicles. Balancing the competing demands of distance and demand constraints, the algorithm meticulously fine-tuned the routes to achieve optimal efficiency and resource utilization.

As for the Output Analysis, upon completion of the simulation, a comprehensive analysis of the output was conducted to evaluate the effectiveness of the route optimization process. The simulation generated optimized routes for each vehicle, providing detailed insights into the sequence of transit points to visit and the quantity of goods to be picked up or delivered at each point.

Key aspects of the output analysis include:

- *Route Sequencing:* The simulation delineated the optimal sequence of transit points for each vehicle, ensuring efficient traversal of the logistics network while minimizing detours and backtracking.
- *Goods Allocation*: By analyzing the demand data, the simulation accurately allocated goods to be picked up or delivered at each transit point, optimizing resource utilization and ensuring timely fulfillment of customer orders.
- *Capacity Utilization:* The output analysis assessed the extent to which vehicle capacities were utilized, providing valuable insights into potential opportunities for further optimization and efficiency improvements.
- *Total Distance Travelled:* A critical metric in logistics optimization, the total distance traveled by the vehicles was meticulously evaluated to gauge the effectiveness of the route optimization algorithm in minimizing transportation costs and fuel consumption.

3.8.4 Simulation Results

The results of the VRP simulation highlight the efficacy of the optimization approach in improving route efficiency and resource utilization:

- Optimized Route Planning: The simulation successfully generated optimized routes for each vehicle, minimizing total travel distance and ensuring timely delivery to all transit points. By leveraging distance matrices and demand data, the VRP algorithm effectively balanced route lengths and distribution workload across the fleet.
- Maximized Vehicle Capacity: With a clear understanding of vehicle capacity constraints, the simulation optimized route assignments to fully utilize the available capacity of each vehicle. This maximization of vehicle capacity translates to fewer trips and increased delivery efficiency, ultimately reducing operational costs.
- Centralized Depot Operations: The utilization of a single depot as the starting and ending point for all routes streamlined logistical operations and facilitated efficient vehicle coordination. By centralizing depot operations, the simulation minimized deadhead miles and improved overall route efficiency.

In summary, the VRP simulation exemplifies the power of optimization techniques in addressing complex logistics challenges. By leveraging TransCAD, Python and advanced algorithms, logistics companies can design efficient routing solutions that minimize costs, maximize resource utilization, and enhance overall operational performance.

Table 19: Optimized route planning results

Vehicle	Route	Total Distance (km)	Time (h)
1	0 Load(0) → 0 Load(0)	0	0
2	0 Load(0) → 6 Load(48) → 7 Load(94) → 10 Load(132) → 8 Load(181) → 0 Load(181)	27.87	5.5
3	0 Load(0) → 5 Load(23) → 4 Load(65) → 3 Load(75) → 2 Load(122) → 0 Load(122)	22.3	4.46
4	0 Load(0) → 0 Load(0)	0	0
5	0 Load(0) → 1 Load(21) → 14 Load(52) → 13 Load(82) → 12 Load(106) → 11 Load(163) → 9 Load(184) → 0 Load(184)	36.3	7.26

After meticulous optimization, the simulation achieved remarkable success in routing 5 vehicles to efficiently serve 15 transit points while maximizing vehicle capacity utilization and minimizing total distance traveled. Leveraging sophisticated algorithms and precise input data, the simulation yielded tangible improvements in logistics efficiency and operational performance. Key highlights of the results finalization include:

- Optimized Routing: The simulation generated highly optimized routes for each of the 5 vehicles, strategically sequencing transit points to minimize travel distance and maximize delivery efficiency. By balancing factors such as distance, demand, and vehicle capacity, the optimized routes ensured timely and cost-effective delivery to all transit points.
- Effective Vehicle Capacity Utilization: Through careful route planning and allocation of goods, the simulation maximized the utilization of vehicle capacities, ensuring that each vehicle operated at peak efficiency. By efficiently consolidating multiple deliveries within a single trip, the simulation minimized the number of vehicles required and reduced overall transportation costs.
- Minimized Total Distance Travelled: One of the primary objectives of the simulation was to minimize the total distance travelled by the fleet of vehicles. By optimizing route assignments and prioritizing proximity-based deliveries, the simulation significantly reduced travel distances, resulting in lower consumption and reduced impact.
- Corresponding Time Calculation: Considering the speed of the vehicles to be 5 km/hr, the simulation calculated corresponding travel times for each route. This information provides valuable insights into delivery timelines and enables logistics managers to accurately plan and coordinate operations, ensuring timely fulfillment of customer orders.

Table 20: Optimization impact

Metric	Result
Optimized Routing	Success
Vehicle Capacity Utilization	High
Total Distance Traveled	Reduced

Corresponding Time	Calculated

In conclusion, the results finalization of the simulation underscores the transformative impact of optimized routing on logistics operations. By harnessing advanced algorithms and precise data analysis, logistics companies can unlock new opportunities for efficiency, sustainability, and profitability in the dynamic landscape of modern supply chain management.

3.8.5 *Logistics Simulation and Calculated KPIs*

As we progress forward, the deployment of automated logistics simulation remains pivotal in our endeavor to comprehensively analyze the project's pilot sites and their associated Logistics Key Performance Indicators (KPIs). Despite encountering delays in the real-life implementation of logistics pilots, we are steadfast in our commitment to finalize the logistics simulations and meticulously represent their data. This culmination of efforts is slated for completion by June 2024 (Month 54), aligning with the timeline outlined for Deliverable D13.4, the Logistics Impact Assessment.

The forthcoming steps entail a thorough examination of the project's pilot sites through the lens of automated logistics simulation. By leveraging advanced simulation techniques, we aim to extract actionable insights that illuminate the performance and efficiency of each pilot site's logistics operations. Through this analysis, we will scrutinize various Logistics KPIs, including but not limited to delivery times, inventory turnover rates, transportation costs, and environmental impact metrics.

While the delay in real-life pilot implementations presents challenges, it also affords us the opportunity to refine and optimize our logistics simulation models. This additional time allows for a more comprehensive validation of the simulations against real-world scenarios, ensuring their accuracy and reliability in capturing the intricacies of logistics operations.

The data representations derived from the logistics simulations will serve as invaluable inputs for the Logistics Impact Assessment expected in SHOW Deliverable D13.4. By synthesizing the findings from the simulations with real-world data and observations, we aim to provide stakeholders with a holistic understanding of the project's logistical impact.

In summary, the forthcoming months will be dedicated to finalizing the automated logistics simulations, analyzing the project's pilot sites, and deriving meaningful insights through the calculation of Logistics KPIs. Through diligent execution and meticulous analysis, we remain steadfast in our commitment to delivering a comprehensive Logistics Impact Assessment that informs decision-making and drives continual improvement within the project's logistics framework.

3.9 Salzburg

3.9.1 Enhanced Simulation

As to the Salzburg site was not running for an extended period after the new vehicle was put in service, very few real data could be collected and used in the simulation. The timetables of the shuttle in Koppl were adjusted, the new vehicle speeds and the speeds of the Shuttles and DRT (50 km/h instead of 20 km/h) were adjusted appropriately.

The main focus in the simulations after D10.3 was set to look at hypothetical scenarios and the outcomes of automating PT-lines and hence shortening intervals between busses. Next to an update of the scenarios from D10.3, to the faster vehicle times, in addition a scenario was simulated, that assumed a switch of all public transport lines to automated vehicles, making it feasible, to shorten intervals of all public transport to 10 minutes, i.e., on each public transport route, a vehicle was simulated every 10 minutes. The 10 minute intervals were used to get to an interval timetable which avoids long waits at any.

