SHared automation Operating models for Worldwide adoption
SHOW

Grant Agreement Number: 875530

D8.1: Criteria catalogue and solutions to assess and improve physical road infrastructure

This report is part of a project that has received funding by the European Union's Horizon 2020 research and innovation programme under Grant Agreement number 875530

Legal Disclaimer

Executive Summary

News on how leading tech-companies are providing cars with autonomous driving functions and creating new options for mobility soon are becoming ever more frequent. However, the demand for further automation in mobility is also a challenge that will require new systems to enable the future of automated driving. With shared automated transportation modes expected to be ready for road-use in the next ten to twenty years, fundamental innovations are needed to guarantee a fully functional and operational system to provide seamless interactions between automated vehicles and the physical infrastructure.

Employing a holistic approach, this document discusses core contents of physical road infrastructure, based on intense desk research combined with surveys among OEMs and the pilot sites in the SHOW project universe. This allows us to focus not only on results obtained in different places on this world, including under different circumstances/set-ups, but also hear the voices of those working on the actual implementation of automated vehicles (AVs).

The desk research led to an extensive compendium of projects involving automated vehicles in different surroundings and operational states, ranging from SAE-level one up to currently level four. With this compendium also specific outcomes of each project were summarized for future reference.

One frequent result, according to OEMs was that the main point of success of a pilot site or AV operation is the quality of the digital twin of the test site, the so-called digital map.

With this detailed representation of all elements visible to vehicle sensors, such as lane markings and other physical elements, the influence of infrastructure elements on driving behaviour could be optimized, but there are some other influences such as slopes or own vehicle speeds that created problems during operation phases.

One very consistent finding was, that all planning and building of AVs was focused on existing infrastructure, i.e. the underlying operation systems were created to work with existing and not newly added elements, such as optimized lane markings, safety barriers and transportation hub designs. This begs the question of which new elements are needed to create on-point supply for seamless operation of public transport services, such as maintenance and charging facilities. With curbside management additional problems could arise, as the physical infrastructure itself will have to be changed and the operation systems need to be adapted.

One main result of this deliverable are checklists for physical infrastructure elements and public transport hubs, ready to be used when assessing the readiness for autonomous vehicle operations.

The last three chapters of this report cover the utilization of all previous results and findings in software, simulation tools and a workflow. One result was the in this task by AIT developed road segmentation tool, that helps identifying present infrastructure on road segments and classify them based on different types of interactions with autonomous vehicles. Another result was the basic set-up of a simulation framework for public transport hubs and stations, that will be expanded on during further work packages the SHOW project. Finally, we devised a workflow for creating digital dynamic maps, as described in the last chapter. Both results become handy when the implementation of pre-testing and design of AV-routes take place in simulation frameworks, described in the second to last chapter of this report.

Document Control Sheet

Start date of project:	01 January 2020
Duration:	48 months
SHOW Del. ID & Title:	Deliverable 8.1: Criteria catalogue and solutions to assess and improve physical road infrastructure
Dissemination level:	PU
Relevant Activities:	A8.1: Physical infrastructure and dynamic maps
Work package:	WP8: Infrastructure functions and systems
Lead authors:	Isabela Erdelean (AIT), Andreas Hula (AIT), Thomas Matyus (AIT), Veronika Prändl-Zika (AIT), Paul Rosenkranz (AIT), Christian Rudloff (AIT), Andrea Schaub (AIT), Christian Stefan (AIT)
Other authors involved:	Anastasia Bolovinou (ICCS), Silvia Capato (SWARCO), Marek Vanzura (CDV), Karl Rehrl (SRFG), Sven Ochs (FZI), Pekka Eloranta (SITOWISE)
Internal Reviewers:	TNO, ATE
Actual submission date:	04/06/2021 (M18)
Resubmission date:	08/06/2022
Status:	RESUBMITTED
File Name:	SHOW_D8.1_Criteria-Catalogue-Physical-Road-Infrastructure_revised_V2

Document Revision History

Version	Date	Reason	Editor
0.1	16.04.2021	Initial version for feedback	Veronika Prändl-Zika (AIT)
0.2	19.04.2021	Feedback on initial version	Christian Stefan (AIT)
0.3	19.04.2021	Feedback on initial version	Andrea Schaub (AIT)
0.4	19.04.2021	Update references	Veronika Prändl-Zika
0.5	29.04.2021	Deliverable structure adapted	Veronika Prändl-Zika
0.6	06.05.2021	Feedback by A8.1 partners and Maria Gemou addressed	All AIT colleagues
1.0	07.05.2021	Finalising for SHOW peer review	Veronika Prändl-Zika
1.1	31.05.2021	All reviewer comments incorporated	Veronika Prändl-Zika and AIT Team
1.2	31.05.2021	Peer reviewed version sent for submission	Veronika Prändl-Zika and AIT Team
2.0	04.06.2021	Submitted version to Project Coordinator	SHOW Mgt team
2.1	04.06.2021	Finalisation for submission	Henriette Cornet, UITP
2.2	30/11/2021	Revised version that addresses the EC review comment	Veronika Prändl-Zika and AIT Team
3.0	01/12/2021	Final revised version for resubmission by Technical Manager	Maria Gkemou (CERTH/HIT)
3.1	07/06/2022	Final revised version, as per the EC request on 27/05/2022, for resubmission by Coordinator	H. Cornet (UITP) J. Beckmann (UITP)

Acknowledgement

We would like to thank all partners in A8.1 (ATE, CDV, CERTH, DTU, ERICSSON, FZI, ICCS, SIEMENS, SITOWISE. SRFG, SWARCO, TECNALIA) for their constructive contributions and discussions. In addition, we would like to thank the SHOW test site managers who participated in our surveys and interviews, as well as project managers from European and national projects and initiatives, and OEMs, all of whom shared their knowledge and helped us understand the current role of physical road infrastructure for automated driving from different perspectives.

Table of Contents

List of Tables

List of Figures

Abbreviation List

Abbreviation	Definition
ACEA	European Automobile Manufacturers' Association
AD	Automated Driving
ADAS	Advanced driver-assistance systems
ADS	Automated driving system
AV	Automated Vehicle
BRT	Bus Rapid Transport system
CAN	Control Area Network
CAV	Connected and Automated Vehicle
C-ITS	Cooperative Intelligent Transport Systems
C-V2X	Cellular V2X
DDM	Digital dynamic map (synonymously used to HD map, defined in chapter 5)
DI	Digital infrastructure
EU	European Union
GDF	Geographic Data File
GDPR	General Data Protection Regulation
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HAD	Highly automated driving
HAV	Highly automated vehicle
HD map	High-definition map
HMI	Human-Machine Interface
I2V	Infrastructure to Vehicle
ICT	Information and communications technology
IMU	Inertial measurement unit
ISO	International Standardization Organisation
ITS	Intelligent Transportation System
LDM	Local Dynamic Map
LDW	Lane Departure Warning
LiDAR	Light Detection And Ranging
LKA	Lane Keeping Assistant
MaaS	Mobility as a Service
MV	Machine Vision
NDS	Navigation Data Standard
OADF	Open AutoDrive Forum
ODD	Operational Design Domain

Abbreviation	Definition
OEM	Operational Equipment Manufacturer
OSM	OpenStreetMap
PI	Physical (road) infrastructure
PT	Public Transport
ROI	Region of Interest
SAE	Society of Automotive Engineers
SLAM	Simultaneous Localization and Mapping
TSDR	Traffic Sign Detection and Recognition
TWSI	Tactile walking surface indicators
V2I	Vehicle to Infrastructure
V2X	Vehicle to X (X represents any entity capable of receiving C-ITS communications)
VRUs	Vulnerable Road Users
WP	Work Package

1 Introduction

1.1 Purpose of the document

This document aims to present the results of the work done on task *A8.1 Physical infrastructure and dynamic maps*. Within A8.1 the role of physical infrastructure (PI) for urban automated road transport has been assessed from different perspectives, resulting in an overview of the physical infrastructure measures implemented at the partner test sites, options and recommendations on physical infrastructure adaptations and steps/a workflow to consider when setting up a digital dynamic map.

In a first step, intensive desk research has been carried out on different aspects on physical road infrastructure.

As a result, requirements for the physical road infrastructure were listed (see Chapter 3), whereby infrastructure elements/conditions such as lane markings, traffic signs, sight distances and public transportation hubs were identified as relevant for automated mobility in urban areas. Existing standards were analysed and their relevance for automated road transport was assessed, infrastructure requirements for automated driving were defined and check-lists created (see Chapter 3.3).

The current role of physical infrastructure for automated road transport was investigated by searching for examples in recent literature, European and national projects as well as by conducting interviews with relevant stakeholders of these initiatives in automated driving (see Chapters 3.4, 3.5).

In Chapter 4, the current PI at the SHOW test sites was subjected to an analysis with regard to critical – potentially risky – PI elements for automated driving in order to gain insights into how problematic road sections are evaluated by the different test sites. In addition, the type of remedial actions taken to ensure adequate road safety were investigated. To this end, SHOW partner test sites were asked to provide input by responding to surveys on the current state of the physical infrastructure and on adjustments already made or planned at the test sites to make them fit for automated driving. See Chapter 4.2 – which largely builds on the findings of Chapter 3 – for the specific measures per PI element undertaken at the SHOW test sites. This information provided insight into the importance that test site managers placed on each PI element for AD in terms of safety.

Chapter 5 presents the SHOW segmentation tool which supports AD test sites in assessing safety levels of given road segments on their routes.

Additionally, in Chapter 6 the need for simulation frameworks implementing public transport hubs and stations in combination with autonomous vehicle operations to gain better insights into complex scenarios was laid out in detail. Such frameworks are needed because automated public transport is still operated on a small scale and these frameworks should help to understand more complex scenarios in a cost-efficient way.

And finally, in Chapter 7 the features and a semi-automated workflow for setting up a digital dynamic map were elaborated.

Chapter 8 will conclude this deliverable and summarize the most important findings made in in A8.1.

The appendices contain material used for the various surveys in A8.1 as well as the segmentation tool manual.

1.2 Intended Audience

This deliverable was designed to address current open questions regarding PI in the context of automated driving for both the internal SHOW consortium and external stakeholders. Within the SHOW consortium, the primary audience is pilot site managers and those involved with the physical infrastructure at the sites (e.g. road authorities, city planners, public transport operators). Yet, outside of the SHOW consortium, the contents of this deliverable should be just as relevant to automated vehicle providers or researchers working on optimizing physical infrastructure for AVs or on the development of HD maps. Additionally, this deliverable wishes to aid those responsible for traffic safety at the SHOW pilot sites, by means of instruments such as a safety evaluation tool for physical infrastructure, which was developed in A8.1 and is part of this deliverable. As this deliverable aims to give general recommendations on physical infrastructure adaptations for automated driving, presents the physical infrastructure at the SHOW pilot sites and proposes a workflow for the generation of HD maps, it is intended to also be useful for external stakeholders like road authorities and planners outside the SHOW project, pilot site managers from other projects, the research community, as well as OEMs in the field of automated mobility.

1.3 Interrelations

Physical infrastructure is hard to be separated strictly from digital infrastructure. On the one hand digital infrastructure often needs physical infrastructure e.g. to fix sensors, cameras etc. on PI assets, on the other hand, challenges with physical infrastructure and associated safety issues could be overcome with digital infrastructure (e.g. if the sight distance is limited due to physical infrastructure, it can be expanded via communicating the missing areas, perceived from stationary sensors or other vehicles. For this communication, digital infrastructure is needed).

Also, this deliverable discusses digital dynamic maps, which can be categorized as physical infrastructure since they present a copy of the real environment, but as they also include dynamic real-time information and are represented digitally, they could be categorized as digital infrastructure as well. Therefore, interrelations with WP 8.2 On-site digital and communication infrastructure exist.

For the purpose of the document, we try to distinguish between physical and digital/communication infrastructure as follows:

Table 1: Distinguishing physical and digital infrastructure elements based on [1]

ODD attribute	Physical / Digital infrastructure
Road	Physical
Road markings	Physical
Traffic signs	Physical
Shoulder or kerb	Physical
Road furniture	Physical
Speed range	Physical
HD map	Digital representation of physical infrastructure: Addressed in this deliverable

ODD attribute	Physical / Digital infrastructure
Satellite positioning	Digital[1]
Communication	Digital
Information system	Digital
Traffic management	Digital – addressed in A8.3
Fleet supervision	Digital

The communication systems often need physical infrastructure to be functional (like road furniture for real-time information on public transport, RSUs, traffic lights). Here we define those parts as physical infrastructure, that can be used without digital infrastructure. To give some examples, this includes:

- Road furniture as a physical element on the road, that could be used as a landmark within a digital dynamic map.
- RSUs are considered as digital infrastructure, as they are useless without it. The existence of such an element can be acknowledged physically e.g. in limiting sight distances.
- Traffic lights are physical infrastructure when acknowledging their physical position and classic visual signals – any other form of communicating right of way is considered digital infrastructure.

Besides the relations between physical and digital infrastructure there is also a strong interrelation with the activities at the SHOW pilot sites (WP12) as they provided information on the status and planned adaptations for physical infrastructure, as well as the use of HD maps. In addition, they are a target audience to consider the use of the requirements defined in this deliverable to evolve their pilot sites.

Finally, there are interrelations to WP10, as knowledge gained within this deliverable on PT hubs will be used as an input for the simulations and WP1 (A1.3), as the use cases defined in D1.2 are used in the deliverable. Also, there are interrelations to the system architecture and communications layers in WP4 (A4.1 and A4.2) in the field of digital dynamic maps, where data is shared and communicated.

[1] GNSS signal availability and quality is discussed within the interviews with pilot site managers outside of SHOW and the desk research for digital dynamic maps but not addressed specifically.

2 Methodological Approach

This chapter presents a description of the methodology employed to achieve the goals of task A8.1 and on which the subsequent chapters are based on. The methodological approach was two-fold: firstly, a wide desk research of the latest literature was performed on physical infrastructure elements for AD, existing standards and regulations, segmentation of physical infrastructure, public transport hubs and digital dynamic maps. Subsequently, a series of surveys and interviews were developed to further gain relevant knowledge by addressing OEMs, EU projects, national initiatives and pilot site managers on the topics of physical infrastructure requirements for AD and Digital Dynamic Maps respectively.

Furthermore, objective quality criteria and relevant standards relating to physical infrastructure for automated driving were investigated in the existing literature, the results of which can be found in sub-chapters 3.1 and 3.2.

In order to provide information on the available physical infrastructure at the pilot sites, a dedicated software tool was developed to classify different road elements due to specific site characteristics and provide a methodology for a quick-scan road safety assessment concerning lane markings, traffic signs and sight distances.

Deliverable 4.1 of SHOW also offers a review of additional available standards used in PT, along with indications on their applicability and current usage. The conceptual architecture view in D4.1 includes all PI and DI actors/interfaces as derived from SHOW UCs' review and offered relevant findings also for A8.1.

The following SHOW UCs, which guided the work in A8.1, were considered:

- Use case 1.1: Automated passengers/cargo mobility in cities under normal traffic & environmental conditions
- Use case 1.2: Automated passengers/cargo mobility in cities under complex traffic & environmental conditions
- Use case 3.4: Automated service at a bus stop.

These use cases were specifically selected because they are most relevant for the impact of physical infrastructure on automated driving. The other SHOW use cases do not have direct impacts on the physical infrastructure and vice versa.

2.1 Desk research

2.1.1 Physical road infrastructure

An in-depth desk research was performed across state-of-the-art literature. To understand the full scale and scope of the research, a wide set of key words was developed along with the task participants, in order to identify as many projects, papers, reports and other documents that could be relevant for this analysis. Table 2 presents the key words used in the literature review for identifying the requirements for physical infrastructure adaptations for automated urban mobility.

Table 2: Key words for desk research

Key words	
• Road infrastructure for automated driving • Urban automation • Testing on public roads • Urban use case • Automated shuttle bus • Physical road infrastructure • Lane markings • PT stations • Hubs • Road infrastructure requirements for AV	• Public test sites • Automated buses • Validation of results on public roads • Urban shared mobility • Autonomous shuttle buses • Technological challenges for deployment • Role of road infrastructure on automation • Physical infrastructure adaptations

The inception point for the literature review was a list of 19 ongoing and completed EU projects, funded under the H2020 funding frame, recommended by the project officer of SHOW during the project kick-off meeting. Furthermore, this search was complemented by a wide investigation across national projects and initiatives, EU databases and knowledge bases (such as TRIMIS [2], connectedandautomateddriving.eu [3] and CORDIS [4]), as well as research papers, journal papers and other documentation that included results on urban automated mobility.