Table 21: Scenarios that were simulated for the Salzburg pilot site

Scenario	Description
Baseline	regular public transit with 2020 timetable
Scenario A	six high-frequency autonomous shuttle bus lines going at 50kph (similar to scenario A from report 2, but with increased speed, adapted according to enhanced speeds of new shuttle). The shuttle in Koppl operates 34 trips per day (including the bus timetable for bus 152), all other shuttles 49 trips between 6:00 and 22:00 (20 minute interval)
Scenario A2	in addition to the shuttle buses (with the same timetable as in scenario A): <=10 min intervals & operating hours at least 05:00-23:00 for all buses serving the six regions: regional buses 140, 150, 156 + local buses 143, 144, 148, 151, 152, 153, 154, 155
Scenario B	DRT one vehicle per area
Scenario C	DRT 5% of all stations (per area) start with a vehicle
Scenario D	DRT 10% of all stations (per area) start with a vehicle
Scenario E	DRT 15% of all stations (per area) start with a vehicle
Scenario F	DRT 20% of all stations (per area) start with a vehicle
Scenario G	DRT 100% of all stations (per area) start with a vehicle

While the simulation was run on the same area as before, including the complete state of Salzburg, the main simulation area for the DRTs and the densification of PT intervals are shown in Figure 37.

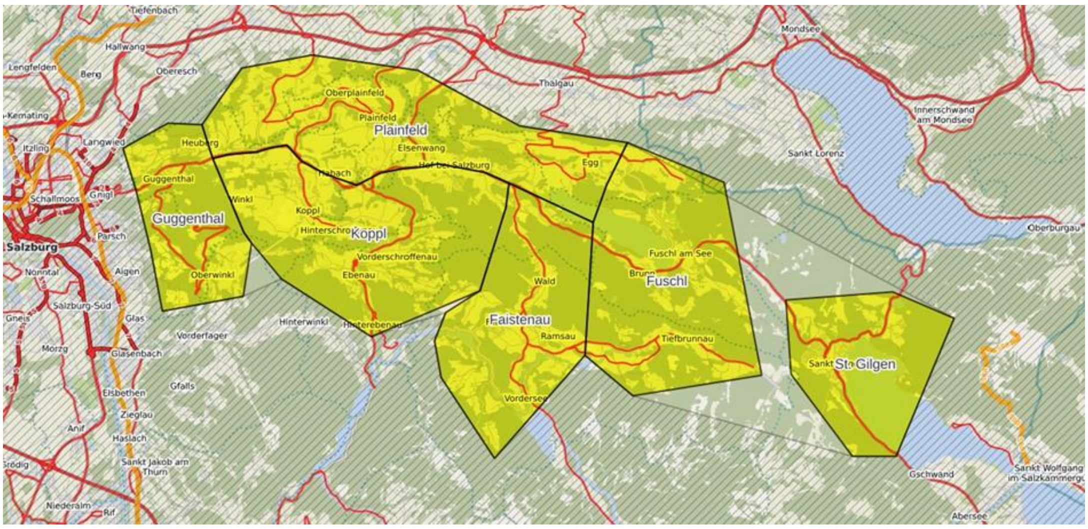


Figure 37: The main study area of the Salzburg simulations is highlighted in yellow. It is further split into six regions corresponding to six separated service areas for DRT fleets

For each region the DRT stations were placed so that when applying a radius of 300 meters to each station more than 90% of the residential area is covered. Scenarios C-G then use a certain percentage of these stations (see Table 21). For scenario A2 bus lines relevant for the simulation area were densified. The number of DRT stations and relevant bus lines are shown in Table 22.

Table 22: DRT regions

Region	Number of DRT stations	Relevant local bus lines
Faistenau	44	155
Fuschl	45	148, 155
Guggenthal	27	151
Koppl	71	152, 154
Plainfeld	83	143, 144, 148, 153
St. Gilgen	19	-

In Figure 37 one can see the higher frequencies of bus lines in the study area that could be achieved by running automated vehicles in the area with a densified schedule. Due to the majority of lines running in the center of Salzburg (left edge of picture) the changes in frequencies seem small, but on the Koppl branch of bus line 152 the number of PT connections increases from 24 to 34 connections per direction per day.

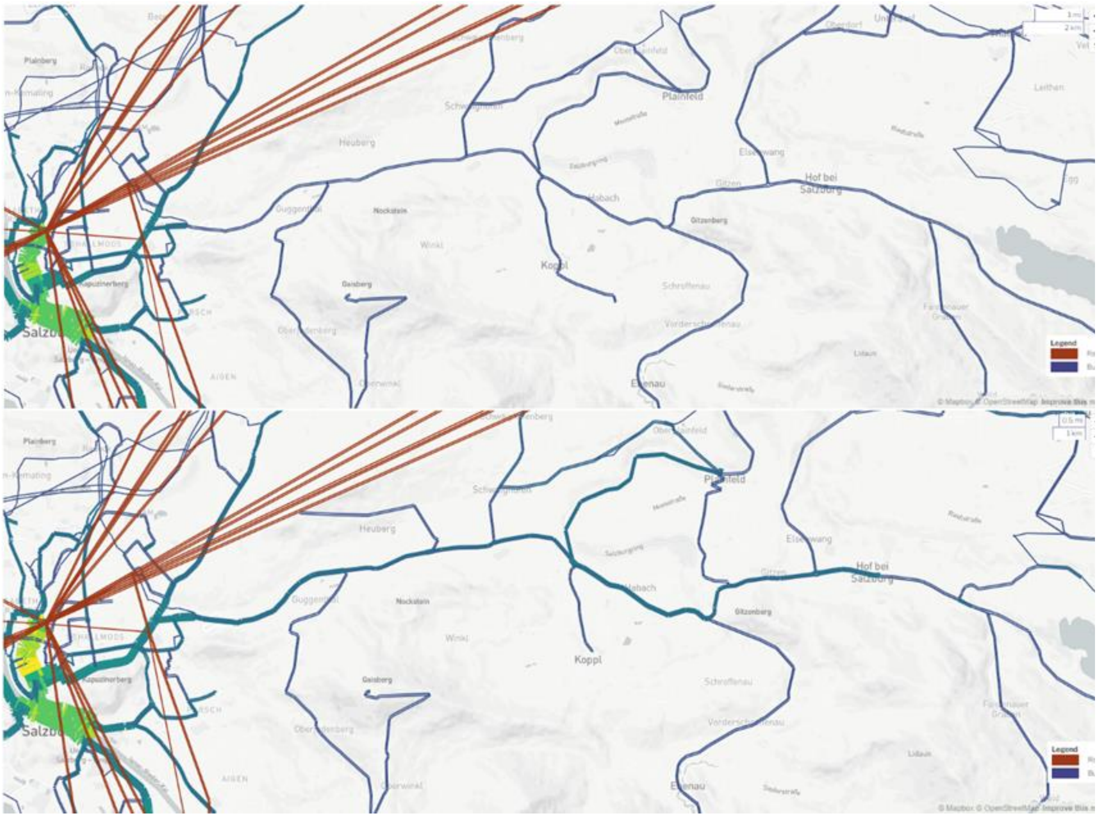


Figure 38: Difference in number of busses in study area. The dominating number of busses runs in the city of Salzburg, but one can see the densification in the study area on the thicker lines

Next to improvements in the simulation, improved analysis capabilities were also implemented. This includes a detailed analysis tool for different public transit lines, allowing a detailed test on the number of rides on different public transport lines during the day.

In addition to the new scenarios, a few changes to the simulation setup were also included in the latest runs of the simulations. These are as follows:

- instead of the proprietary Ariadne routing framework (developed by AIT) the `SwissRailRaptor` MATSim module is used to calculate intermodal access and egress for walking and the six DRT fleets
- The more powerful `DiscreteModeChoice` module is used instead of `Sub-tourModeChoice` to allow for choices between all common modes and all DRT fleets while only using the DRT fleets for trips where it makes sense geographically

For the DRT fleets the following specifications were used:

- **available** 24/7
- **costs** 18€/h = 30cents/min (scoring should be the same as with pt
- **two available seats** for ride-sharing (actually three seats in total)
- **no pre-booking**

3.9.2 Feedback of pilot site data

The main new feature of the simulation is the possibility to use a detailed analysis of transport lines. In the case of the Salzburg Mega Site, a DRT shuttle replaced the bus line 152 in Koppl. The timetables of the first phase and the proposed second phase of the test can be seen in Figure 39. It can be seen that the shuttle in second phase is four minutes faster due to the increased speed limits of the new shuttle. For D10.3, the time table of phase one was applied in the simulation. For D10.4 the shuttle in Koppl ran from 5:30 until 23:30 with 34 trips in each direction with the time-table of the shuttle being joined with the time-table of the bus line 152 which runs on the same route..

Haltestelle	1	2	3	4	5
Koppl Ortsmitte	13:24	14:24	14:54	16:24	16:54
Koppl Fuchsluck	13:27	14:27	14:57	16:27	16:57
Koppl Grabnerbauer	13:31	14:31	15:01	16:31	17:01
Koppl Sperrbrücke/Sperrweg	**13:34**	**14:34**	**15:04**	**16:34**	**17:04**
Koppl Sperrbrücke/Sperrweg	**13:42**	**14:42**	**15:12**	**16:42**	**17:12**
Koppl Grabnerbauer	13:45	14:45	15:15	16:45	17:15
Koppl Fuchsluck	13:49	14:49	15:19	16:49	17:19
Koppl Ortsmitte	13:52	14:52	15:22	16:52	17:22

Haltestelle	1	2	3	4	5	6	7	8	9	10
Koppl Ortsmitte	**12:24**	**12:54**	**13:24**	**13:54**	**14:24**	**14:54**	**15:24**	**15:54**	**16:24**	**16:54**
Koppl Fuchsluck	12:26	12:56	13:26	13:56	14:26	14:56	15:26	15:56	16:26	16:56
Koppl Grabnerbauer	12:28	12:58	13:28	13:58	14:28	14:58	15:28	15:58	16:28	16:58
Koppl Sperrbrücke (D)	12:30	13:00	13:30	14:00	14:30	15:00	15:30	16:00	16:30	17:00
Koppl Sperrbrücke (C)	12:42	13:12	13:42	14:12	14:42	15:12	15:42	16:12	16:42	17:12
Koppl Grabnerbauer	12:44	13:14	13:44	14:14	14:44	15:14	15:44	16:14	16:44	17:14
Koppl Fuchsluck	12:46	13:16	13:46	14:16	14:46	15:16	15:46	16:16	16:46	17:16
Koppl Ortsmitte	**12:48**	**13:18**	**13:48**	**14:18**	**14:48**	**15:18**	**15:48**	**16:18**	**16:48**	**17:18**

Figure 39: Timetables of the Koppl AV Shuttle in the first (top) and second (bottom) phase

Unfortunately, the shuttle did not run for an extended period in phase 2, so no real data for that phase is available. However, the new speeds of the shuttles were implemented for D10.4 for scenarios A and A2. In addition, usage of the shuttle (and the bus 152 outside shuttle run times) was analysed in more detail. Figure 40 shows the daily distribution of passengers.

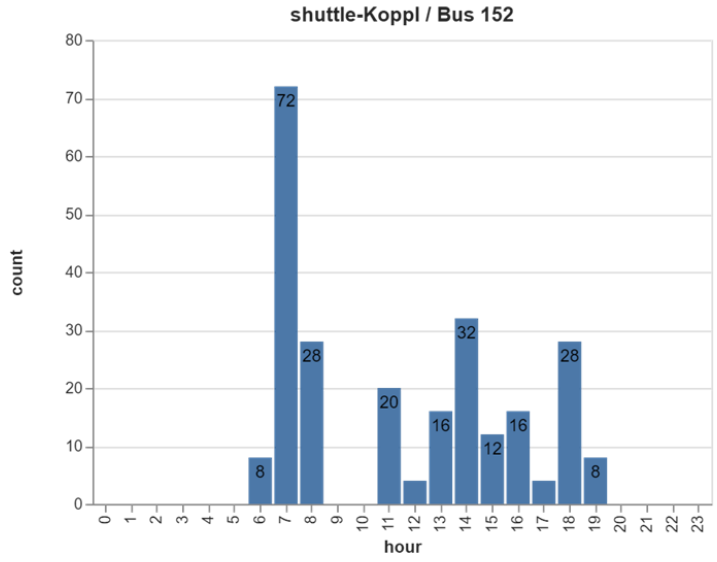


Figure 40: Passengers on the shuttle/bus 152 in the simulation scenario A

One can see that the highest number of passengers in the simulation can be found during the morning rush hour, hence it is necessary to run a larger vehicle than the shuttle. During other times, the count of passengers is lower, making it feasible to run the shuttle (e.g., in the hour two to three, there are 4 shuttles running). With the new, larger vehicle in phase 2, transporting 32 passengers in four vehicles is feasible.

In the scenario A2, the timetable of buses feeding the shuttle is denser while the timetable at the shuttle itself stays the same with 34 departures per day. This leads to higher passenger numbers throughout the day. One can see that the number of passengers increases for most times during the day.

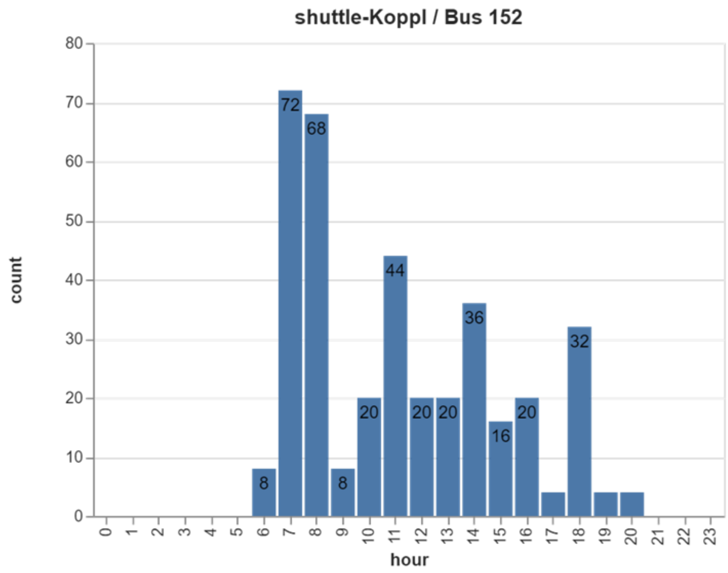


Figure 41: Usage of the Kopple PT Line 152/Kopple shuttle after densification of the timetable

In Figure 41 one can see that for most of the bus lines in the area the number of passengers rises significantly due to a densification of the timetables made possible by automation of the fleet. Only bus 140 running north of the study area, which is the most used bus in the base scenario, does not increase its ridership.

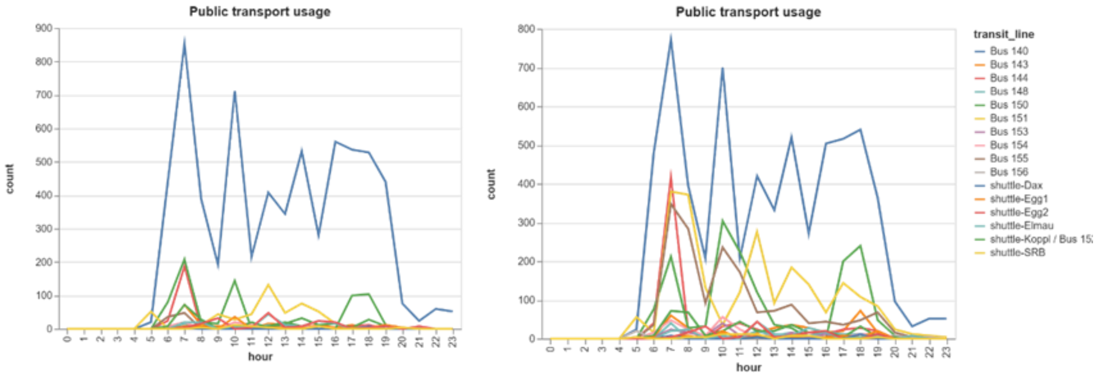


Figure 42: Passenger numbers for buses in study area before and after densification of timetables

3.9.3 Simulation-based impact analysis

A large part of the city-wide simulation analysis is the effect automated vehicle can have on the transport behavior and the mode-usage in an area.

Scenarios B – G show how rising penetration of DRT-vehicles in different areas of operation were analyzed in the last deliverable. The study in D10.3 showed that depending on the size of the operation area, starting at a penetration rate of 10-15% of stops initially equipped with a DRT vehicle in the morning, the benefits of further added DRT vehicles decline fast. In particular, kilometers driven by the vehicle fleet stop increasing, with total km driven by DRT vehicles staying around 6000km for all scenarios D-E and occupancy rates increase only from 1.46 to 1.55 from scenario D-E.