The initial search results were recorded in a spreadsheet, which included brief data on each project/initiative identified. The following data were included in the first data collection step:

- **Name**: Full name of project/initiative
- **Start, End, Duration**: Date of the start and end of the project, as well as its duration
- **National/EU**: The source of the project, whether national or EU funded
- **Website**: URL of the project website
- **Brief scope**: Short description of the project aim
- **Relevance for SHOW A8.1**: Through a brief analysis of the project results (if public), a description of the relevant findings for the work of task 8.1
- **Further investigation**: a recommendation whether the project/initiative should be investigated in more depth

Based on the recommendations mentioned above, a selected number of projects were investigated further, by going through the project deliverables and/or by contacting the project manager/contact person for a potential cooperation. Furthermore, as mentioned above, EU databases such as TRIMIS [2] and CORDIS [4] were explored to further identify potential national initiatives and projects that could provide relevant results. The partners were also tasked with reporting on initiatives and projects from their own countries and regions. The final step was to assign specific literature for review to each partner contributing to the task. A common template was developed and used to further describe and present the results of the relevant projects for Activity 8.1.

More than 60 projects were reviewed. After an initial selection process, based on the data collected in the spreadsheet as well as expert assessment of the task partners, a total of 18 EU projects and 3 national projects were considered for further investigation.

Whenever information was not available publicly, the project manager was contacted in the subsequent stakeholder interview step. Figure 1 presents an overview of the distribution of EU and national projects and initiatives included in the first round of desk research. In addition, journal and conference papers were identified and analysed for potentially relevant data. The results of this review can be found in Chapter 3.4.

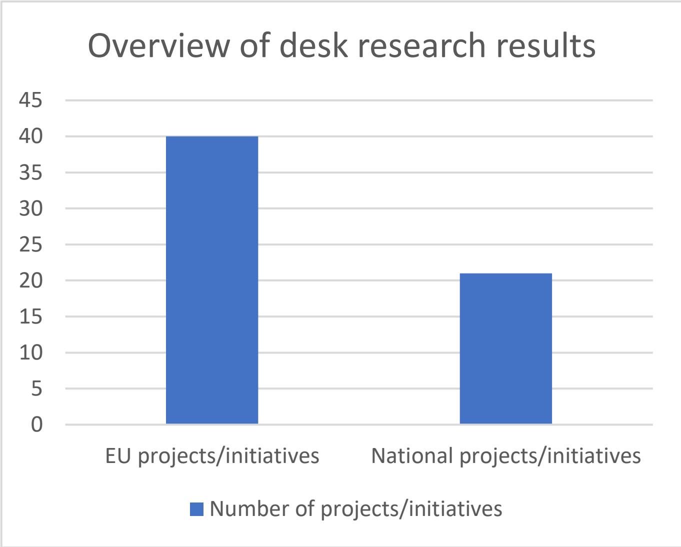


Figure 1: Overview of results of desk research.

2.1.2 Segmentation of physical road infrastructure

The physical infrastructure (PI) at the pilot sites is of major importance for assessing if it needs to be improved for automated urban mobility to function seamlessly. Based on stakeholder interviews and a literature research, a classification process for different road segments (intersections, curves/turns, pedestrian crossings, etc.) was defined to determine what constitutes a representative safety level for a given type of site. The process was finalized in several internal workshops and integrated in a software tool to make the segmentation process more applicable.

Table 3: Key words for desk research on physical infrastructure.

Key words
• Lane markings • Traffic signs • Sight distances • Infrastructure requirements for AD

2.1.3 Public Transport hubs

On the topic of Public Transportation (PT) hubs, desk research was performed to determine necessary adaptations to PT hubs to make them ready for the inclusion of automated transit options. This included a scan of the projects described in section 2.1.1 as well as scientific literature and public reports.

Due to the current status of automated vehicles in public transit, current research focuses on small fleets of automated vehicles in public transit. Thus, little practical experience of the inclusion of AVs in Public Transport Hub environments was gained so far, since the functionality of transit hubs can really only be tested in practice once certain numbers of vehicles and passengers are present at these hubs. As a result, the research in this area concentrates on simulation studies and provides only limited input and recommendations for the design of AV-ready PT hubs.

Due to this shortcoming, the following approach was used to determine recommendations and gaps in research that can be filled within the SHOW project (WP10):

1. Knowledge on regular PT hubs were extracted from literature and national standards for PT hubs.
2. The recommendations for regular PT hubs were scanned for necessary adaptations known from literature and gaps in knowledge on the inclusion of AVs into existing PT-hub infrastructure using the list of keywords in Table 4.

Table 4: Key words for desk research on PT hubs.

Key words
• physical infrastructure • digital Infrastructure • V2X • public transport hubs • autonomous public transport • pedestrians and autonomous vehicles

Two results were derived from this method. First, a description and a list of recommendations given in Chapters 3.2.4, 3.2.5 and 3.3.4 and second a guideline for simulation studies to be performed as part of SHOW WP 10 given in Chapter 6.

2.1.4 Digital Dynamic Maps

To accurately represent the state of the art for acquiring and managing the different data sources of digital dynamic maps a review of available expertise was conducted. It consisted of online research and a review of the above-mentioned projects on physical infrastructure regarding the topic of digital dynamic maps. Also, other projects and information on digital dynamic maps was provided to the project consortium via direct expertise or contacts to working groups.

As the concept of digital dynamic maps is developing very fast, the online research was kept general in scope in order to figure out which topics were currently most actively researched. Also, the search focused on publications from 2019 or newer. The key words used can be seen in Table 5.

Table 5: Key words for desk research on Digital dynamic maps.

Key words
• HD maps • Maps automated driving • Static map automated driving • Automated driving map • Lanelet2

The key word "HD maps" lead to the most results. The specific search on Lanelet2 resulted from the knowledge that some test sites use this format. In total, about 45 scientific papers and other publications were found.

While looking through the projects for physical infrastructure, it was also checked whether they addressed digital dynamic maps. In total, there were 7 EU-projects and 3 national projects found.

In addition, working groups and reports from the scientific network of the responsible persons for digital dynamic maps were included in the search. This led to an additional 5 documents included in the desk research.

2.2 Interviews

2.2.1 Interviews with OEMS and other EU and national initiatives

To complement the literature review, a set of brief questions was developed in order to collect further data on the road infrastructure requirements and adaptations necessary for urban automated mobility. The questions were sent and discussed with two of the OEMs involved in the SHOW project, as well as with managers of eight EU and national projects and urban automation pilots identified in the literature review. Overall, two OEMs and eight project managers were contacted resulting in answers from two OEMs, four European projects and one national initiative.

The list below provides the questions used for the interviews.

1. How did you take into account the physical road infrastructure when preparing the pilot tests in your project (e.g. traffic signs, lane markings, junctions, sight distances, slope, road condition)?
2. What physical road infrastructure did you consider relevant for the planning of the pilot tests?
3. Did you use physical infrastructural elements to increase the level of awareness/safety for automated vehicles?
4. How does the automated vehicle take into account the physical road infrastructure on the road?
5. What infrastructure elements do the vehicle's sensors (cameras, LIDAR, radar) detect/ need to detect in order to ensure operation? (e.g. lane markings, traffic signs)
6. How could infrastructure elements impede the vehicle's operation? (for e.g. traffic sign obscured by vegetation, road slope level)
7. In case of lost GPS signal, how does the vehicle continue operation and how is it influenced by the physical infrastructure?
8. How do the following road infrastructure elements influence the vehicle's operation?

   a. Visibility, reflectivity and detectability of lane markings (especially in adverse conditions)
   b. Traffic signs (consistency, standardization, detection)
   c. Quality, material, slope of road surface
   d. Sight distances and visibility at junctions (definition of minimal sight distances)
   e. Accessibility and safety of PT hubs and stations
   f. Temporary road works.
9. What are the requirements that the current generation of vehicles set to the infrastructural environment?

The results of these interviews can be found in Chapter 3.5.

2.2.2 Interviews with pilot site managers targeting the use of DDM

For further knowledge about digital dynamic maps and especially their use at the SHOW test sites, interviews with the test site managers were conducted. There was a questionnaire created, which consisted of the following questions:

1. Which data elements are used by the pilot sites in the HD map (data catalogue available)?
2. Is it simply a virtual track or a more comprehensive representation of the physical environment?
3. Which formats are used to represent the HD map (OpenDRIVE, Lanelet2, IPG Road5, NDS Open Lane Model, other)?
4. How is the HD map generated?
5. Who is the map provider?
6. What is the HD map used for (driving, positioning, ...)?
7. How is the data quality assured?
8. How are traffic rules represented?
9. How do the pilot sites handle map updates? Are there any processes defined/in use?
10. What about local dynamic HD maps? Are they used? If yes:
    a. How are they generated?
    b. Which dynamic data is used for?
    c. Which data interface are used?
11. Which software tools are used to manage HD maps?
12. Are there already plans how to generate/update maps in future?

All Mega and Satellite site managers of SHOW were contacted between June and November 2020 to find out if they already use or are planning to use digital dynamic maps and if so, a telephone conference to discuss the questionnaire was proposed. Telephone conferences were held with six test sites, while two test sites preferred to fill the questionnaire electronically.

In the phone conferences, additional general questions on the test site or specific questions on their view on challenges were asked. Overall, from 11 of the 14 Mega and Satellite sites answers were given, although three out of them explained that they do not use such maps or were not able to give information at this phase.

The results of these interviews can be found in Chapter 7.1.2.

3 Physical road infrastructure requirements for automated urban mobility

Chapter 3 uses a literature review to analyse in detail the quality requirements for PI that are necessary for automated driving (AD) with regard to safe operation (subchapters 3.1 to 3.3). Subchapters 3.4 and 3.5 bring together information on the role of PI for AD in EU and national projects and initiatives.

All this forms the basis for the research approaches and structure of the surveys in Chapter 4, which presents the conclusions drawn from the theoretical work in this chapter and places them in the context of the SHOW test sites.

3.1 Impact of physical infrastructure elements on AD

Multiple factors are involved when discussing the successful implementation of Automated Driving Systems at different automation levels, but a major factor is technical reliability. The reliability of these systems strongly depends on their optimal functionality under varying road infrastructure and transnational differences.

According to [5], infrastructure-related factors such as road surface conditions, road edges and road delineation influence AV performance (e.g. lane assistance systems).

The following chapters investigate in detail objective quality criteria for physical infrastructure including the visibility and detectability of lane markings, traffic signs and sight distances.

It is important to emphasise here that the information obtained in this chapter formed the basis for the assessment of the existing physical infrastructure at the SHOW pilot sites (see Chapter 4).

3.1.1 Lane markings

Lane markings include longitudinal markings, arrows, transverse markings, text and symbols and serve among else to delineate the roads, to separate opposing traffic streams and to divide the total road area into sub-areas for different road users [6]. Road markings together with road studs form the means of horizontal signalisation.

The following lane marking parameters influence machine-vision performance in multiple ways, also due to the fact that some of them interact with each other. Hence, adapting all measures at once doesn't necessarily mean that the detection rate of lane markings will reach an optimum. Furthermore, international standards and norms (see chapter 3.2) limit the scope of national road administrations concerning infrastructure requirements in favour of a harmonized transnational approach.

Luminance coefficient (Q_d):

Daytime dry luminance coefficient (Q_d) is a key factor for daytime pavement marking visibility. An object on the road is identified as something different from the road itself if a sufficient contrast exists between the object surface and the road surface, i.e. it is either lighter or darker than the road. Q_d depends on both the light reaching the object and the road and on the way the light is reflected toward the observer [7].

The luminance coefficient is often used to characterize emission or reflection from flat, diffuse surfaces. Luminance levels indicate how much luminous power could be detected by the human eye looking at a particular surface from a particular angle of view. Q_d is thus an indicator of how bright the surface will appear.

Concerning daytime visibility of lane markings, [8] states that the reflection in daylight or under street (diffused) lighting has limited impact on machine vision performance when other factors are consistent and at acceptable levels. Jurisdictions around the world have varying Q_d performance standards. For example, in Croatia, the minimum Q_d has a range between 100 mcd/lx/m^2 to 160 mcd/lx/m^2, depending on the type of line markings and Swedish research recommends a minimum Q_d value of 85 mcd/lx/m^2 [9]. Austrian regulations [6] require at least Q_d > 100 mcd/lx/m^2 for white road markings on asphalt roads and Q_d > 130 mcd/lx/m^2 for cement concrete under dry conditions.

NCHRP 20-102(06) research report [10] suggests that in order to achieve consistently high MV detection confidence ratings, the contrast ratio of the longitudinal pavement markings relative to the adjacent pavement should be used as a validation measure.

Austroads Research Report AP-R633-20 [8] advocates a minimum 3-to-1 Q_d contrast ratio (marking Q_d to pavement Q_d) between pavement markings and surrounding substrate to support machine-vision-enabled, lane-guidance functions. While the off-road trials showed some support for a lower contrast ratio of 2.5 to 1 (see Figure 2), there were some concerns over the positive influence on results of the sharp edge of the pavement markings. To be conservative, the contrast ratio of a minimum 3-to-1 was recommended.

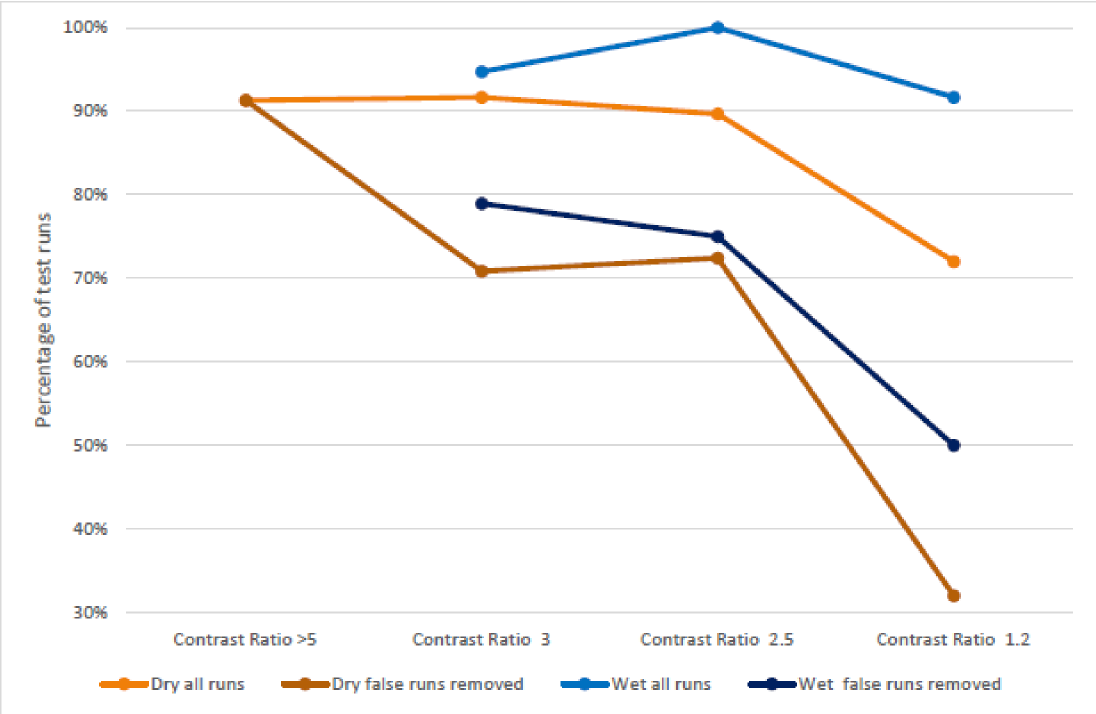


Figure 2: Pass rate at reduced contrast ratios [8].