Here we concentrate on the Scenarios A, A2 and G in the analysis. Scenario G is chosen to show the potential of automated services if they are rolled out to fulfill the maximal demand for automated DRT legs.

The most relevant KPIs for the study of hypothetical automated fleets is the change that can be achieved by automating public transport, and hence shifting trips from motorized individual transport to public transport. So, the modal splits for the different scenarios were calculated. For a trip-based modal split for inside, source and destination traffic (all trips starting or ending in the study area), it can be seen that car stays the dominant mode of transport with over 74% modal split for all scenarios. This is due to the fact, that driving is still the fastest mode of transport for a lot of trips. Therefore, for the majority of trips, the mode stays the same. However, there is a significant reduction of car trips for scenarios A2 and G, where a further increase in supply of automated vehicles seems infeasible.

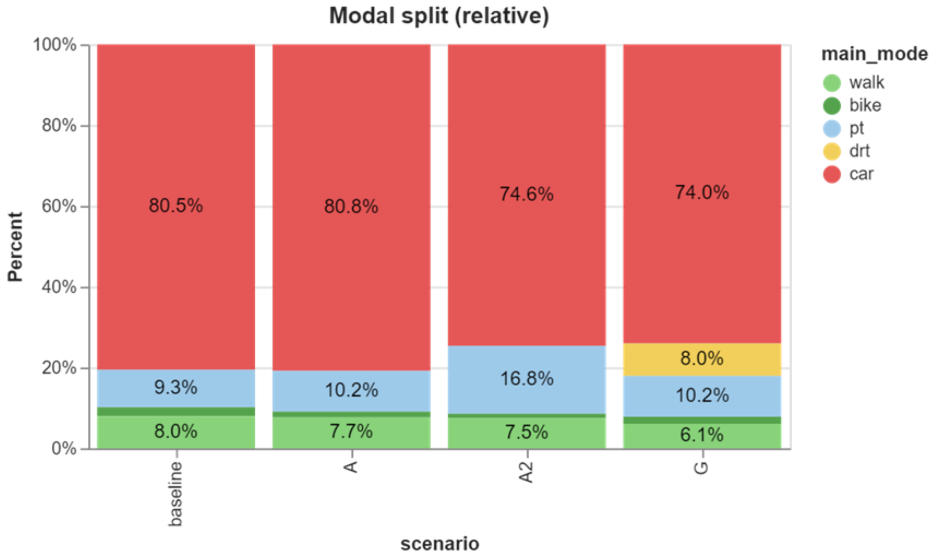


Figure 43: Trip based modal split including all trips with sources and destinations in the study area

This picture is even more, unbalanced when looking at the modal split of people by distance travelled (Figure 43). So, in particular longer car trips are not replaced, since the car offers door to door transportation without transfers.

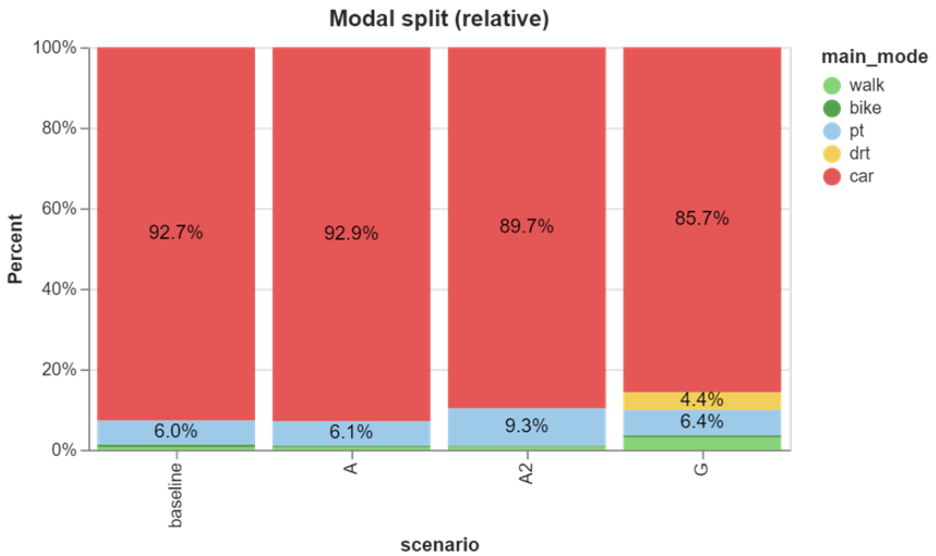


Figure 44: Distance based modal split for trips starting or ending in the study area

Looking at trips that stay within the study area, the picture is a little different. Here one can see that there are car kilometres replaced by PT and DRT kilometres. However, one can also see that the number of kilometres travelled by bike and foot is decreasing.

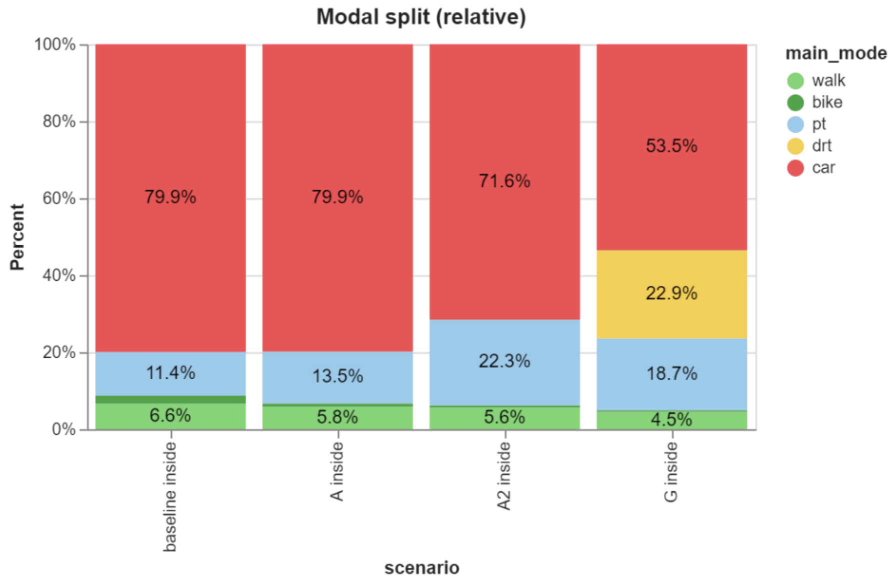


Figure 45: Modal split by distance of trips within the study area

When it comes to access to the transport system for disadvantaged people, the simulations show, that people with different car availability need to share the ride with a different person less through the introduction of automated vehicles. In Scenarios A2 and G the number of people without access to cars switch in around 4.6% and 3.2% of the cases where they used to ride with other people to other modes that become available. For people who have cars available only sometimes, that numbers even increase to 7.9% and 10% respectively. This suggests that access to the transport system becomes easier for people without or with limited access to cars.

Similarly, for age categories 6-15 and elderly who cannot drive yet or anymore, the usage of private cars drops by 8.4% (A2) and 4.4% (G) for kids and 5.5% (A2) and 8.7% (G) which suggests that the accessibility increases even without the use of cars with better autonomous offers. However, autonomous PT and DRTs do not solve car dependency in rural areas for disadvantaged groups completely.

Figure 46 shows the number of trips per mode and activity. One can see, that with a densification of PT more work trips are shifted from car to PT than with an introduction of DRTs. There a large number of shopping trips is shifted.