<u>Retroreflectivity</u> (R_L):

Retro-reflectivity is the ability of a road marking to reflect light from a vehicle's headlights back to the driving position of a vehicle (see Figure 3). Initially it will be determined by the amount of glass beads spread on the line. The continuing performance of the line is determined by the amount and quality of glass beads included in the body of the road marking. Retro-reflectivity is measured using a piece of equipment known as a Reflectometer and is expressed in mcd/m^2/lux.

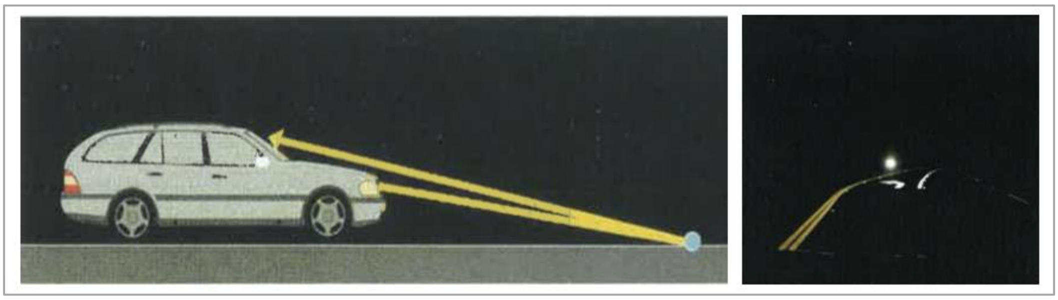


Figure 3: Lane marking retroreflectivity

Retroreflectivity R_L of pavement markings is a proxy for night visibility. Research shows that pavement markings with a very low retro-reflectivity due to ageing, tend also to score low in factors related to daylight visibility, i.e. a low night visibility is also poor during the day [11]. While the ageing or wearing mechanisms are not entirely the same for the Q_d and R_L of pavement markings, there is a correlation such that pavement markings with a higher R_L are expected to have a corresponding higher luminance coefficient Q_d.

According to [8], the LKA line detection performance deteriorates as R_L reduces over time. Retroreflectivity levels higher than 100 mcd/lx/m^2 lead to increased LKA average detection rates in comparison to lane markings with $R_L \leq$ 100 mcd/lx/m^2 (see Table 6).

Table 6: Machine-vision performance for R_L higher than 100 mcd/lx/m^2 [8].

Light	Pavement	LKA average detection rate	LKA detection rate 95% confidence interval	Mobileye average interval	Mobileye quality 95% confidence interval
Day	Asphalt	90.0%	98.5% – 99.5%	2.733	2.697 – 2.766
	Concrete	93.5%	90.4% – 96.4%	2.922	2.894 – 2.947
Night	Asphalt	98.7%	97.8% – 99.4%	2.945	2.925 – 2.963
	Concrete	99.6%	98.8% – 100%	2.892	2.859 – 2.922

At the 2017 TRB Annual Meeting, [12] published research on pavement marking retroreflectivity levels under varying road conditions. Overall, higher retroreflectivity R_L increases the machine-vision detection ratings up to about 400 mcd/lx/m^2 where the ADS camera confidence rating reaches its maximum.

Based on an overview of existing national practices and research and discussions between consumer associations, safety organisations, vehicle manufacturers and sign and marking industries, EuroRAP [13] states that road markings on Europe's roads should adopt a simple and memorable "150 x 150" standard. Firstly, lane and edge marking should be a consistent 150 millimetres wide and secondly, these markings in the dry should reflect light at 150 mcd/lux/m^2.

Austroads Research Report AP-R633-20 [8] conclude that most state road agencies in Australia have adopted the Austroads Harmonisation of Pavement Markings and National Pavement Marking Specification [14]. With varying funding available, they have applied either a systematic pavement marking upgrade program, reinstatement-after-roadwork strategy, or upgraded through regular maintenance to achieve the suggested 150 mm-width edge line with a minimum retroreflectivity of 150 millicandelas.

Table 7: Line marking performance limits [8].

Parameter	Minimum		**Source:** AS 4049.1, AS 4049.2, AS 4049.3, AS 4049.4
	Value	**Units**	
Dry retroreflectivity	• 100 (global standard) • 150 (recommended as intervention level)	mcd/lx/m^2	• Retroreflectivity measured using a 30 metre geometry reflectometer • appropriate minimum intervention level – the pavement will take longer to 'wear down' the to the intervention level
Wet retroreflectivity	• 80 • 100 (recommended for concrete pavements)	mcd/lx/m^2	• In general, large Type D Glass Beads needed to provided wet-night visibility • Pavement retroreflectivity falls to near zero and pavement markings are considered reasonably visible at values as low as 80 mcd/lx/m^2 • Concrete pavement/light aggregates can significantly reduce contrast

Line marking width:

Provides a distinct edge for machine vision to detect and interpret existing line markings on the road surface. According to [8] wider lines help automated vehicles to distinguish between real line markings and other misleading longitudinal structures such as tar seams, tyre marks or cracks in the asphalt.

Line widths smaller than 80mm are unlikely to be detected by machine vision and hence used as AV lane guidance. In contrast, line markings wider than 100mm generally provide (mean) LKA detectability of more than 95%, no matter if the pavement is asphalt or concrete and what type of line (dashed, solid) has been used.

This result is in accordance with a similar US study [12] where 6-inch (152 mm) lane markings were compared to 4-inch (102 mm) markings. The wider pavement markings performed better, especially at long testing distances. In addition, wider pavement markings appear to counter lower retroreflectivity levels, indicating that the service life of pavement markings may be extended when 6-inch markings are used in place of 4-inch markings.

A minimum line width of 100 mm is generally supported, as are wider line widths (150 mm) to support machine-vision-enabled, lane-guidance functions. When the visibility of pavement markings is good for both R_L and Q_d, pavement marking line widths, longitudinal lines, whether 100 mm or 150 mm, may be read by machine vision systems with a similar level of success [8].

Lane colour:

The lane colour provides little value for lane marking detectability apart from aiding contrast ratio algorithms in some vehicles, mostly for light-colored pavements (e.g. concrete). According to [8], yellow lines are reasonably well read by AV but solid white lines that appear amid groupings of yellow lines disrupt lane-keeping functions. To improve machine vision performance, old line markings, regardless of their colour, should be removed before new line markings are applied.

Road pavement material:

Pavement ‘brightness’ can degrade machine-vision systems’ ability to detect longitudinal pavement markings in some conditions because it reduces contrast between the pavement marking and substrate. Small statistically significant differences between asphalt and concrete in LKA daytime detection (aggregated over all line widths) indicate that both solid and dashed lines on concrete pavement are less detectable by machine vision than the same corresponding line type on asphalt (see Figure 4). No difference between asphalt and concrete during night-time conditions were found during the test trials.

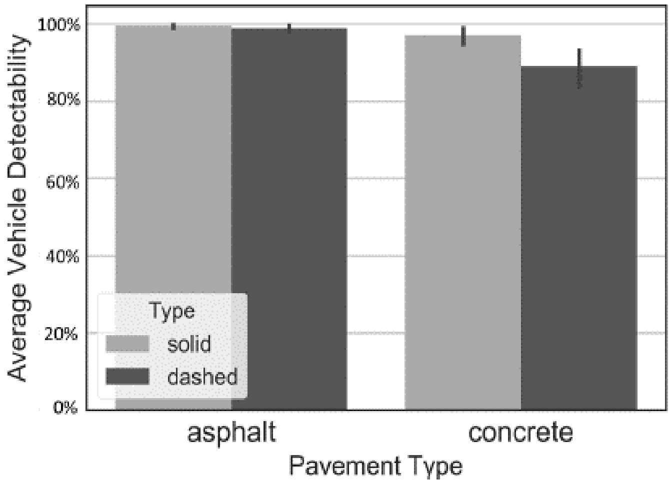


Figure 4: Average daytime vehicle detectability for different pavement/line types [8].

Line spacing:

Pavement marking configurations, such as longitudinal pavement marking’s dashed line spacing and exit diverge triangles, were identified as having an impact on the performance of machine-vision-enabled, lane-guidance functions. LKA systems for AD usually detect solid lines better than dashed lines, no matter if the road surface is asphalt or concrete (see Table 8). Yet, the impact of line spacing is speed-based and also depends on the quality of the line marking.

Table 8: Summary of average performance metrics for different line marking types [8].

Statistics	Solid continuous markers	Dashed line markers
Sample size	4,950	4,873
Mean Vehicle LKA Detectability	0.91	0.79
Mean Vehicle LKA Detectability (95% confidence interval)	0.907 – 0.921	0.78 – 0.80
Mean Mobileye Quality	2.78	2.52
Mean Mobileye Quality (95% confidence interval)	2.77 – 2.80	2.50 – 2.54

The type of line marking to be used differs by road class and use case, according to (inter-)national norms and regulations (see Chapter 3.2). Dedicated lane markings (e.g. edge lines) are harmonized across Europe and cannot be varied.

Lane width:

Based on consultation with vehicle manufacturers [8], vehicles need to travel on lanes with a certain width range to activate LKA and LDW features. The minimum width varies between manufacturers. On-road and off-road evaluations also provided some support that too-narrow lanes (those narrower than 2.8 m) are challenging for the machine vision systems of most vehicles tested, particularly if the narrow lane has no edge lines. Literature review and stakeholder engagement indicated some vehicles may have reduced pavement marking detection at lane widths less than 3.0 m.

Bigger lane widths may cause issues for some vehicles' detectability, i.e. vehicles can unexpectedly lose lane keep functions.

In contrast, narrow lane widths (smaller than 2.5m) are often used to disable lane support systems in order to prevent AV to "bounce" of lane boundaries and creating customer dissatisfaction.

3.1.2 Traffic signs

Vertical traffic signs are signs placed along the roads that inform drivers of road conditions and restrictions or the possible direction of travel. They are source of information for a driver, which are designed to provide information at a glance. That also means they are designed to stand out of surrounding, thus, detection challenge is well defined. Traffic sign recognition is one important feature for automated vehicles especially in mixed traffic (automated vehicles and common vehicles). That ensures situational awareness of every traffic participant. Traffic signs are standardized but vary around the globe. In Europe, traffic signs are standardized through "Vienna Convention on Traffic Signs and Signals".

Shapes are used to categorize different kinds of signs: circular signs represent prohibitions including speed limits, triangular signs represent warnings, and rectangular signs are used for recommendations or to supplement information [15]. It needs to be mentioned that European effort to standardize traffic signs was created in 1968, but there is still a significant variety of traffic signs across countries, sometimes even throughout the country. For instance, inter-variability occurs mostly in those countries which do not follow the common convention, intra-variabilities are seen in countries which do follow the convention [15], [16]. In Europe, there is established size, shape, and other parameters, but every state can choose its own symbols or pictograms with its own meaning. Figure 6 shows this kind of diversity. For example, Croatia and France use two similar, but different signs (symbols) for pedestrian crossing (Figure 6 second row) and Belgium uses signs for speed limits with and without additional unit ("km" in case of Belgium). Germany uses different symbols for pass-right signs (Figure 6 fourth row) and Croatia uses different background colour for danger and prohibitory signs (Figure 6, first and third rows) [17].

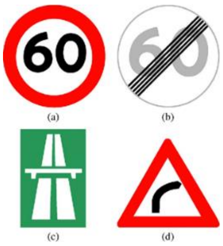


Figure 5: Examples of European traffic signs [16].

Figure 6: Symbol and inter-variability of European traffic signs [17].

Figure 7 shows placement of traffic sign by a road and at a highways. Correct placement is important for human driver as well as for TSDR system to see them in every traffic situation.

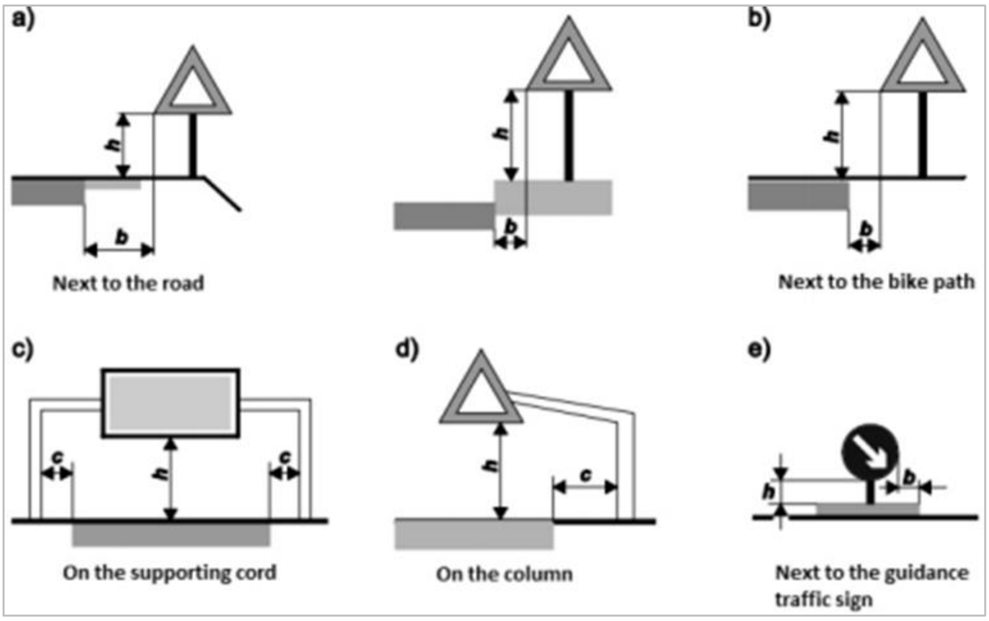


Figure 7: Placement of traffic signs [18].

Figure 8 shows values of the location dimension for different road types and represents standards for traffic signs placements in urban, highway and peri-urban environments.

Least lateral distance, m						
inhabited area	curbs next to the road		*c*	outside the inhabited area	*b*	*c*
	yes	no				
	b					
Byway	0,25	0,50	1,25	v_t < 50 km/h*	0,75	1,25
Highway	0,50	0,75	1,50	50 ≤ v_t < 100 km/h	1,00	1,50
City Highway	1,25	1,25	2,00	v_t ≥ 100 km/h	1,50	2,00

Least lateral distance, m	
Type of traffic sign and location	*h*
Over the road	≥ 4,70
Next to the road where pedestrian traffic is not available	≥ 1,20
Bike path, sidewalk or where pedestrian traffic is not available	≥ 2,25***
Signboards and railway crossing pre-warning sign	0,60 ≤ 0,80
Portable traffic signs	0,20 ≤ 0,30

Figure 8: Technical specification e-UT-04-02-11-2012 - construction, application and location [18].

Traffic signs anomalies

In addition to visibility conditions, marking defects, shadows, divergent and inconsistent placement of signs can lead to misunderstanding and thus an accident. Human drivers are able to overcome these discrepancies, but traffic sign recognition systems need to be taught to properly categorize signs under unusual conditions.

This problem can be solved by collecting data of these anomalies and integrating them into simulation testing. First step in learning process is anomaly classification such as visibility, brightness, recognizability, position and the complexity of sign at the permitted speed [19]. Sign recognition and response to them is further complicated by traffic restrictions on individual road sections.

Figure 9: Example of non-standard sign location [18].

Another important factor is the size of the text, which must be recognizable from a sufficient distance, as well as the quality of the text must be sufficient. The amount of information on signs must be readable for humans in the required period of time. Some traffic signs may contain too much information, which can cause problems or ambiguities.

Figure 10: Example of a devalued sign text [18].

Figure 11: Example of a sign with excessive amount of information [18].

Anomaly classification method

To classify anomalies, several methods exist. One of them is based on evaluating classes of errors. These error classes are quality, condition, quantity, visibility, perception, recognizability, clarity and interpretability at the permitted speed. To prevent accidents, a classification system would help to evaluate traffic signals based on various aspects. Based on the developed methodology, each attribute will receive a numerical value, thanks to which it would be possible to determine the robustness of the system. [18]

	Visibility 1= not visible 5= visible	Clarity 1= dirty 5= clear	Recognizability 1= not recognizable 5= recognizable	Position 1= Improper 5= standard	Simplicity 1= complex 5= simply
Figure 2. 	1	4	2	2	4
Figure 3. 	5	2	2	2	1
Figure 4. 	5	5	5	5	1
Figure 5. 	5	5	1	1	1
Figure 7. 	5	5	1	5	5

Figure 12: Traffic sign anomaly classification [18].

Traffic sign database

The traffic sign database is a basic requirement in the development of TSDR ("Traffic Sign Detection and Recognition") systems. This database is used for the TSDR learning and testing process, as it contains a large number of traffic signs with various conditions.

Dataset	Country	Classes	TS Scenes	TS Images	Image Size (px)	Sign Size (px)	Include Videos
GTSDRB (2012 and 2013)	Germany	43	9000	39,209 (training), 12,630 (testing)	15 × 15 to 250 × 250	15 × 15 to 250 × 250	No
KULD (2009)	Belgium	100+	9006	13,444	1628 × 1236	100 × 100 to 1628 × 1236	Yes, 4 tracks
STSD (2011)	Sweden	7	20,000	3488	1280 × 960	3 × 5 to 263 × 248	No
RUGD (2003)	The Netherlands	3	48	48	360 × 270	N/A	No
Stereopolis (2010)	France	10	847	251	1920 × 1080	25 × 25 to 204 × 159	No
LISAD (2012)	US	49	6610	7855	640 × 480 to 1024 × 52	6 × 6 to 167 × 168	All annotations
UKOD (2012)	UK	100+	43,509	1200 (synthetic)	648 × 480	24 × 24	No
RTSD (2013)	Russia	140	N/A	80,000+ (synthetic)	1280 × 720	30 × 30	No

Figure 13: Publicly available traffic sign database [20].

Detection, tracking and classification method

TSDR is currently a driver support system that is used to warn drivers in adverse conditions. The vision-based system usually has the ability to detect and recognize all traffic signs, even those that may be partially obscured or distorted [21], [22] . Its main task is to locate a sign and distinguish it from others [22], [23], [24]. The TSDR procedure can be divided into three phases: detection, monitoring, and classification. Detection refers to the location of traffic signs on the input scene of a video recording, while classification determines what type of sign it is. [25], [26]. In other words, the detection system generates a possible region of interest (ROI) that probably belongs to a traffic sign, while the classification receives all possible ROIs and specifies the traffic sign in more detail or rejects the given area of interest as a false detection [27], [28]. Figure 14 shows the function of the traffic sign detection system. As shown in the figure, the system is able to operate in two modes, a training mode in which a database can be created by collecting a set of traffic signs for learning and verification, and a test mode in which the system can recognize a traffic sign with which it has not been acquainted in advance. In training mode, the image of the traffic sign is acquired by the camera and stored in a database of images to be classified and performed for system learning.

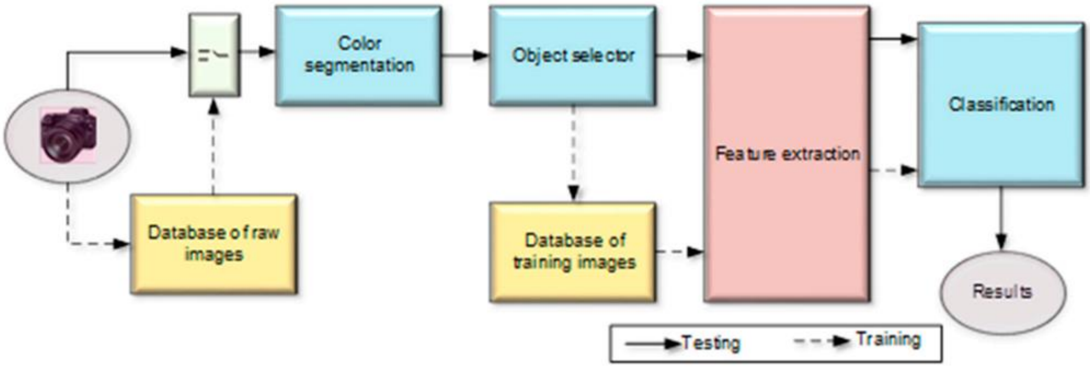


Figure 14: Traffic sign detection system scheme [22].

According to [29], the selection of features has two functions in increasing performance in the learning process. The first function is to eliminate noise and redundant information, thus gaining a better representation and facilitating classification. The second function is to facilitate the subsequent calculation by reducing the property space. In the diagram, the properties are then extracted from the frames and performed in the next step of the classifier training. In the test mode, the same procedure is used, but the extracted properties are used for direct classification of the traffic sign using a pre-trained classifier.

Detection phase

The initial phase in any TSDR system is the localization of potential areas of sign placement from the natural image scene [25], [30], [31]. Traffic signs usually have a specific colour scheme (red, blue, white, etc.) and specific shapes (round, square, triangular, etc.). These inherent features differ from other outdoor objects, making them suitable for computer vision processing and automatically allowing the TSDR system to distinguish road signs from the background [32], [33]. Therefore, detection methods are shape-based, colour-based or hybrid [30], [34].

Method based on colour

The colour-based method is taking advantage of the fact that the road sign is designed to be easily distinguishable from its surroundings, therefore they are coloured with highly visible contrasting colours [25]. These colours are extracted from the input image if the region of interest is found using various processes. The colour-based method has low requirements for computational performance, good reliability and other characteristics that can improve the detection performance [33]. Although, this method can be used only with a high-resolution dataset and not with grayscale images [31]. In addition, there are other problems when using the chromaticity parameter of sensitivity to various factors, such as the distance to the target, weather conditions, time of day, as well as reflectivity, age and condition of the signs markings [25], [30]. Captured images are divided into pixels that share similar colour properties [34]. Then the road signs are extracted using colour thresholding and segmentation based on intelligent data processing. According to [35], detection methods are based on RGB colour space (Red, Green, Blue) [36], [37], hue, saturation, and value (HSV) of colour space [38], [39] or colour space by hue, saturation, and intensity (HSI) [40] and others. The most common colour-based detection methods are shown in Figure 15.

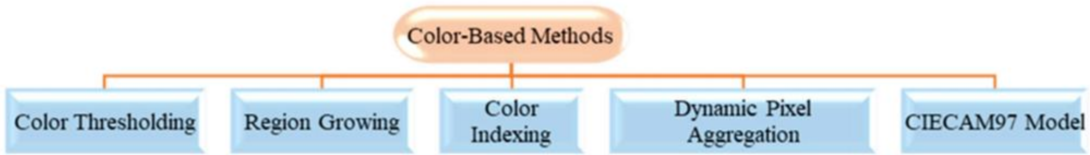


Figure 15: The most used colour-based detection methods [22].

Method based on shape

Just as traffic signs have specific colours, they also have very well-defined shapes that allow them to be detected. The detection of a traffic sign through its shape is governed by the shape detection algorithm by finding the contours and approaching them to reach the final decision based on the number of contours [23], [30]. The advantage is that a ROI occurs [41]. The disadvantage, however, is the need for large computing power [42]. In addition to this disadvantage, one could mention partially covered markings, faded, blurred, or deformed traffic signs. Detection of traffic signs in this method is performed from the edges of the image by analysis using a structural or complex approach [30] [28].

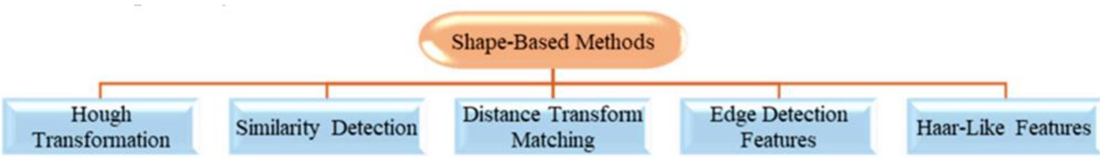


Figure 16: The most used shape-based detection methods [22].

Hybrid methods

As mentioned above, both colour-based and shape-based methods have their advantages and disadvantages. Therefore, researchers have recently tried to improve the efficiency of the TSDR system by combining colour and shape properties. For hybrid methods, the shape is then evaluated after taking into account the colour. Segmentation is performed to narrow the search space, and then shape detection is implemented and applied to those segmented regions [42]. Some studies have combined these two different approaches into detection algorithms [43][44][45][46][47][48].

Tracking phase

In order to increase the accuracy of the information used in identifying the traffic sign, the signs are tracked using a model of movement and time propagation of information. This tracking process is very important for real-time TSDR applications that verify the correctness of a road sign and track the sign to avoid handling the same detected sign more than once, [49].

The monitoring process is performed using a camera mounted on the vehicle, which provides the TSDR system with follow-up images of potential signs. Accepted signs that are further worked with are only those that have appeared more than once. If one of the objects does not prove to be a sign, it is removed to shorten the calculation time [50]. According to [51], the most commonly used tool in the monitoring process is the Kalman filter (see Figure 17). [22]

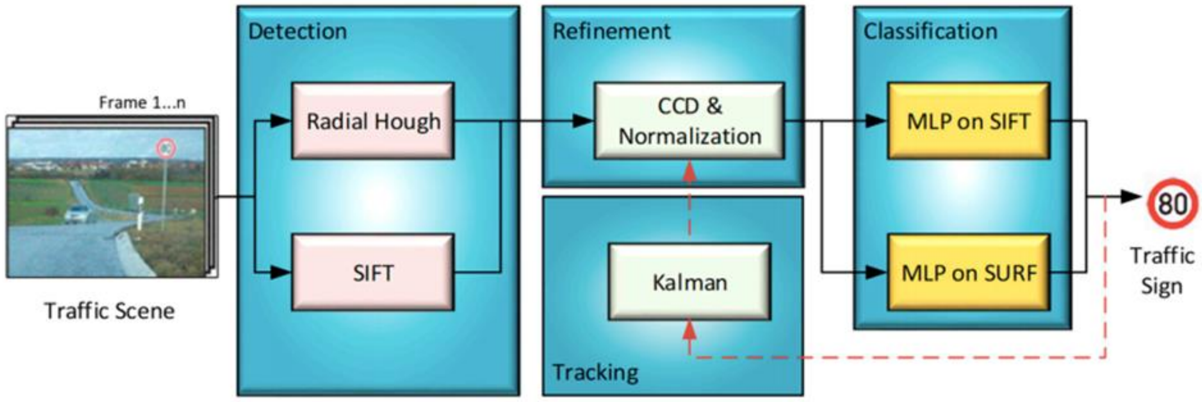


Figure 17: TSDR system includes tracking process based on Kalman filter scheme [52].

Classification phase

After locating regions of interest (ROIs), classification techniques are used to determine the content of the detected traffic signs [53]. Capture of the information the sign communicates is achieved by reading the inner part of the detected traffic sign using the classifier method, which is not based on colour or shape detection. The classifier usually takes a certain set of functions as input that distinguishes candidates from others. The most common classification methods are shown in Figure 18.

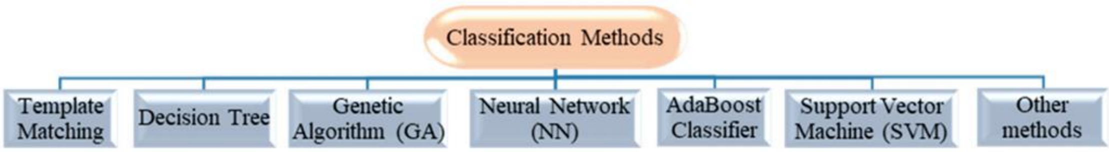


Figure 18: The most used classification methods [22].

Current system challenges

TSDR as an essential part of ADAS is designed mainly for real-time operation to increase driver safety by rapid detection and interpretation of traffic signs. However, there is a number of external challenges that this system may face that significantly reduce its performance. Figure 19 shows the challenges that need to be addressed in the further development of TSDR.

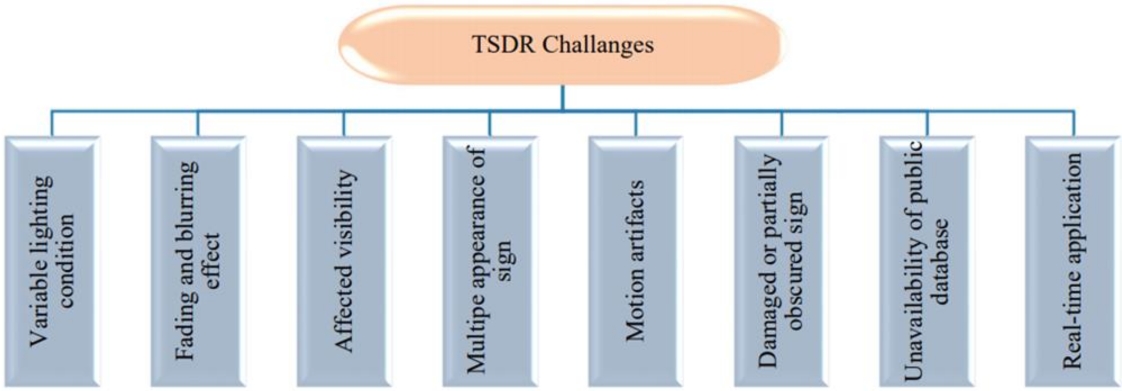


Figure 19: TSDR system challenges [22].

The current challenges are described in detail:

- Variable lighting conditions: Variable lighting conditions are one of the key issues to be considered during the development of the TSDR system. As already mentioned, one of the main characteristics of traffic signs is their unique colouration, which distinguishes them from background information, which facilitates detection. In the outdoor environment, however, changes in lighting greatly affect the colour of the road sign, influencing colour information as not completely reliable for main feature detection. To meet this challenge, methods based on adaptive colour threshold segmentation and highly efficient shape symmetry algorithms have recently been proposed [34], [22].
- Fading and Blurring Effect: Another important problem with TSDR is fading and blurring of road signs caused by distortion from rain or snow. These conditions can increase the number of false positives and reduce the effectiveness of the TSDR system. This problem is well eliminated by the hybrid method based on shape detection [22], [54].
- Affected visibility: Light emitted by vehicle headlights, shadows, and other weather-related factors such as rain, clouds, snow, and fog can lead to poor visibility. Recognizing a sign from an image taken in such cases is a challenging task, and a simple detector may not detect these traffic signs. To solve this problem, it is necessary to improve the quality of the captured images and clarify them using image pre-processing. Pre-processing allows image filtering and converts input information into a usable format for further analysis and detection [55], [22].
- Multiple Occurrence of a Sign: When detecting traffic signs, especially in urban areas that are more crowded with signs, several traffic signs that appear at the same time and similar shapes of man-made objects can cause looping and lead to false detection [22].

- Artefacts in images: Images are captured from a moving vehicle and often a low-resolution camera is used, so these images usually appear blurred. Recognizing blurred images is a difficult task and can lead to false results. In this regard, a possible solution may be the TSDR system, which integrates colour, shape, and motion information. In such a system, the reliability of recognition is increased by incorporating detection and classification with tracking by means of a temporary fusion of information [45]. Detected traffic signs are monitored and individual detections from individual frames (t-t0,..., t) are temporarily combined for total recognition.
- Damaged and partially covered sign: A characteristic feature of the road sign is its unique shape. However, the shape can be altered in many cases by damage, which can cause complications. This can be solved by using hybrid colour segmentation and shape analysis [22], [29].
- Unavailability of a public database: A database is a fundamental requirement for the development of a TSDR system. Used for learning and testing detection and recognition methods. One of the obstacles in this area of research is the lack of a large, well organized and freely accessible public database. A possible solution to this problem is to create a single global database containing a large number of images and videos of roads in different countries around the world. This database must contain all categories of traffic signs in all possible weather conditions and physical conditions of the signs [22].
- Real-time applications: Traffic sign detection and recognition are required to be able to work in real time. Accuracy and speed are the two main requirements of a practical application. Achieving these requirements requires a system with efficient algorithms and powerful hardware. A good choice are learning methods based on neural networks with GPGPU technology [56].

3.1.3 Sight distances

Sight distances stands for distances where driver can behold another vehicle and respond correctly. Ideal sight distance enables a driver of a vehicle approaching an intersection to break and avoid collision, if needed. The introduction of autonomous vehicles will bring new opportunities to improve the safety, mobility, and efficiency of the transportation system. One benefit of emerging autonomous vehicles is that this technology may not only eliminate many driver errors but could also eliminate or mitigate pedestrian collision. Companies and researchers are developing automated vehicle technologies that can function reliably on today’s roads, despite the imperfections of this existing infrastructure. Maintaining and improving road infrastructure, however, could speed up deployment, avoid costlier technology needed to cope with road imperfections, and increase the reliability of automated vehicles. This section will describe standards on sight distances in a directional arc, views at crossroad, observation fields and observation triangles.