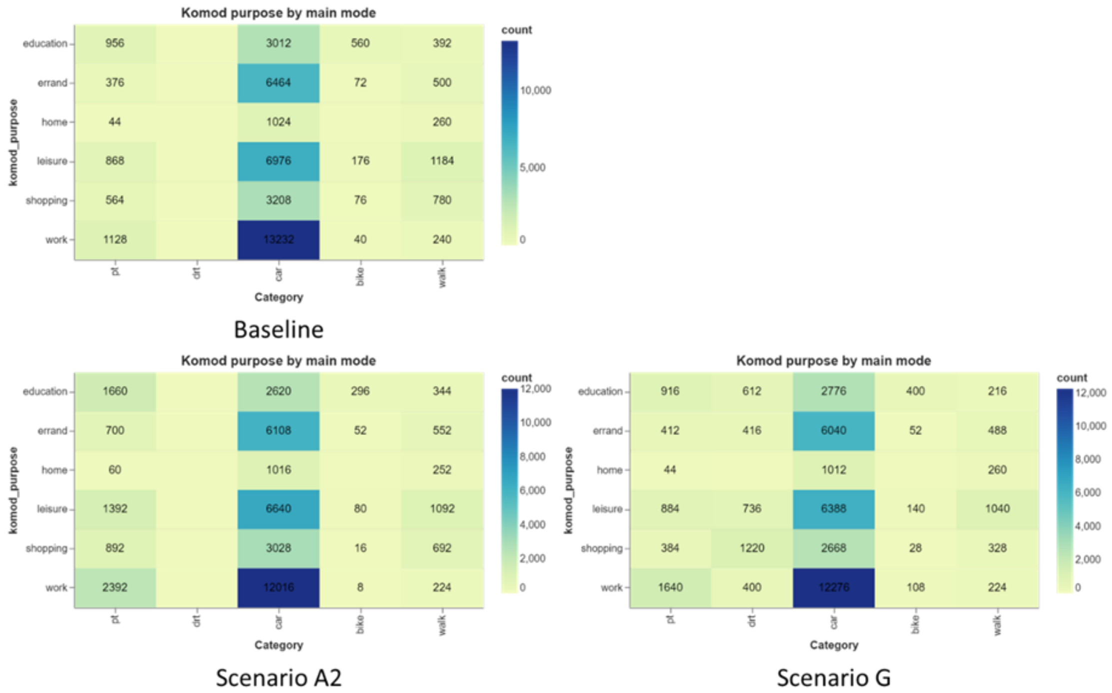


Figure 46: Number of trips per mode and activity

Finally, the MATSim simulation allows to show the change in network loads on links in the system. In Figure 47 one can see such a change for the Koppl area. One can see, that the network loads for the main road decreases while the addition of DRTs increases the network loads on minor roads in the DRT-areas. The network loads would also allow for a link-based estimation of noise and emissions along the roads. However, these would be only very crude estimates since details on the vehicle fleet as well as detailed acceleration-profiles for the vehicles are not part of the queuing-based simulation in MATSim and hence were out of scope for the SHOW project.

Figure 47: Changes in network loads (number of daily vehicles traveling a long a link) from the base scenario to scenario G: The red lines mark increases in network load (due to DRT on minor roads) and blue marks decreases in network load (e.g., on the main road from the study area to Salzburg)

Finally, a list of KPIs was calculated for the different scenarios, capturing the above graphs. The CO_2 emissions are given for the whole car fleet in kg/day since no comparison per vehicle is possible in a mesoscopic simulation. In addition, one can see, that there are added empty runs by the automated DRT to pick up passengers at the stops in scenario G of 18.75% of the total kilometers travelled by DRT with an average occupancy rate of 1.35 passengers.

KPI	Baseline	Scenario A	Scenario A2	Scenario G
Speed per vehicle type Car in km/h	54.86	54.83 (0.08%)	54.86 (0.14%)	54.22 (-1.03%)
Total travel time in network per vehicle type – Car in s/km	65.72	65.66 (-0.08%)	65.62 (-0.14%)	66.4 (1.04%)
Modal Split (nr trips) – Car in %	80.5	80.8	74.8	74
Modal Split (nr trips) - PT in %	9.3	10.2	16.6	10.2
Modal Split (nr trips) – DRT in %	-	-	-	8
Modal Split (nr trips) - Bike in %	2.2	1.4	1.1	0.6
Modal Split (nr trips) - Walk in %	8.0	7.7	7.5	6.1
Modal Split (person km travelled) - Car in %	92.7	92.9	89.7	85.7
Modal Split (person km travelled) - PT in %	6.0	6.1	9.3	6.4
Modal Split (person km travelled) – DRT in %	-	-	-	4.4
Modal Split (person km travelled) - Bike in %	0.6	0.4	0.3	0.6
Modal Split (person km travelled) - Walk in %	0.7	0.6	0.7	2.9
Average vehicle speed in a network - Car	65.2	65.4	65.7	65.9
Total (direct) Emissions of a vehicle (CO_2) – Car in kg/day	4888.2	4936.4 (1%)	4444.4 (-9.1%)	3690 (-24.5%)
Percentage of vehicle-km run empty in %				18.75

Table 23: KPI list for the Salzburg site (with changes to baseline in brackets)

3.10 Trikala

3.10.1 Enhanced simulation based on pilot site data

Pilot operation at the site of Trikala commenced in December 2023. Two retrofitted shuttles (Peugeot e-Traveller) operating in automated mode serve pre-defined stops along a peri-urban route in the city of Trikala, Greece (Figure 48). During pilot operation, information is collected in fixed time intervals pertaining to the status of the automated shuttles (location, speed, and acceleration). The latter data are analyzed to examine the driving behavior of the shuttles in automated mode and parametrize the characteristics of the relevant vehicle type in the microscopic traffic simulator SUMO. The evidence-based parametrization of the characteristics of the automated shuttle vehicle type in SUMO enables the realistic replication of the automated shuttle's behavior in the simulated environment. Thus, the assessment of the impacts of automated shuttles on conventional traffic and the environment is based on empirical evidence and not purely on hypotheses regarding their behavior as in previous deliverables D10.2 and D10.3.

Figure 48: Physical shuttles operating at the Trikala pilot site

Specifically, the distributions of instantaneous automated shuttle speed (Figure 49) and instantaneous automated shuttle acceleration (Figure 50) were estimated in the form of box and whisker plots for the time-period between 1st January 2024 and 1st February 2024. According to Figure 49, the median and maximum shuttle speeds were 20.0 and 30.0 km/h respectively, while the interquartile range (IQR) spanned between 11.0 and 25.6 km/h. According to Figure 50, the median and maximum shuttle accelerations were -0.003 m/s2 and 7.85 m/s2 respectively, while the interquartile range (IQR) spanned between -1.25 and 1.23 m/s^2. The results presented in Figure 49 and Figure 50 allow the selection of values for the vehicle type parameters shown in Table 24 (maximum speed, deviation from maximum speed while driving unimpeded for surrounding vehicles, desired acceleration, desired deceleration, emergency deceleration). The acceleration and deceleration ability of the automated shuttles is selected according to the data values of the 1st and the 3rd quartiles of the acceleration distribution. Maximum speed and emergency deceleration are selected as the maximum and minimum values of the speed and the acceleration distributions respectively. The automated shuttle is assumed to precisely follow its maximum desired speed when unimpeded by surrounding vehicles, traffic control elements and the road geometry.