At international level, the standard ISO 39001 deals with traffic safety. ISO 39001-Road safety (RTS) management specifies requirements for a road traffic safety (RTS) management system to enable an organization that interacts with the road traffic system to reduce death and serious injuries related to road traffic crashes which it can influence. In Section 6 "planning" there is a list of "performance factors" that covers among other things – Road design and safe speed especially considering separation (on-coming traffic and vulnerable road users such as pedestrians, cyclists, and horse riders), side areas and intersection design.

<u>Views in a directional arc</u>:

The prescribed sight length for stopping must be observed in the directional curve. The required field of view is defined by the envelope curves determining the travel tracks in the length Dz or Dp (see Figure 20) and are provided by:

- on directionally divided roads in space:
  - middle dividing strip
  - unpaved part of the curb
- on directionally undivided roads in space:
  - unpaved part of the curb
  - to the right of the inner edge

To ensure a view across the area outside the body of the road, a viewing field to stop at 0,30 m below the edge of the crown of the road and a viewing field to overtake to a height of 0,60 m above the edge of the road shall be designed (see Figure 20).

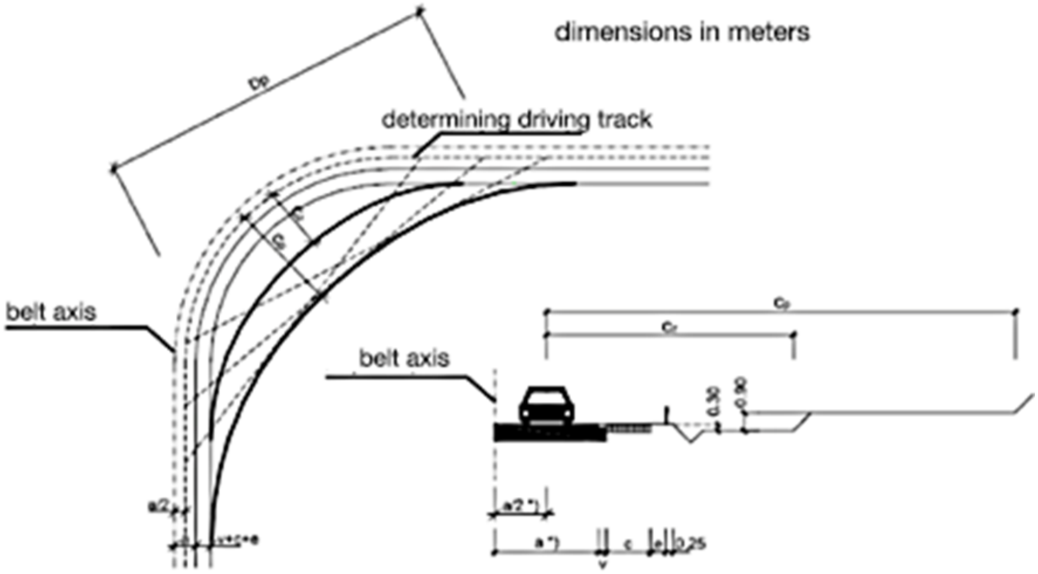


Figure 20: View in the directional curve for stopping and overtaking [57].

<u>View at crossroads</u>

Intersections must be well-arranged that all road users have:

- main road - sufficient visibility at least to stop the vehicle before entering the intersection
- side road - guaranteed view for the decision to cross or connect to the main road without stopping

On side roads, there must be a view of the whole traffic sign, which adjusts the priority in driving on the main road (see Figure 21).

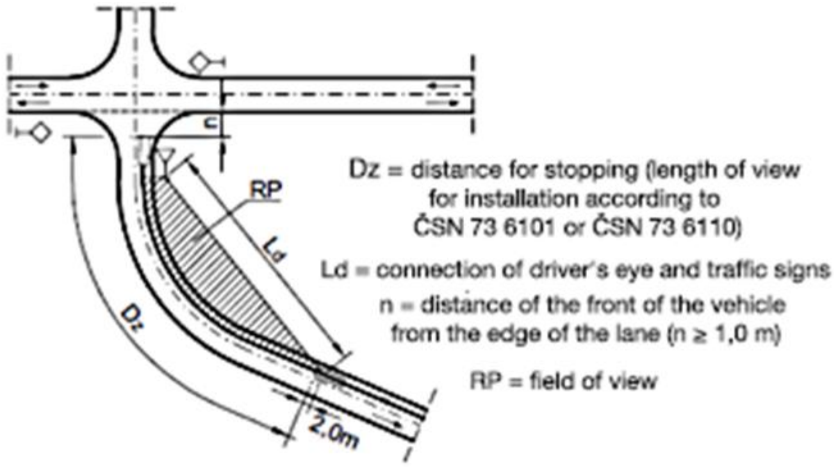


Figure 21: View field enabling a view of the vertical traffic signs and traffic lights [58].

The view between the rays of the intersection and the respective lanes is provided by observation triangles. The lengths of the sides of the triangle depend mainly on:

- maximum permitted speeds (or standard speeds)
- way of adjusting driving priority (right of way)
- layout of the main road

There must be no obstacles in the viewing triangle. Objects in the viewing triangle are considered to be an obstacle to the view:

- higher than 0,25 m
- closer than 0,15 m

The sighting point of the vehicle on the side roads is at a distance of 2,0 m from the front of the vehicle and at the height of 1,0 m above the road (this point represents the driver's eyes). From this point, part of the vehicle approaching the main road at a height of 0,5 m above the ground must be visible.

Observation fields and observation triangles

The driver on the side road must have a view that allows him to find out in time the arrangement of the priority in driving according to traffic signs and to reduce the speed or stop in front of the intersection. The field of view is determined according to the figure (see Figure 21).

The distance for stopping Dz (see Figure 21) is equal to the length of the sight for stopping on roads. To determine the sighting triangles, the following conditions apply:

1) determining priority on roads

- Arrangement A - junction on the main road with the sign "Main road" and on the secondary road with the sign "Stop, give way".
- Arrangement B - Intersection on the main road with the sign "Main road" and on the secondary road with the sign "Give right of way"
- Arrangement C - junction with right-hand traffic

2) composition of the traffic flow on the side road

3) requirement to provide a view for a certain group of vehicles (see Figure 22 + Figure 23)

4) Four typical transverse road traffic arrangements:

- Two-lane communication
- three-lane road (two-lane road with added lane for turning left)

- four-lane road with a central dividing strip with a total width of 4,0 m
- four-lane road with a middle tram strip 7,0 m wide

5) Speed characteristics

- uniform acceleration of vehicles according to the table (see Figure 22)
- vehicle deceleration 2,0 m / s^2
- reaction time for the vehicle on roads with a driving priority of 2,5 s
- permissible limit of the standard or maximum permitted speed of vehicles on the main road caused by road traffic to 75 %

Intersection movements with the largest viewing triangles are decisive for determining the view at level crossings. This is a turn to the left from the side road with respect to the vehicle coming to the junction on the main road from the right and a right turn from the side road with respect to the vehicle coming to the junction along the main road from the left.

Scheme A for an intersection with a sign adjusting the priority on the side road "Stop, give priority to driving" is shown in Figure 24. Vehicle B arrives at the junction from the right on the main road and compares the view for vehicle A, which turns from the side road to the left. Furthermore, a view is determined for the vehicle A branching from the side road to the right towards the vehicle C coming from the main road from the left. The designation is similar for the inter-section with priority in driving on the side road with the traffic sign "Give way" (Figure 25) and for the intersection with priority on the right (Figure 26) View triangles for arrangement C.

Group	vehicles representing the group	vehicle length in m	uniform acceleration in m · s – 2
1	car and vans	6,00	2,2
2	garbage truck, truck, bus	10,00	1,7
3	articulated bus, articulated vehicle	18,00	1,3
4	the longest vehicle according to a special regulation	22,00	1,2

Figure 22: Traffic flow composition [58].

sides of the observation triangle on the side road in m								
transverse arrangement of the secondary road	unbuilt-up area				built-up area			
	group				group			
	1		2, 3, 4		1		2, 3, 4	
	Y_{B1}	Y_{C1}	Y_{B1}	Y_{C1}	Y_{B1}	Y_{C1}	Y_{B1}	Y_{C1}
a	30	20	35	35	20	15	25	25
b	40		40		30		30	
c	55		55		40		40	
d	65		70		50		50	

Figure 23: Arrangement A – lengths of sides of triangles [58].

sides of the observation triangle on the side road in m								
transverse arrangement of the secondary road	unbuilt-up area				built-up area			
	group				group			
	1		2, 3, 4		1		2, 3, 4	
	Y_{B1}	Y_{C1}	Y_{B1}	Y_{C1}	Y_{B1}	Y_{C1}	Y_{B1}	Y_{C1}
a	30	20	35	35	20	15	25	25
b	40		40		30		30	
c	55		55		40		40	
d	65		70		50		50	

Figure 24: Arrangement B – lengths of the sides of the triangle on the main road [58].

sides of the observation triangle on the main road in m						
speed [km/h]	unbuilt-up area			built-up area		
	X_{B1}		X_{c1}	X_{B1}		X_{c1}
	a, b[b)]	c,d	a, b, c, d	a, b	c,d	a, b, c, d
20	20	30	20	15	20	15
30	40	50	40	30	40	30
40	55	70	55	45	55	45
50	70	85	70	55	70	55
60	85	105	85	70	85	70
70	100	125	100	80	100	80
80	115	145	115	–	–	–
90	130	160	130	–	–	–

Figure 25: Arrangement B – lengths of the sides of a triangle on a side road [58].

The view of the junction from the vehicle on the side road must not be in a blind spot of the view from the vehicle (see Figure 26).

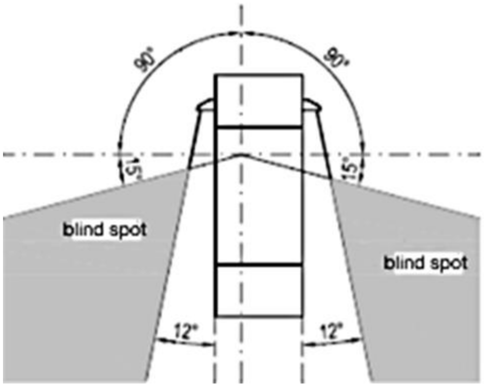


Figure 26: Visible areas from the vehicle [58]

Situation in some European countries.

Figure 27 shows guideline values with some extra countries for comparison [23].

Country	Driver eye height (observation point height)			Observed point height (obstacle height)		
	flat	Crest curve	Sag curve	flat	Crest curve	Sag curve
Denmark	1.0m	1.0m	2.5m	-	0.5m	0.5m
France	-	1.0m	-	-	0.6m	-
Germany	-	1.0m	-	-	1.0m	-
The Netherlands	1.1m	1.1m	-	0.5m	0.5m	-
Switzerland		1.0m	2.5m		0.15m	
United Kingdom	-	1.05m-2.00m	-	-	0.26m-2.00m	-
Austria*		1.0m				
Italy*, Sweden*		1.10m				
United States*		1.08m				
Canada*, Australia*		1.05m				
Japan*, Israel*		1.20m				

Figure 27: Driver eye height and observed eye height per country [60].

Figure 28 shows a perception-reaction time and the associated stopping sight distance (SSD) in different countries. It can be noticed that there is some amount of variation on SSD characteristics among these countries.

Country	Perception – Reaction time (s)	Stopping Sight Distance (SSD) (m)								
		50 km/h	60 km/h	70 km/h	80 km/h	90 km/h	100 km/h	110 km/h	120 km/h	130 km/h
Denmark	2	54	71	90	111	134	160	187	217	248
France	2	50		85		130		195		280
Germany	2	54	71	90	111	134	160	187	217	248
Ireland	-	70 50 50	90 70 50	120 90 70	160 120 90		215 160 120		295 215 160	
The Netherlands	Variable by design speed	60 (1.5s)			105 (2s)		170 (2.25s)		260 (2.5s)	
Switzerland	2		62		100		147		208	
United Kingdom (85 km/h instead of 80 km/h)	-	70 50	90 70	120 90	160 120		215 160		295 215	

Figure 28: Stopping Sight Distance and Perception-reaction times per country [59].

Figure 28 shows that most countries prescribe a fixed perception reaction times of 2 seconds. Dutch guidelines prescribe different PRTs for different speeds which deviates from other countries. Looking at the SSDs, it can also be seen that the differences between the SSDs for most countries are small, except for Ireland and the UK where the preferred SSD requirements are about one third higher than for the other countries. In overall, there is a consensus about what the SSD requirements are. The oldest guidelines from this selection are the Swiss guidelines which are dated back to 1983, it can be concluded that these requirements have not changed much over time. The design guidelines in Ireland follow for the most part the UK design guidelines. Both countries recommend higher minimum SSDs than other countries. However, the Irish and UK guidelines provide road designers with two steps of relaxations of the SSD. One step down resulting in equal SSDs compared to other European countries and two steps down being considerably smaller than the minimum SSDs from other countries. As the guidelines do not provide a background on the SSD design values, the differences cannot be explained based on these guidelines. Currently some guidelines already mention fixed observation points in determining which sight distance should be measured. The following figure provides an overview of the values per country [24].

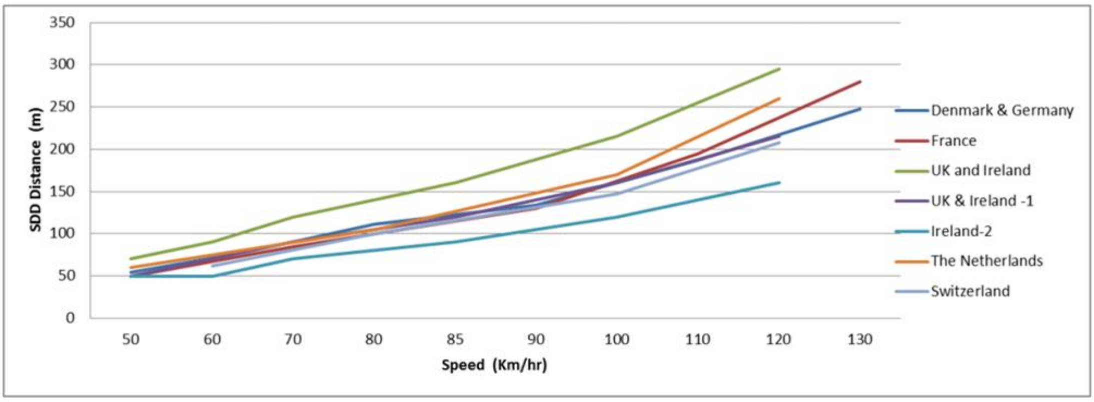


Figure 29: Fixed observing points in curves based on which sight distance could be measured per country. Note: lane width may also differ per country [59].

All countries except the UK and Ireland refer to a single value of SDD for any particular speed. The UK refers to a desirable minimum value and a 1 step relaxation, whilst Ireland uses two steps of relaxation to create absolute minima for designers to consider at any particular location. These steps relate to one speed level reduction for each step (i.e. 215 m = desirable minimum at 100 km/h or one step relaxation at 120 km/h). All other countries use a balanced approach to design to account for different speed characteristics and only require a single value of SSD to be considered. UK CEDR Call 2013 defines the whole route in terms of 'bendiness' to assess the appropriate level of SSD for each key component, i.e. bend or junction where no relaxations in SSD are permitted. As the UK and Ireland use the same values for the 'desirable' value of SSD and 1 step relaxation, they have been combined in the graph above.

The speed employed in the analysis of stopping sight distance is typically the design speed, in particular for vertical sight restrictions. As noted above, some authorities allow the running speed or operating speed to be used. Since the design coefficient of friction element of the SSD equations is determined for wet pavements, and drivers were expected to slow on wet pavements, this is believed to be more relevant for those countries. However, research by AASHTO [61] has demonstrated that drivers do not slow adequately on wet pavement. Apparently, there is a need to determine a clear definition for selecting the determining factor. The relationship between Design Speed and other key identifiers of the vehicle speed has rarely been fully documented: i.e. Mean speed, Operating Speed and 85th percentile speed.