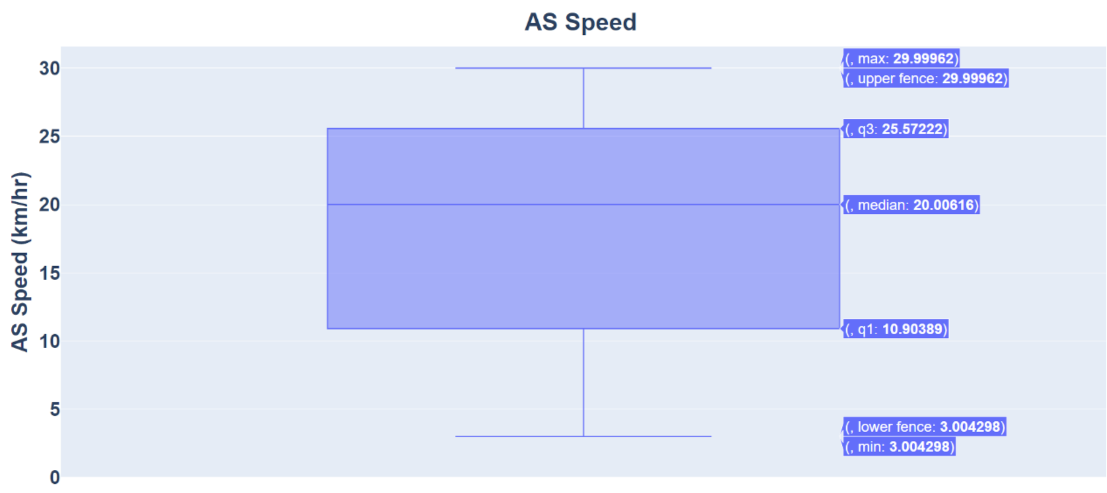


Figure 49: Boxplot view of instantaneous automated shuttle speeds

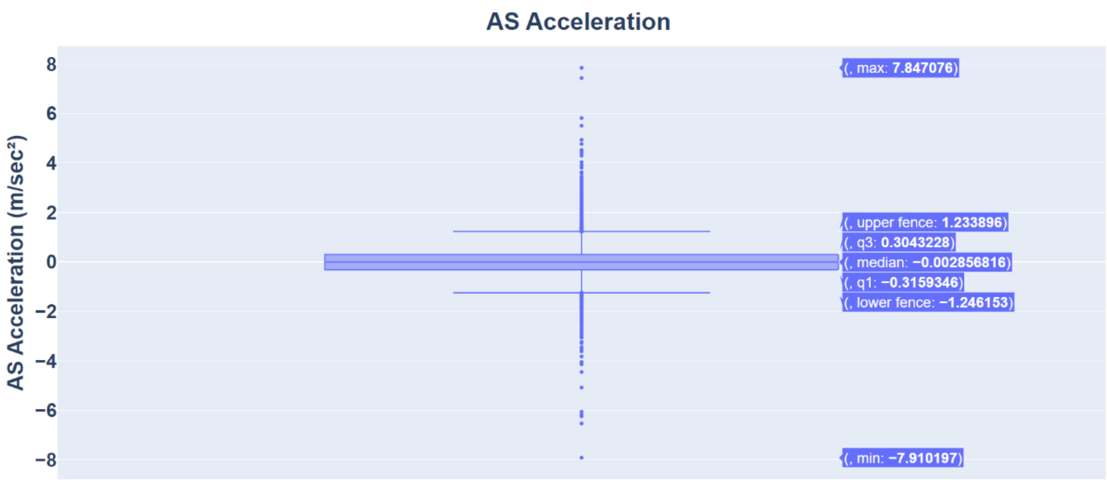


Figure 50: Boxplot view of instantaneous automated shuttle accelerations

Table 24: Parametrization of the automated shuttle characteristics in SUMO

Parameter Name	Parameter Description	Value
maxSpeed	The vehicle's maximum velocity (in m/s)	8,30
speedFactor	The vehicles expected multiplier for lane speed limits and desiredMaxSpeed (scalar)	1,00
accel	The acceleration ability of vehicles of this type (in m/s²)	1,23
decel	The deceleration ability of vehicles of this type (in m/s²)	-1,25
emergencyDecel	The maximal physically possible deceleration for the vehicle (in m/s²)	-7,9

3.10.2 Simulation-based impact analysis

The existing legislature demands that automated shuttles operate at speeds lower than the posted speed limits for safety reasons. Additionally, automated shuttle transitions of control (ToC) and minimum risk maneuvers (MRM) might further disrupt normal traffic operations and temporarily cause local congestion phenomena. On the other hand, priority of automated shuttles at signalized intersections is expected to improve the quality of service provided by the automated shuttles but might adversely impact regular traffic. Moreover, future passenger demand might warrant the operation of more shuttles and in higher frequency. Thus, it is important to assess the traffic and environmental implications of the introduction of automated shuttles in conventional road traffic landscapes under various conditions. The simulated scenarios shown in Table 25 place focus on higher operation frequency of automated shuttles, ToCs and MRMs, and signal priority for automated shuttles.

Table 25: Overview of the scenarios at the Trikala pilot site

Scenario	Content
Scenario 1 (Base)	The current traffic situation without AS as the baseline scenario.
Scenario 2 (2 AS)	It is based on Scenario 1 with 2 AS, each running once per hour at a maximum speed of 30 km/h, and serving at the pre-defined stops.
Scenario 3 (2 AS-ToC)	As Scenario 2, but only 1 AS performs Transition of Control (ToC) and subsequently a Minimum Risk Manoeuvre (MRM).
Scenario 4 (2 AS-GP)	As Scenario 2, but AS receive priority at signalized intersections.
Scenario 5 (4 AS)	It is based on Scenario 1 with 4 AS, each running once per hour at a maximum speed of 30 km/h, and serving at the pre-defined stops.

The traffic impacts of automated shuttles for the 4 different simulation scenarios have been evaluated based on three traffic performance measurements (average speed, delay time, and number of stops). The latter performance measurements are explicitly reported for the different vehicle types that the simulation analysis encompasses (LVs: Legacy Vehicles, BUS: Conventional Buses, AS: Automated Shuttles). The environmental impacts of automated shuttles have been assessed based on the carbon dioxide (CO_2) emissions per kilometer driven for the whole vehicular fleet. Additionally, the energy consumption of the automated shuttles per kilometer driven is reported separately for the different simulation scenarios.

Figure 51 depicts the average vehicle speed per vehicle type for the different simulated scenarios. The introduction of the automated shuttles in Scenario 2AS induces a 3,78 % reduction in LV speed compared to the Base Scenario. The latter reduction becomes higher when the operation frequency of automated shuttles increases in Scenario 4S. As expected, the lowest average automated shuttle speed is observed when the automated shuttle is forced to execute a ToC and subsequently an MRM. On the other hand, the maximum average automated shuttle speed is observed when priority is provided to automated shuttles at signalized intersections. Interestingly, the sequence of ToC and MRM from a single automated shuttle in Scenario 2 AS-ToC, as well as the provision of signal priority to all automated shuttles in Scenario 2 AS-GP do not adversely impact the average speed of LVs compared to Scenario 2AS.

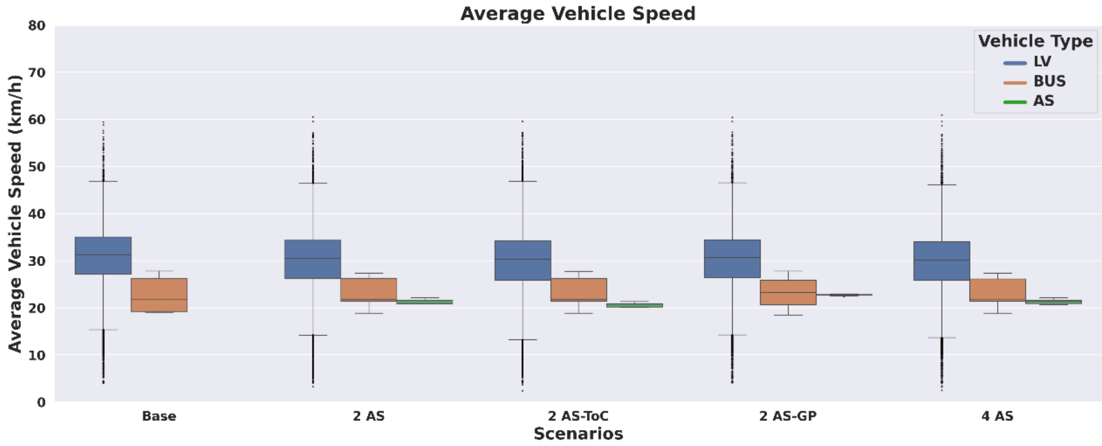


Figure 51: Boxplot depicting average vehicle speed per vehicle type

Figure 52 depicts the average vehicle delay per vehicle type for the different simulated scenarios. The introduction of the automated shuttles in Scenario 2AS induces a 4,5 % increase in average LV delay compared to the base scenario. The latter increase becomes higher when the operation frequency of automated shuttles increases in Scenario 4S. As expected, the highest average automated shuttle delay is observed when the automated shuttle is forced to execute a ToC and subsequently an MRM. On the other hand, the lowest average automated shuttle delay is observed when priority is provided to automated shuttles at signalized intersections. Interestingly, the sequence of ToC and MRM from a single automated shuttle in Scenario 2 AS-ToC, as well as the provision of signal priority to all automated shuttles in Scenario 2 AS-GP do not increase the average delay of LVs compared to Scenario 2AS. Similar trends are observed for the number of stops per vehicle type depicted in Figure 53.