In many instances there does seem to be interchangeability between Design Speed and Operating Speed, but no clear definitions or relationships are given. The initial views were that there was little commonality between the various countries. This could be explained by the differences in application of operating speed and design speed. The UK and Ireland practice of including 'stepped' alternatives for SSD could potentially take account of the situation above where Design and Operating speed are interchangeable. For consistency if a single value of 1 step relaxation for both these countries is used, their profile of SSD lies within the same grouping as other European countries.

3.2 Existing standards on road infrastructure elements for AD

The following subchapters present an overview of relevant standards for lane marking requirements and traffic signs since those two physical infrastructure elements offer the highest potential to improve physical infrastructure for automated urban mobility. Nevertheless, SHOW Deliverable 4.1 also offers a review of additional available standards used in PT along with comments on their applicability and current usage.

Additionally, standards for sight distances and accessibility and safety of public transport (PT) hubs are listed.

3.2.1 Lane markings: visibility and detectability

Road markings are traffic signs that can contain a variety of messages for different road users, such as the use of driving lanes, pedestrian crossings, or indicate regulation for stopping, parking, and more. Depending on their purpose, they can be designed differently. Road markings include longitudinal markings, arrows, transverse markings on the road surface, etc.

There can be a distinction made between two categories of road markings: type I (non-reflective) and type II (reflective) markings.

Type I markings are still widely used on European roads for their cost-efficiency. They can be applied as strips, thermo- or coldplastics. These kinds of markings are dusted with retroreflective glass beads. The disadvantage of type I markings lies in the reduced visibility under bad (wet) weather conditions (e.g., fog, rain) especially during night-time. When wet, a water film originates on top of the marking and affects its retroreflectivity, impairing the visibility of the marking. To overcome this limitation, type II markings were developed [62].

Type II markings are structured or profiled markings that include reflective material (e.g., glass beads) that protrude a few millimetres on top of the carriageway (and a potential water film) to ensure a better visibility under bad weather conditions [62]. Type II markings have been prescribed with high traffic density and high speeding traffic, such as freeways and highways [63].

Two main requirements can be specified for road markings:

- Road markings need to be reliably visible during daytime and night-time and during different weather conditions.
- They need to be designed in a way that there is no danger for passing road users (e.g., by using skid resistant material).

To completely cover these two requirements, the following characteristics of road markings have been regulated:

- Material (specification)
- Material (adhesion)
- Visibility and retroreflectivity
- Colour
- Skid Resistance
- Durability
- Design and size
- Testing procedures

In the next paragraphs, the regulations for the most relevant characteristics of road markings for SHOW are presented.

Design and size, Colour

International standards on the design of road markings are outlined in the Vienna Convention on Road Signs and Signals (1968) [35]. The (Vienna) Convention on Road Signs and Signals is an international treaty that obliges the ratifying countries to adopt the respective rules in their national law. However, the national law is relevant and binding, the Convention does not overrule national law. The treaty was ratified by most European countries (one exception is Spain who signed but did not ratify it). Lane markings must therefore be in line with the agreements set out there [64].

As stated in the agreement, road markings should be of skid resistant material and they should not protrude more than 6 mm above the level of the carriageway. Road markings should be white or yellow. For temporary markings, different colours should be used than for permanent markings. Transverse markings should be wider than longitudinal markings (Convention on Road Signs and Signals, 1968/2019). [35]

Visibility and retroreflectivity

Regulations regarding reflection under daylight (including the luminance factor β, and the luminance coefficient under diffuse illumination Q_d), as well as regarding retroreflection under vehicle headlamp illumination are presented under EN 1436:2018 - Road marking materials - Road marking performance for road users and test methods [6].

This European standard specifies the various levels of performance for road users of white and yellow road markings. It also describes test methods and conditions of measuring the various performance characteristics. Performance of road markings is expressed in terms of reflection in daylight or under road lighting, retroreflection in vehicle headlamp illumination, colour and skid resistance combined with durability. These specifications also introduce the importance of wet-night visibility road markings.

Clearly visible road markings are considered key for autonomous vehicles. They support the human driver today and will support the machine in navigating through the roadway in future. Some/Many current automated vehicle systems assume that lane markings exist, are clear and, more importantly, are visibly distinct. Camera sensors, integral component of advanced driving assistant systems, use lane marking to ensure that the vehicle stays on course.

Therefore, safety is dependent on the visibility of road markings and on the quality of the lane markings' optical properties. In addition, since adverse weather conditions and worn-out road markings still pose great challenges to camera sensors, high-quality road marking systems can help meeting the challenges of camera technology and offer potential for innovation.

Regulations on road markings

Up to now, there are no unified European laws regarding road markings characteristics. However, there are several European standards constituting the base for national directives and regulations.

The norms at European level should generally be made national law in the respective member countries. However, this has not always been done. The CEN/CENELEC regulations do not overrule national legislation, hence, despite possible conflicts, the respective national regulations shall be considered.

The following table provides an overview on the national regulations for visibility and retroreflectivity characteristics of road markings. [64]

Table 9: National regulations for visibility and retroreflectivity characteristics of road markings.

Country	Visibility	Retroreflectivity R_L		
	Minimum luminance factor β	Dry	Wet	Rain
European Standard	100 (Q2) [EN 1436]	100 [EN 1436]	25 [EN 1436]	25 [EN 1436]
France	100(Q2) for retroreflectant material; 130 (Q3) for non retroreflectant material; 80 (Q1) for temporary markings [EN 1436]			
Germany	130 (Q3 – used condition) / 160 (Q4 – new condition) [ZTV M13]	Type I and II: 100 (R2– used condition) / 200 (R4– new condition) [ZTV M13]	Type II: 25 (RW1– used condition) / 50 (RW3– new condition) [ZTV M13]	-
Greece	100 (Q2) [EN 1436]	100 [EN 1436]	25 [EN 1436]	25 [EN 1436]
Italy	100 (Q2) [EN 1436]	100 [EN 1436]	25 [EN 1436]	25 [EN 1436]
Spain	B2 or Q2 (on bituminous pavement) B3 or Q3 (on concrete pavement) [EN 1436]	R3 [EN 1436]	RW2 (Type II-RW) and RW3 (Type II-RR) [EN 1436]	RR2 (Type II-RR) [EN 1436]

3.2.2 Traffic signs

Table 10: Summary of relevant international standards for traffic signs.

Standard	Scope
EN 12899-1:2007 Fixed, Vertical Road Traffic Signs – Part 1: Fixed Signs, Requirements.	EN 12899 specifies requirements for complete sign assemblies (including supports), signs (sign plates with sign faces), sign plates (without sign faces) and for other major components (retroreflective sheeting, supports and luminaires).

Standard	Scope
2016 No. 0000 ROAD TRAFFIC: The Traffic Signs Regulations and General Directions 2016.	The Traffic Signs Regulations and General Directions (TSRGD) 2016 prescribe the designs and conditions of use for traffic signs, including road markings, traffic signals and pedestrian, cycle and equestrian crossings used on or near roads.
23 CFR § 655.603.	To prescribe the policies and procedures of the Federal Highway Administration (FHWA) to obtain basic uniformity of traffic control devices on all streets and highways
Standards Australia. (2001). AS 1743. Road Signs - Specifications. Standards Australia.	This Standard specifies graphics, layout and size requirements together with an abridged materials and manufacturing specification for the manufacture of the standard road signs provided for in AS 1742.
NZ Transport Agency. (2010, October). Traffic control devices manual.	This document seeks to incorporate links to a number of appropriate policies, standards and guidelines and forms a logical link between New Zealand practice and the Austroads Guide to traffic management.
1968 Convention on Road Traffic (2006 consolidated version)	International treaty designed to facilitate international road traffic and to increase road safety by establishing standard traffic rules among the contracting parties

3.2.3 Sight distances and visibility at junctions

Table 11: Relevant international standards for sight distances and visibility at junctions.

Standard	Scope
Department of Transport, 1993. Design Manual for Roads and Bridges, Road Geometry, Links, Part 1, TD 9/93, Highway Link Design, England	The standard sets out the elements of design and principles for their co-ordination, for geometric design of an existing carriageway or new build situation.
Garber, N.J., and Hoel, L., A., Traffic and Highway Engineering, 3rd Edition. Brooks/Cole Publishing, 2001	The book is designed for students in engineering programs where introductory courses in transportation, highway, or traffic engineering are offered. The emphasis of this book is the area of traffic and highway engineering.
A Policy on Geometric Design of Highways and Streets. 4th Ed. American Association of State Highway and Transportation Officials. 2004.	This AASHTO's "Green Book" [61] contains the latest design practices in universal use as the standard for highway geometric design and has been updated to reflect the latest research on superelevation and side friction factors as presented in NCHRP Report 439. New exhibits in Chapter 3 will help designers

Standard	Scope
	to quickly and accurately determine the side friction factor used for horizontal curve design, the superelevation rates for various curve radii, and the minimum radii with normal crown for each of the five maximum superelevation rates.
A Policy on Geometric Design of Highways and Streets. 4th Ed. American Association of State Highway and Transportation Officials. 2004. See Exhibit 9-54. Time Gap for Case B1—Left Turn from Stop	The book presents access needs and controls in the context of functional classification and reviews the functional characteristics. The chapter "Design Controls and Criteria" includes the largest section devoted specifically to access management. Access classification is identified as "the foundation of a comprehensive access management program" that "relates the allowable access to each type of highway in conjunction with its purpose, importance, and functional characteristics".
A Policy on Geometric Design of Highways and Streets. 4th Ed. American Association of State Highway and Transportation Officials. 2004. See Exhibit 9-54. Time Gap for Case B1—Left Turn from Stop	These policies represent design guidelines agreed to by the state highway and transportation departments and the Federal Highway Administration (FHWA). Guidelines for highway geometric design are presented in A Policy on Geometric Design of Highways and Streets [61], which is based on many years of experience and research.
"Manual on Uniform Traffic Control Devices (MUCTD)". United States Department of Transportation – Federal Highway Administration. Part2c –Warning signs.	Traffic control devices shall be defined as all signs, signals, markings, and other devices used to regulate, warn, or guide traffic, placed on, over, or adjacent to a street, highway, pedestrian facility, or bikeway by authority of a public agency having jurisdiction.
A Policy on Geometric Design of Highways and Streets. Washington D.C.: American Association of State Highway and Transportation Officials. 2004.	A Policy on Geometric Design of Highways and Streets, 7th Edition, 2018 [61], commonly referred to as the "Green Book," contains the current design research and practices for highway and street geometric design. The document provides guidance to highway engineers and designers who strive to make unique design solutions that meet the needs of highway users while maintaining the integrity of the environment. It is also intended as a comprehensive reference manual to assist in administrative, planning, and educational efforts pertaining to design formulation. Design guidelines are included for freeways, arterials, collectors, and local roads, in both urban and rural locations, paralleling the functional classification used in highway planning.

3.2.4 Accessibility of PT hubs and stations

Concepts of planning PT hubs and stations are relying mainly on local conditions. Accessibility and functionality are often reduced due to other existing transport modes and the corresponding infrastructure.

When it comes to planning operations for accessibility of PT hubs and stations, the physical infrastructure is mentioned in a very broad way, the main focus is often set on KPI calculation based on catchment areas, distance to the next PT hub and service quality. Although this is a very important aspect when it comes to demand generation, this is only softly related to the contents of this document.

During research of this chapter, the most detailed planning guidelines were found in the Austrian normative environment, as shown below. In Austria, planning and constructing PT hubs and stations is based on inputs found in normative documents as shown in the following list:

- **Austrian Normative A 3011**: Graphic symbols for public information - General principles (1994) [65]
- **Austrian Normative A 3012**: Visual guiding systems for public information - Orientation supported by directional arrows, graphic symbols, text, light and color (1994) [66]
- **Austrian Normative B 1600**: Accessible built environment - Design principles (2017) [67]
- **Austrian Normative B 1601**: Accessible healthcare facilities, assistive housing, and workplaces - Design principles (2013) [68]
- **Austrian Normative 2450-1,-2,-3**: Lifts, escalators and passenger conveyors (2019) [69]
- **Austrian Normative V 2100**: Technical aids for visually impaired and blind persons - Tactile references on control panels for pedestrians (2014) [70]
- **Austrian Normative V 2101**: Acoustical and tactile auxiliary signals for traffic-lights - Technical aids for partially sighted and blind persons (2015) [71]
- **Austrian Normative V 2102**: Tactile walking surface indicators (TWSI) - Technical aids for blind and partially sighted persons (2018) [72]
- **Austrian Normative V 2103**: Remote activation options for acoustics and tactile signals and information - Technic aids for partially sighted and blind people (2020) [73]
- **Austrian Normative V 2104**: Technical aids for visually impaired, blind and mobility impaired persons - Safety devices for construction and dangerous sites (2012) [74]
- **Austrian Normative V 2105**: Technical aids for visually impaired and blind persons - Tactile inscriptions and information systems (2011) [75]

These documents allow a clear and predefined way of creating and adapting transport hubs and stations as shown example wise in Figure 30.

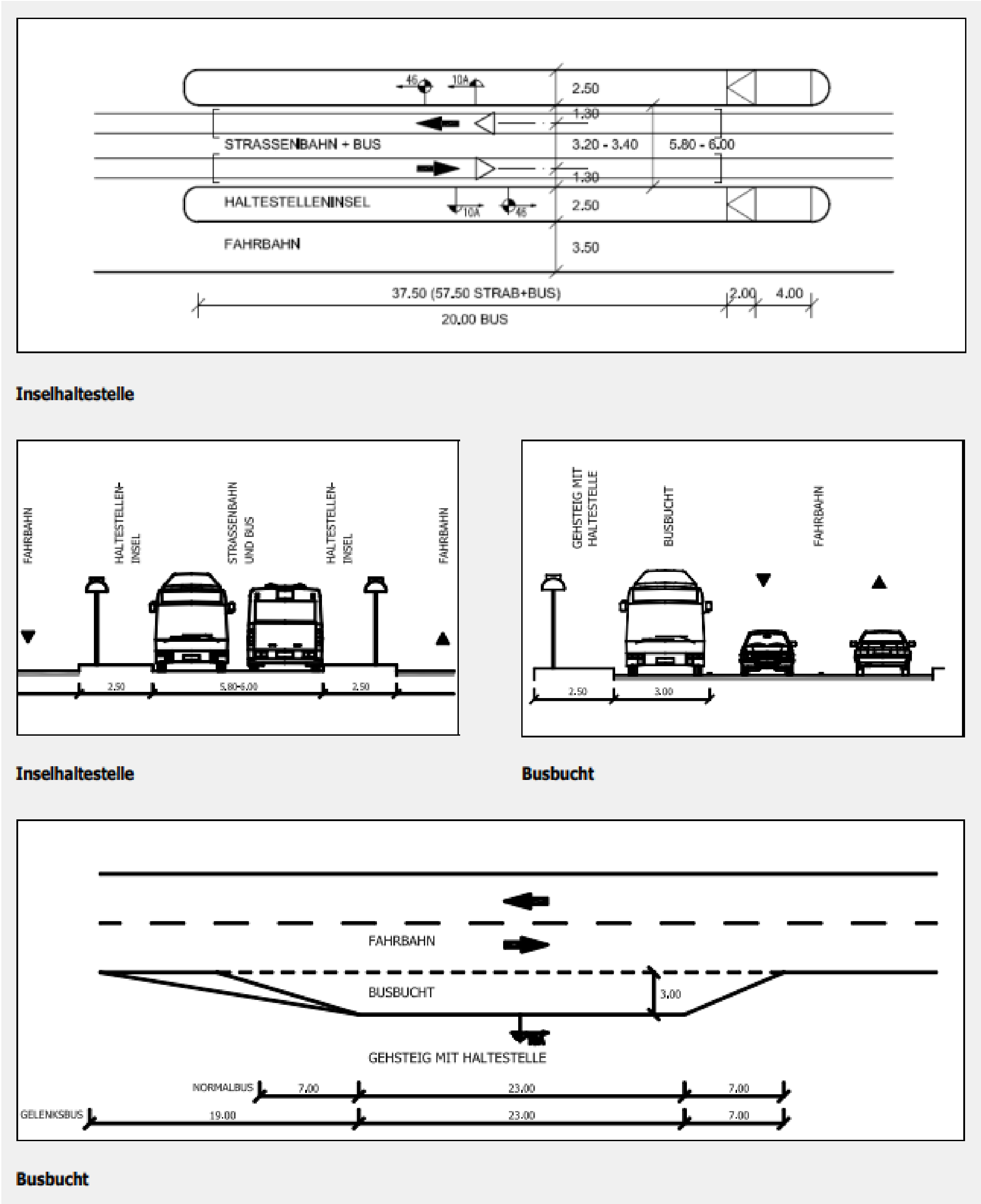


Figure 30: Dimensions of public transport stations on road sections [76].

Based on this list, the city of Vienna develops and constantly checks their transport hubs and station designs. Remarkable is, that these station designs are based on assumptions on non-automated transport modes.

In combination with documents and regulations guiding the construction and planning of the physical accessibility of public transport hubs another topic is the design of operational functionality. In planning methods often travel times, service quality parameters and distance between parking, public transport and/or other transport lines/modes are taken into consideration. These points are characteristic for the overall functionality of the transport hub.

All regulations mentioned above are clearly missing out needs and requirements for automated driving in public transport. The current approach to design AV systems according to guidelines could contain problems as the flexibility of current infrastructure elements only support non-autonomous vehicles in terms of human eye visibilities and no further approach on communication between autonomous vehicle systems and the infrastructure itself (V2I, I2V).

Current AV-systems in the public transport / shared public transport field of operation are usually limited to small shuttles with limited capacity, also in pre-COVID times. With an approach in the U2/U5 metro project by the Vienna transport operator Wiener Linien a fully automated metro line is currently under construction and will be opened in 2026. While the additional track length of metro line U2 will be used by “normal” metro rolling stock, the metro line U5 will be using fully automated metro trains called “the X-wagon”.

The x-wagon is fully automated and driverless, supervised by an operator at central control centre of Wiener Linien. With this new approach a severe safety issue emerged. While metro lines U1-U6 are operated by human drivers that can initiate emergency stops by detecting dangerous situations, the autonomous vehicles rely on their on-board systems. To reduce costs for various security measures regarding obstacle detection, a simple solution to support these systems was included into the planning process: automatic doors, activated by the train itself, also known from BRT systems in e.g. Brazil and shown in Figure 31.

Figure 31: Safety doors with x-wagon © YF Architekten und Franz&Sue/YF Architekten und Franz&Sue/Wr. Linien [77].

Based on an intensive review by McKinsey & Company [78] of current infrastructure in regard to autonomous vehicles, the transport consultancy McKinsey & Company tried to answer the following question in 2019:

“What infrastructure improvements will promote the growth of autonomous vehicles while simultaneously encouraging shared ridership?”

In this insights-report the following aspects were identified:

- Support facilities
- Staging areas
- Curb modifications
- Mobility hubs

Support facilities are needed to support autonomous fleets in terms of service and charge AVs. In focus of city cost-benefit terms, a private operator could save a lot, as these facilities are run by them and the only effort of cities is to be the regulatory authority. Transportation officials must be thoughtful about the placement of these facilities to avoid disrupting the urban environment and damaging health, traffic, and civic life.

Staging areas are important in times where AVs are in idle mode and not used due to low demand, for example during work hours. A certain percentage of these vehicles could be used in a shared operation context, but the majority would be then free floating or simply placed at the point of exit of the former passenger. A very promising solution is to redefine and reuse parking lots, as they are not used by common cars anymore.

Curb modifications come into point of view, as soon as current parking solutions are not used anymore, e.g. due to changes in car ownership behaviour or measures to provide price barriers towards cars entering the city level. On the one hand, existing parking spaces could be used in a more dynamic pricing scheme, where open spaces in the city centre will be charged more than parking spaces at the outskirts. The other way is to redesign and repurpose these parking spaces in a way to support AVs and autonomous transportation of goods. There could be specific drop-off zones near retail usages that provide a reduced number of cars entering that area due to shared AV systems. With redesign of curbs and curbside-management a push towards and support of AVs could also be triggered as the access is placed closer to the initial demand.

Mobility hubs: For each success story of transport modes a very important point is the transition and transfer between different modes. Again, the first/last mile problem occurs, as there is often a very high classified transport mode available, but it is missing the crucial point of providing transport for the last mile between itself and the passenger’s home. With new transportation modes such as e-Scooter and bike sharing, the problem was approached, additional smaller AV systems could provide more solutions. This is the big point to focus when designing/redesigning public transport hubs in the future.

Figure 32 shows a combined solution of all mentioned items in a public transportation system extended by AVs. As current predictions are looking forward to years around 2040/2050 heavy influenced by the existence of AVs in a broader way, there should be a long-term planning approach in each city.

This steps up from simply exchanging or extending existing signage and stop signs with a digital version of them to a city-wide transportation management system, covering all fields of transportation. Roadways themselves will also need to evolve as AVs become the dominant form of transportation. For instance, officials might consider the extent to which safety enhancements, such as raised curbs or guardrails, are beneficial. While a distracted human driver might accidentally veer over the curb or into another lane, the probability of such accidents is expected to be lower with AVs.

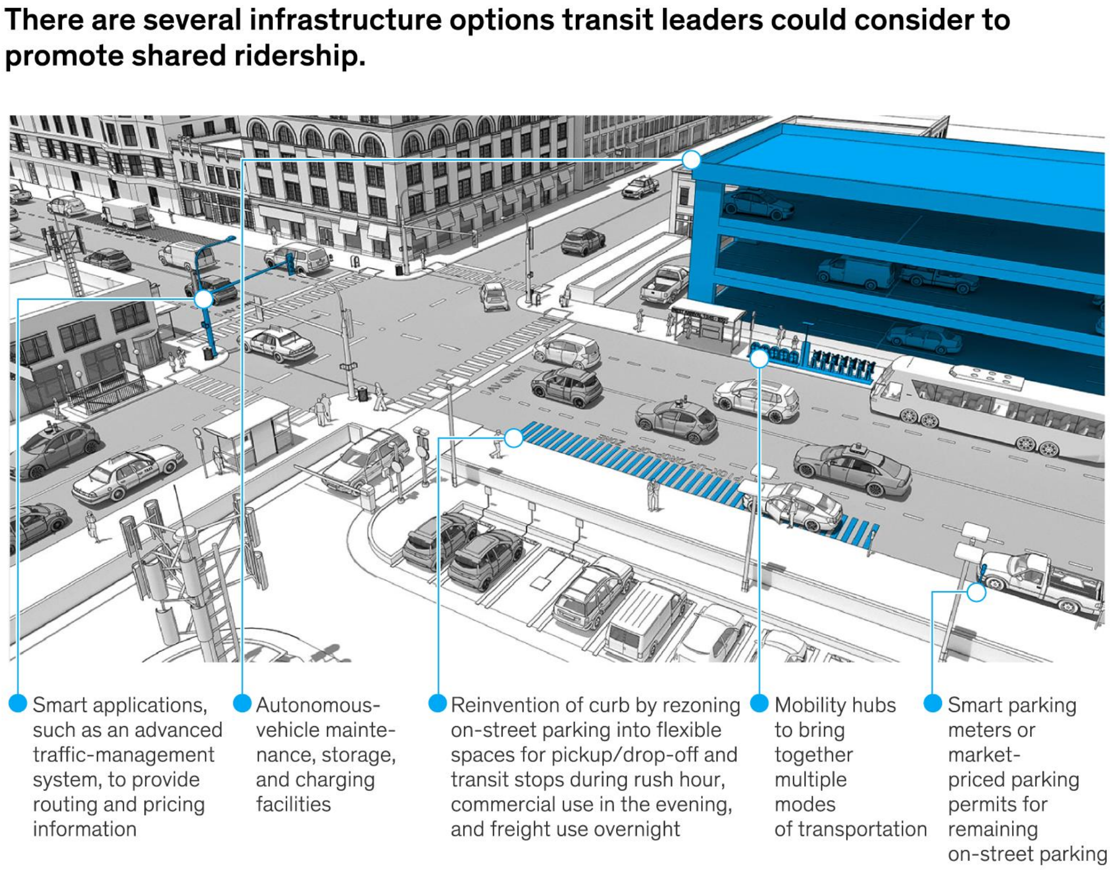


Figure 32: Infrastructure elements identified by McKinsey & Company [78].

It should be clear, that the future infrastructure is not a one-shot implementation, as the percentage of AVs in operation will rise in a certain way and not instantly. This means, that the adaption of all infrastructure elements is bound to the developments in AVs. Also, the digital infrastructure should be taken into consideration, as the physical infrastructure is normally a given instance, the digital infrastructure needs to be focused on to create everything needed for AVs operational success.

With existing infrastructure, another problem must be solved: the last mile. Existing infrastructure of public transport is built to contain and support linear public transport systems, on-demand services and MaaS are still in their beginnings. With the ability to solve the last mile problem, these concepts need to be implemented, mainly on every important transport hub or station. This could lead to several scenarios and outcomes:

- With implementation of digital infrastructure along physical infrastructure, there are options to pull transport users not only from other modes, but also from less important stations to bigger hubs, when providing last mile options from there.
- Digital infrastructure is far more important to (re)develop as it has to handle increasing level of information throughput, traffic management and V2X communication. The physical infrastructure itself should be a highly supporting factor.
- City planning must adapt, not only creating support in the road infrastructure, also energy and communication infrastructure need to be included in any planning efforts, due to higher demand on both ends.

With enough information for every user a better and more robust route planning is possible and traffic system management could bring less travelled miles and less traffic on road sections.

3.2.5 Safety of PT hubs and stations

There are not many documents dealing with safety in Public Transport Hubs. However, “Identifying Best Practices for Mobility Hubs” by Saki Aono [79] deals with safety and autonomous vehicles. Also “Mobility Hubs – A Reader’s Guide” [80] for the City of Los Angeles deals with safety of hubs and stations. Safety and security are seen as important support services for mobility hubs. Indeed, one of the main objectives of PT and mobility hubs is to ensure safety and security for all travelers using hubs. According to Aono as a place with high pedestrian activity, the design and infrastructure within PT hubs need to foster a sense of safety for passengers. Following this, safety in the PT hub context refers to pedestrian oriented design, where passenger movement is protected from surrounding vehicle traffic, including autonomous vehicles. Safety should also be considered across all ages and abilities as well, allowing people of different abilities and familiarity with mobility services to travel and use a variety of services easily. The perception of safety can also be enhanced through implementing security measures that help reduce crime in these areas. Thus, PT hubs should be driven by high quality customer service. There is an emphasis on safety and security through designs and initiatives that create a sense of place and foster safety. Safety is also related curb designs and they should be designed to improve pedestrians’ safety for instance changing from autonomous shuttles to trunk line services. As an example, Aono mentions QueueY, an imagined pickup and drop-off location for autonomous vehicles in corridors surrounding public transport hubs. The design converts curb-side parking areas into areas of pickup and drop-off zones. In the proposed design, the waiting area is weather protected and equipped with solar powered lights to enhance safety and easy wayfinding.

Figure 33: Pickup and drop-off location for autonomous vehicles in corridors surrounding public transport hubs.

Aono also states that it is essential for PT/mobility hubs to enhance the benefits of AV technology, while mitigating the potential challenges and conflicts. Given that many cities have begun pilot testing the role and incorporation of AVs, it is important for mobility hubs to accommodate this new technology as it becomes increasingly adopted. Therefore, PT hubs need to consider flexible design and infrastructure that will allow for the incorporation for AVs in the future.

“Mobility Hubs – A Reader’s Guide” [80] does not report safety issues related to autonomous vehicles and services. However, it states that safety at PT and mobility hubs is enhanced by protected facilities, improved street crossings, strategic lighting, and slower vehicular speeds. Pedestrian infrastructure at PT and mobility hubs should be designed to create a barrier-free, accessible pedestrian network. Pedestrian/vehicular conflicts around PT and mobility hubs should be identified to allow the implementation of mitigation strategies to ensure a safe and comfortable pedestrian and traveler experience. Additionally, providing more than one access point will ensure that persons with disabilities have safe and direct access to or from PT and mobility hubs. Finally, depending on typology and area context different security options can be implemented at PT and mobility hubs. These can include: on-site security personnel, security cameras, panic button apps for smart phones, etc. Maintaining clear sight lines between waiting areas and the surrounding neighborhood can also facilitate natural surveillance (also known as 'eyes on the street') at PT and mobility hubs.

In addition to the above Portland Bureau of Transportation in the USA published in June 2020 a document "Mobility Hub Typology Study" [81]. It states that there should be safe road crossings for people walking and biking and also safe places for autonomous vehicle pick-up and drop-off in the PT hubs. When it comes to autonomous feeder transport there should be easy and safe transfer areas and possibilities to move to the trunk line. Naturally the needs for different special user groups need to be acknowledged.

All in all, there are not too many documents dealing directly with both autonomous services and PT hubs when it comes safety or other operational considerations. To improve knowledge in this area within the SHOW project, section 4.2.1 introduces a simulation setup that will be applied in WP10 to fill some of the gaps in the knowledge on pedestrian safety when interacting with AVs at PT-hubs.

3.3 Definition of infrastructure requirements

3.3.1 Checklist: Lane markings

Based on the results of the literature review and the series of interviews, the following thresholds for lane markings in an urban environment can be derived (see Table 12).

Table 12: Checklist for lane markings for AV in an urban environment.

Parameter	Road condition	Road elements	Threshold
Road design	all road conditions	all road elements	Clear continuity lines on both sides of the lane with no extended gaps and a consistent lane width
Work zones	all road conditions	all road elements	Halt the practice of mixing yellow and white pavement markings on construction sites
Road maintenance	all road conditions	all road elements	Remove redundant markings and phantom markings to minimise any adverse effects on LKA
	all road conditions	all road elements	Apply minimum standards at segments with low-quality road markings (grade 4-5)
	dry	• Tunnels (tunnel length ± 100m)	150 mcd/lx/m^2

Parameter	Road condition	Road elements	Threshold
Retro-reflectivity (night-time)		• Unsignalized intersections (intersection centre ± 50m) • Level crossing (± 50m) • Pedestrian crossing (± 25m) • Bus bay (± 25m) • Cyclist crossing (± 25m)	
		• All other road elements	100 mcd/lx/m^2
Luminance coefficient (daytime)	dry	• Tunnels (tunnel length ± 100m) • Unsignalized intersections (intersection centre ± 50m) • Level crossing (± 50m) • Pedestrian crossing (± 25m) • Bus bay (± 25m) • Cyclist crossing (± 25m)	130 mcd/lx/m^2
		• All other road elements	100 mcd/lx/m^2
Contrast ratio (daytime)	all road conditions	All road elements	Minimum 3:1 contrast ratio between longitudinal pavement markings and the surrounding substrate

3.3.2 Checklist: Traffic signs

Traffic signs are an absolutely crucial element of road infrastructure for human drivers, but they play an important role for AVs as well. Although autonomous vehicles might travel on a well-known route that has been previously mapped and stored to the vehicle's memory, traffic signs can still function as a landmark that allows to locate the vehicle more precisely on the route. In the future, there might not be a need for traffic signs anymore.

Table 13: Checklist for traffic signs for AVs in an urban environment.

Parameter	Road condition	Road elements	Threshold
Sign condition	all road conditions	all road elements	Traffic signs are in a good condition without any wear, that means all symbols are depicted without any damage, there is also no

Parameter	Road condition	Road elements	Threshold
			distortion to the physical parts of the sign
Sign position	all road conditions	all road elements	Traffic signs are placed properly without any tilting and/or in improper direction
Sign visibility	all road conditions	all road elements	Traffic signs are easily visible from the road without any obstruction (trees and other foliage and infrastructure)
Digital signs	all road conditions	all road elements	If there are digital traffic signs, they need to be readable by AV's sensors or wirelessly inform the vehicle via telematics means
Comprehensibility of signs	all road conditions	all road elements	Traffic signs are placed in logical sequence and manner without contradicting each other

3.3.3 Checklist: Sight distances and visibility at junctions

Sight distances are extremely important for human drivers, therefore roads are usually designed in a way that considers the human ability to easily see along the route in order to provide drivers with good visibility and enough reaction time. Regarding autonomous vehicles, their reaction time tends to be faster than the reaction time of human drivers, thus current standards for sight distances might be sufficient for autonomous vehicles as well. Of course, if there is some abnormal road design without properly implemented sight distances rules, then it is necessary to evaluate potential problems for autonomous vehicles.