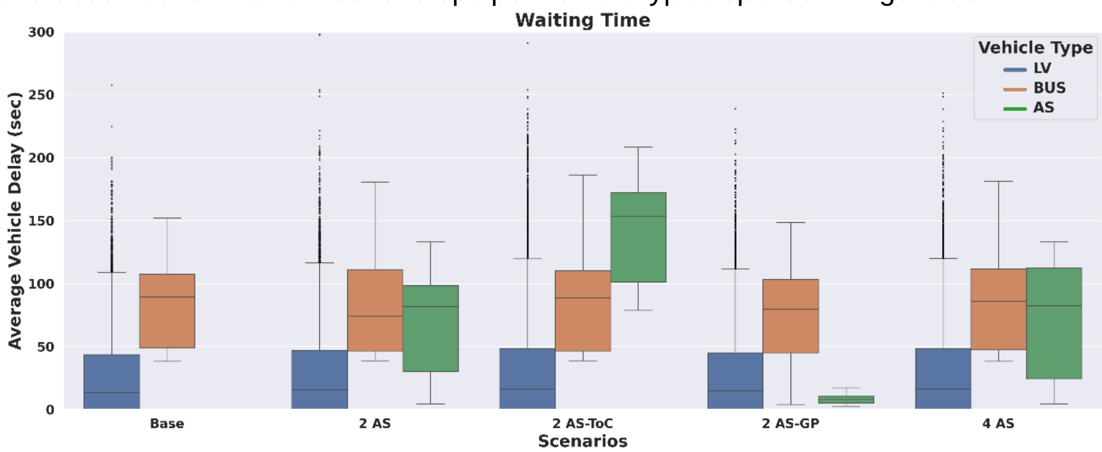


Figure 52: Boxplot depicting average vehicle delay per vehicle type

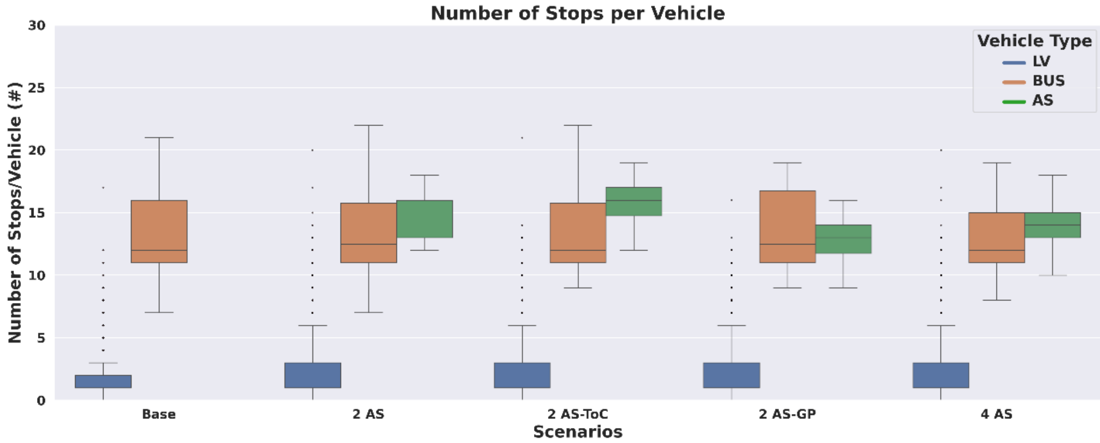


Figure 53: Boxplot depicting number of stops per vehicle and vehicle type

The distributions of automated shuttles' energy consumption per kilometer driven in Scenarios 2 AS, 2 AS-ToC, 2 AS-GP, and 4 AS are depicted in the boxplots of Figure 54. Energy consumption is maximal when the automated shuttle executes ToC and MRM, while it becomes least when signal priority is active for automated shuttles. On the other hand, energy consumption per kilometer driven is not affected by the operation frequency of automated shuttles. Similarly, CO_2 emissions per kilometer driven of the whole simulated fleet is not impacted by ToCs and MRMs, signal priority or the increased operation frequency of the automated shuttles. However, CO2 emissions per kilometer driven for Scenarios 2 AS, 2 AS-ToC, 2 AS-GP, and 4 AS are approximately 2.63 % higher compared to the Baseline Scenario that does not encompass automated shuttles.

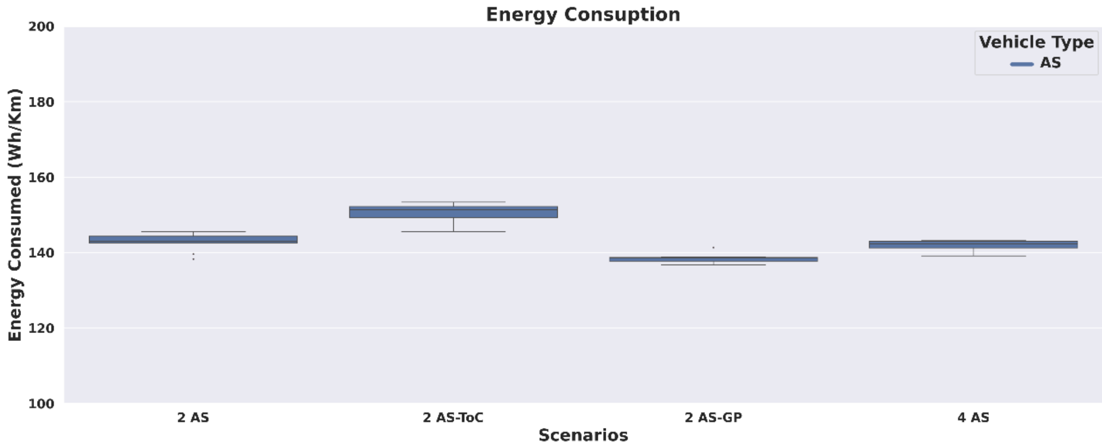


Figure 54: Boxplot depicting energy consumption of the automated shuttles

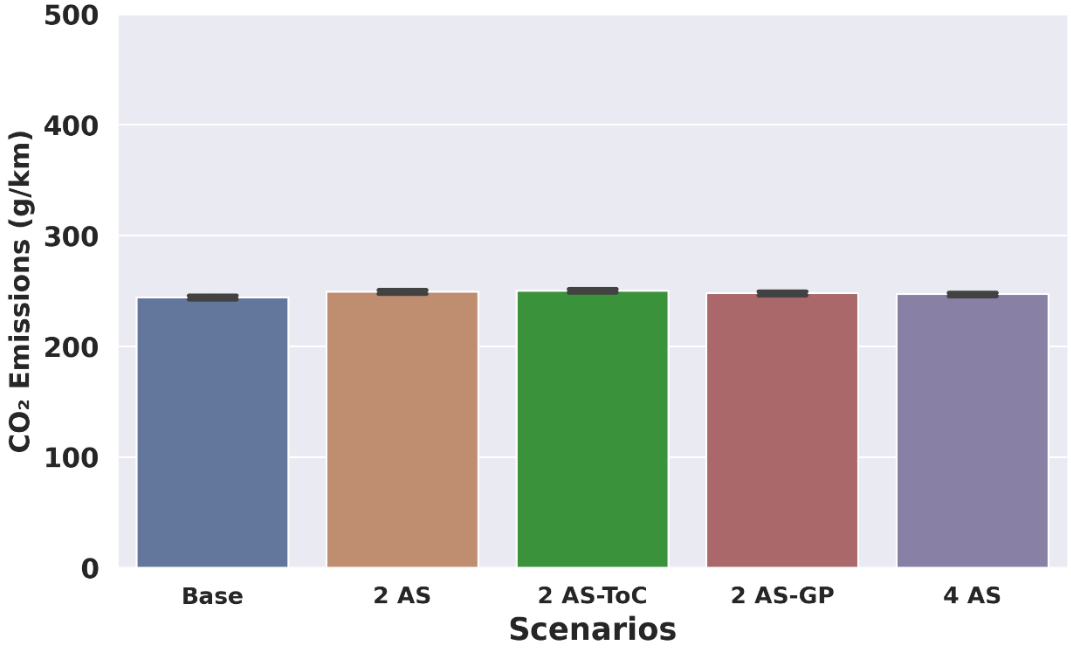


Figure 55: CO_2 emissions per kilometre travelled accounting for all vehicle types

Overall, the introduction of automated shuttles in the fleet mix affects the performance of Legacy Vehicles (LVs) along a peri-urban route of a mid-size city. Specifically, it reduces slightly the operating speeds of LVs and induces higher average delays (Table 26). The magnitude of the effects of automated shuttles on LVs is amplified with the increase of their operation frequency (Table 27). The latter simulation results are reasonable considering that automated shuttles cannot currently drive close to the posted speed limits due to legislative issues. Moreover, the simulation analysis indicates that ToCs and MRMs adversely affect the performance of automated shuttles (lower average operating speed, higher delays, increased energy consumption), while priority at signalized intersections can significantly increase the quality of service provided by automated shuttles. Finally, the operation of automated shuttles yields higher CO_2 emissions per driven kilometer for the entire vehicular fleet.

Table 26: Mean values of KPIs obtained from the simulation analysis of the Trikala Pilot site per scenario and vehicle type.

KPI	Vehicle Type	Scenario				
		Base	2 AS	2 AS-ToC	2 AS-GP	4 AS
Average Vehicle Speed (km/h)	LV	31.27	30.51	30.32	30.71	30.16
	BUS	21.86	21.79	21.79	23.24	21.84
	AS	-	21.57	20.76	22.78	21.33
Average Vehicle Delay (sec)	LV	13.5	15.5	16	15	16.2
	BUS	89.4	74.3	88.55	79.75	85.9
	AS	-	81.55	153.65	8.1	82.35
Number of Stops per Vehicle (#)	LV	1	1	1	1	1
	BUS	12	12.5	12	12.5	12
	AS	-	14	16	13	14
Energy Consumption (Wh/km)	AS	-	143.04	151.76	138.65	142.36
CO_2 emissions (gr/km)	All	243.69	248.31	250.46	247.75	248.88

Table 27: Percental change of KPIs per vehicle type due to the introduction of automated shuttles in the Trikala pilot site simulations.

Impact (Percental Change)	Vehicle Type	Scenario				
		Base	2 AS	2 AS-ToC	2 AS-GP	4 AS
Average Vehicle Speed (km/h)	LV	-	-2%	-3%	-2%	-4%
	BUS	-	0%	0%	6%	0%
	AS	-	-	-4%	6%	-1%
Average Vehicle Delay (sec)	LV	-	15%	19%	11%	20%
	BUS	-	-17%	-1%	-11%	-4%
	AS	-	-	88%	-90%	1%
Number of Stops per Vehicle (#)	LV	-	0%	0%	0%	0%
	BUS	-	4%	0%	4%	0%
	AS	-	-	14%	-7%	0%
Energy Cosumption (Wh/km)	AS	-	-	6%	-3%	0%
CO2 emissions (gr/km)	All	-	2%	3%	2%	2%

4 Insights from simulations

When comparing the simulation-based impact analysis of all pilot sites on microscopic- and macroscopic-level, some universal trends can be observed.

As long as the SHOW shuttles and AVs only supplement the existing public transport and do not replace it, the net result is a slightly higher volume of traffic in the area under consideration, with all the accompanying drawbacks. As a result, a slightly reduced average speed of the network overall can be observed on almost all sites. Depending on the local situation, it ranges from negligible (e.g. Klagenfurt) over a 3.78% reduction of the average speed in the case of Trikala to a maximum reduction of approx. 5% in the case of Linköping. Based on the present KPIs, it is apparently advantageous when the AVs operate on multi-lane roads, such as in Klagenfurt. There, the shuttles can be overtaken if necessary and congestion can be avoided. This also implies that, in addition to public transport demand, proper street design, e.g. additional features, such as multiple lanes, additional bus bays, space for overtaking and less parking possibility, should also be considered when planning AS routes, especially at low operating speed limits. On the other hand, legislative speed limits for shuttles below the permitted road speed limits are extremely disadvantageous, as in the case of Trikala. Such regulations render the AVs into virtually moving traffic obstructions.

The electric shuttles are largely neutral in terms of environmental pollution. Only indirectly can they lead to slightly higher exhaust emission levels due to congestion effects. The specific figures vary slightly depending on the pilot site but can be estimated at less than 1%.

In terms of safety, there is no need to be so overly concerned – an issue that is usually viewed very critically by stakeholders. No collisions were recorded in the simulation at all. However, it should be noted that the simulated vehicles are always assumed to be well maintained and only a limited number of scenarios can be tested.

Looking on the matter at the macroscopic traffic simulation level, the situation looks better, since macroscopic simulations allow mode switches. By shifting mobility toward electric shuttles, individual traffic can potentially be reduced and with it the environmental impact. In both city-wide simulations, a reduction of individual motorized mobility was seen. This also results in reduced GHG-emissions in both cases. While in Salzburg, the emissions from car journeys reduced by up to 24.5% for trips starting or ending in the area served by DRT, the overall reduction in the city is quite small. In Eindhoven, an overall reduction of CO_2 emissions of 0.7% was achieved through the introduction of DRT.

What can be seen in both sites is that DRT trips usually rather replace shorter trips. This results not only in a reduction of car trips, but also in a reduction of walking and cycling trips. In addition, there is a considerable number of empty trips (18.75% in Salzburg and 57% in Eindhoven). This does result in higher traffic loads in certain areas.

In the Salzburg case, different scenarios on penetration rates were studied. First, different penetration rates of DRT vehicles were tested. With the assumption that no-one would have to walk more than 300m to access a DRT-stop, there was a clearly added benefit to add DRT vehicles at around 10% of the stations. Afterwards, the benefits of adding further vehicles in the areas clearly declined. It was also tested which impacts a replacement of the current bus-lines with automated vehicles that run at shorter intervals (10 Minute intervals) would have. This replacement, without adding DRT services for first and last mile results in a similar reduction of car journeys. In addition, here, longer trips are also replaced and there is less of an impact on trips in active modes.

Overall, the introduction of automated vehicles has a positive effect on emissions and a quite small effect on delays in the network. However, to achieve considerable improvements in modal split, there is a need for a relatively large number of automated vehicles.

5 Conclusions

This deliverable gives an overview of the final iteration of simulation conducted at the ten simulation pilot sites. By incorporating real measurement data and experience with the operation of the pilot site, the simulations were refined to make them even more realistic. Subsequently, these more realistic simulations were then used to investigate the impact of the AVs on the existing traffic, the safety, and the environment. Since this is the last deliverable of WP10, the fulfillment of the goals defined in the Grant Agreement are also discussed in depth within a dedicated chapter.

The results of the simulations are slightly ambiguous. At road-level, the performance figures for delays, average speeds and braking maneuvers deteriorate in the presence of AVs, as do the emissions of particulate matter and greenhouse gases. This is simply the result of more vehicles – the AVs – being added to the already existing traffic which usually leads to increased congestion. However, the advantage of AVs can be seen in the overlaying city-level simulations, where the mode of transportation is also considered. By partially eliminating individual vehicles, a reduction in traffic density and greenhouse gases can be observed.

Some findings and recommendations derived from the simulations are potentially important beyond project SHOW. Intuitively, traffic planners would probably refrain from using AVs on multi-lane roads due to the feared complexity. Yet, this is precisely what our studies have shown to be advantageous. Setting the legislative speed of AVs below the maximum allowed speed another issue that was identified as problematic in the simulations. In general, depending on local conditions, the road infrastructure should be adapted to suit the AVs whenever possible, including separate lanes, areas for overtaking and spaces for idle AVs.

The findings and results presented in this deliverable are of particular interest of WP13 (Impact assessment) as the simulation-based impact analysis KPIs are an essential input to their work. The estimated KPIs were defined in advance in consultation with WP13 and evaluated for the respective pilot sites – as far as technically possible and feasible.

Finally, it should be noted that deliverable D10.5 (Simulation Suite) will be published shortly after D10.4, and will include guidance and recommendations, specifically for developers, researchers and external stakeholders who intend to develop replica of the pilot sites developed within SHOW.

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