Table 14: Checklist for sight distances for AVs in an urban environment.

Parameter	Arc conditions	Crossroads	Threshold
Road design	all arc conditions	all crossroads	Roads are designed according to standards and there are no abnormal design solutions that could interfere with visibility along the route
Obstructions	all arc conditions	all crossroads	If there is any obstruction along the route (trees, parked cars, etc.), it needs to be checked whether it negatively influences the visibility
Reflective surfaces	all arc conditions	all crossroads	Make sure there are as little high contrast and shiny areas along the route as possible in order to prevent

Parameter	Arc conditions	Crossroads	Threshold
			phantom detections by certain sensors
Intersection design	all arc conditions	all crossroads	The intersection design allows for a safe entering and/or crossing the road with enough visibility to allow the AV to detect other traffic and act upon it

3.3.4 Checklist: PT Hubs

Implementing PT Hubs in combination with automated driving is based on compromises in both directions. On the one hand, the integration of PT Hubs is easy, as existing structures and physical infrastructure elements could be used, on the other hand additional implementation of digital infrastructure elements are necessary to provide a certain Level of Service to support the acceptance of this automated transport mode.

Table 15: Checklist for implementation of PT Hubs in an urban environment.

Parameter	PT Hub element	Urban environment element	Threshold
Placement	PT Hub in total	Spatial Situation	Placement of PT Hubs are with and without AVs very demanding in spatial terms. Make sure, there is enough room for the placement of all elements, such as maintenance, storage and charging facilities in total.
Connectivity	Autonomous systems and control instances	Digital infrastructure	Connectivity (5G, 6G, ITS-G5) of both passengers and AVs is the digital backbone of each AV-solution. Make sure, there is enough bandwidth and infrastructure available.
Last Mile	Offer at PT Hub	Offer and demand management	Make sure that supply and demand are matching, especially in the “Last mile” context to suppress unnecessary activation of private motorized transport.
Accessibility	Entrance and exit to the PT Hub	Support network for accessing PT Hubs	AVs are providing mobility solutions for people normally not able to access this form of transport and should be accessible in the most direct way possible

Parameter	PT Hub element	Urban environment element	Threshold
Level of Service	Offer at PT Hub	Infrastructure(s), non-PT Hubs	To provide a certain Level of Service at PT Hubs, make sure that (a) the PT at the Hub itself and (b) the PT at non-Hubs are working at their best possible quality.

3.4 Desk research results

In this chapter the results from the screened projects are presented. The project period, funding frame, link to the website as well as a short description of the project is included. Then, for each project, the relevant results for SHOW A8.1 concerning the physical infrastructure are listed.

Project	AVENUE [82]
Period	May 2018, 4 years
Funding	EU (H2020)
Website	https://h2020-avenue.eu/
Description	AVENUE aims to design and carry out full-scale demonstrations of urban transport automation by deploying, for the first time worldwide, fleets of autonomous minibuses in low to medium demand areas of four European demonstrator cities (Geneva, Lyon, Copenhagen and Luxembourg) and later on, of three replicator cities.
Relevant results for SHOW A8.1	The AVENUE project discusses the technological challenges for deploying urban shuttle buses. A major challenge in the further development of an autonomous shuttle system in this respect is balancing the requirements that the current generation of vehicles set to the infrastructural environment, and the requirements that existing urban areas set to the technology of the autonomous busses. As they indicate, the technology prescribes the requirements for the infrastructural environment, which include: An area with a speed limit of 30km/h: As the maximum vehicle speed is 25 km/h, the autonomous shuttles require either a separate driving lane, or the maximum speed should be limited to 30 km/h. [83] • Avoid obstacles • Good GPS signal • Well maintained road - preferably asphalt • Slope <12%

<table>
<tr><th>Project</th><th>HEADSTART [86]</th></tr>
<tr><td>Period</td><td>January 2019, 3 years</td></tr>
<tr><td>Funding</td><td>EU (H2020)</td></tr>
<tr><td>Website</td><td>https://www.headstart-project.eu/</td></tr>
<tr><td>Description</td><td>The HEADSTART (Harmonised European Solutions for Testing Automated Road Transport) project is an EU funded project which started on the January 1st, 2019 and will last for 3 years. The project aims to define testing and validation procedures of Connected and Automated Driving functions including key technologies such as communications, cyber-security and positioning. The tests will be in both simulation and real-world fields to validate safety and security performance according to the key users' needs.</td></tr>
<tr><td>Relevant results for SHOW A8.1</td><td>
Within the HEADSTART project, a survey included questions regarding the road infrastructure and the potential changes necessary for various AV use cases. OEMs, policy makers and research institutes were addressed. Responses mentioned possible improvements to the infrastructure, such as: connectivity, electric vehicle chargers, potholes cancellation, lane markings with reflective paintings, high definition map with regular updates, high precision GPS. [84] [85]
Moreover, one the of use cases addressed in HEADSTART was "Urban Automated Shuttle". The below table includes a description of the use case requirements:
Table 16 HEADSTART Urban use case requirements
<table>
<tr><th colspan="2">Urban Automated Shuttle</th></tr>
<tr><td>Area of operation</td><td>Municipal/regional road tissue, closed campus, airport premises</td></tr>
<tr><td>Road Type</td><td>Open road, other road type users (from pedestrians to cyclists and trucks)</td></tr>
<tr><td>Admissible Road Infrastructure</td><td>Intersections, bridges, traffic lights</td></tr>
<tr><td>Dedicated infrastructure</td><td>Segregated, semi-segregated or non-segregated lanes (lanes should be at least painted whenever not segregated), smart traffic lights to promote green wave movement, dedicated control centre monitoring parts of the route and the inside of the shuttle (respecting GDPR issues), on-board cameras, LiDAR, V2X connectivity, GNSS coverage</td></tr>
</table>
</td></tr>
</table>

	Traffic Density	It ranges per use case and could involve from protected campuses to real life conditions within a city network
	Speed Range	< 50 km/h
	Environmental conditions	Not working in extreme weather conditions
	Vehicle Configuration	Automated mini bus of ~10 seats equipped with sensors, cameras, lidars

Project	LEVITATE [87]
Period	January 2017, 4 years
Funding	EU (H2020)
Website	https://levitate-project.eu/
Description	The aim of the LEVITATE project is to prepare a new impact assessment framework to enable policymakers to manage the introduction of connected and automated transport systems, maximise the benefits and utilise the technologies to achieve societal objectives.
Relevant results for SHOW A8.1	While one of the use cases investigated in the project is automated urban transport, no data on road infrastructure requirements was identified in the project deliverables.

Project	L3Pilot [88]
Period	September 2017, 4 years
Funding	EU (H2020)
Website	www.l3pilot.eu
Description	The overall objective of the L3Pilot project is to test the viability of automated driving (AD) as a safe and efficient means of transportation, exploring and promoting new service concepts to provide inclusive mobility. This high-level objective is detailed as four major technical objectives: (i) create a standardised Europe-wide piloting environment for automated driving, (ii) coordinate activities across the piloting community to acquire the required data (iii) pilot, test, and evaluate automated driving functions and connected automation, (iv) innovate and promote AD for wider awareness and market introduction.
Relevant results for SHOW A8.1	Based on the results of the L3pilot, several observations regarding road infrastructure requirements could be extracted: • The vehicles to be tested can drive at a speed range between 25 and 50 km/h; • The function should be capable to identify other road users, identify traffic lights and act accordingly; • Lack of lane markings, lack of map information as well as complex traffic scenarios (e.g. traffic intersections) could pose challenges; • The vehicle will perform better during good weather conditions (good light, good visibility); light rain should be ok, however extreme weather should be excluded; • Pavement type: all (asphalt, cobblestone); • Driving on streets with tram lines would be ok, while crossing tram lines and railway crossings would be challenging (field of vision, detecting oncoming train); • Road condition: icy and snowy roads should be excluded, as well as roads with standing water; • A good operation will require visible, clearly defined lane markings or clear curbs on both sides of the lane; a (virtual) lane is also needed for handling street-side parking, bicycle lanes – either defined by lane markings or clearly defined on a HD map used by the vehicle; • Lane marking quality: small gaps ok; • An HD map should also enable the vehicle to be rerouted in particular conditions, for example, if roadworks are detected on the planned route. [88][89][90]

Project	InterACT [91]
Period	May 2017, 3 years
Funding	EU (H2020)
Website	https://www.interact-roadautomation.eu/
Description	As automated vehicles (AVs) will be deployed in mixed traffic, they need to interact safely and efficiently with other traffic participants. The interACT project was working towards the safe integration of AVs into mixed traffic environments. In order to do so, interACT has analysed todays' human-human interaction strategies, and implemented and evaluated solutions for safe, cooperative, and intuitive interactions between AVs and both their on-board drivers and other traffic participants.
Relevant results for SHOW A8.1	No data on road infrastructure requirements for automation was identified in the project deliverables (though unsignalized intersections were targeted there and this could be of interest for SHOW UC 3.1)..

<table>
<tr><th>Project</th><th>TrustVehicle [92]</th></tr>
<tr><td>Period</td><td>June 2017, 3 years</td></tr>
<tr><td>Funding</td><td>EU (H2020)</td></tr>
<tr><td>Website</td><td>https://www.trustvehicle.eu/</td></tr>
<tr><td>Descriptio
n</td><td>TrustVehicle aimed at advancing SAE Level 3 AD functions in normal operation and in critical situations (active safety) in mixed traffic scenarios and even under harsh environmental conditions. TrustVehicle followed a user-centric approach and provided solutions that significantly increased reliability and trustworthiness of automated vehicles and hence, contribute to end-user acceptance.</td></tr>
<tr><td>Relevant results for SHOW A8.1</td><td>The project addressed multiple use cases with tests in both simulation and real-world environments. For the use cases, the physical infrastructure elements that were taken into account are shown in the table below. The description is for an urban traffic scenario of an automated backing manoeuvre. [93]

Table 17 TrustVehicle Urban Parking Use case scenario description
<table>
<tr><th colspan="2">Use case scenario description</th></tr>
<tr><td>Area type</td><td>Urban</td></tr>
<tr><td>Environment</td><td>Charging area, Parking Area</td></tr>
</table>
</td></tr>
</table>

	Road	Straight
	Road condition	Narrow Road
	Ground	Dry
	Time of the Day	Day
	Visibility conditions	Full view
	Traffic conditions	Free
	Sensor operating conditions	Clean
	Road markings	Visible
	Speed Range L3 AV	0 - 20 km/h
	Driving direction	Forward, Reverse
	Longitudinal distance	< 3 m
	Lateral distance	< 3 m
	Geography	Flat

Project	BRAVE [94]
Period	June 2017, 3 years
Funding	EU (H2020)
Website	http://www.brave-project.eu/
Description	The main objective in BRAVE was to improve safety and market adoption of automated vehicles, by considering the needs and requirements of the users, other road users concerned (drivers and vulnerable road users) and relevant stakeholders (i.e. policy makers, standardisation bodies, certifiers, insurance companies, driving schools), assuring safe integration of key enabling technology advancements while being fully compliant with the public deliverables.
Relevant results for SHOW A8.1	No data on road infrastructure requirements for automation was identified in the project deliverables, with the focus being mainly on HMI.

Project	VI-DAS [95]
Period	September 2016, 3 years
Funding	EU (H2020)
Website	http://www.vi-das.eu/
Description	This project is positioned to address the goals of improved road safety by development and deployment of ADAS and navigation aids in societally acceptable and personalised manner, based on a reliable combination of the overall traffic scene understanding and essential consideration of the driver's physical, mental, demographic and behavioural state.
Relevant results for SHOW A8.1	While the VI-DAS project deliverables are not available on the project website, the project results and data publicly available indicate that physical road infrastructure requirements were not taken into account in the project work.

Project	ADAS&ME [96]
Period	September 2016, 3 and ½ years
Funding	EU (H2020)
Website	https://www.adasandme.com/
Description	ADAS&ME aimed to develop adapted Advanced Driver Assistance Systems, that incorporate driver/rider state, situational/environmental context, and adaptive interaction to automatically transfer control between vehicle and driver/rider and thus ensure safer and more efficient road usage. To achieve this, a holistic approach was planned, which considers automated driving along with information on driver/rider state.
Relevant results for SHOW A8.1	Within the ADAS&ME project, one use case was identified as potentially relevant: Passenger pick-up/drop-off automation for buses (city bus). However, the use case was analysed with the use of a driving simulator. In the context of data describing the situational/environmental context, distinct sources such as maps, landmarks, weather information, vehicles or infrastructure are gathered by a Local Dynamic Map (LDM), which stores the information depending on the persistency of the information. As shown in Figure 34, the LDM had four layers with different types of data. [97]

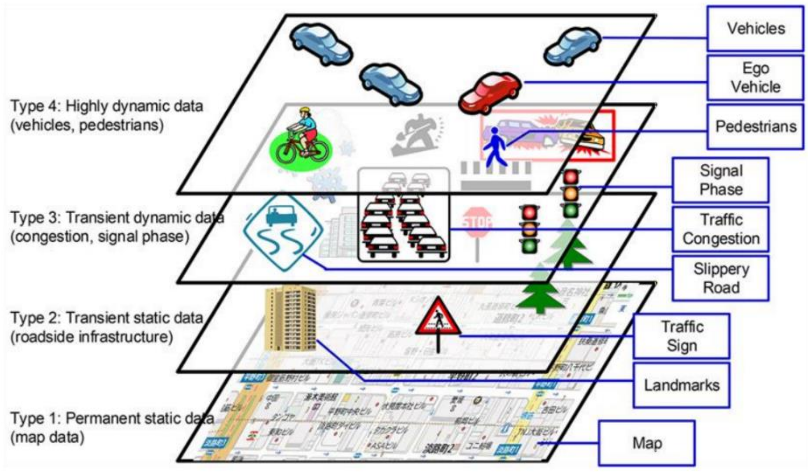


Figure 34 Various layers of Local Dynamic Map

Project	AUTOMATE [98]
Period	September 2016, 3 years
Funding	EU (H2020)
Website	http://www.automate-project.eu/
Description	The objective of AUTOMATE was to develop, evaluate and demonstrate the “TeamMate Car” concept as a major enabler of highly automated vehicles. This concept consists of viewing driver and automation as members of one team that understand and support each other in pursuing cooperatively the goal of driving safely, efficiently and comfortably from A to B.
Relevant results for SHOW A8.1	The project worked only with the GPS (GNSS) location of the vehicle and the use of ITS systems to detect emergencies on the road. The project deals only with passenger vehicles on the motorway environment.

Project	CoEXist [99]
Period	May 2017, 3 years
Funding	EU (H2020)
Website	https://www.h2020-coexist.eu/
Description	CoEXist was a European project which aimed at preparing the transition phase during which automated and conventional vehicles will co-exist on cities' roads. The mission of CoEXist was to systematically increase the capacity of road authorities and other urban mobility stakeholders to get ready for the transition towards a shared road network with an increasing number of automated vehicles using the same road network as conventional vehicles.
Relevant results for SHOW A8.1	Several use cases were identified as relevant as potentially relevant for Activity 8.1: Shared space; Signalized intersection including pedestrians and cyclists. The following recommendations could be extracted from the project deliverables relates to physical infrastructure for automated vehicles: • Increased visibility of traffic signs • Increased presence of traffic signs indicating the presence of AVs on the road in the area • Removal of obstacles • Increasing the space between the vehicle carriageway and the no traffic area which can help AVs better identify pedestrians that may execute risky movements • Highlighting the AV's route through different pavement heights, textures and colours may provide the necessary indications for pedestrians when crossing the road; • Wider, raised or rumbled lane markings or coloured and raised strips at waiting areas in the intersection may provide AVs with more time to react and understand their environment;

Project	INFRAMIX [100]
Period	June 2017, 3 years
Funding	EU (H2020)
Website	https://www.inframix.eu/
Description	The main objective of INFRAMIX is to prepare the road infrastructure with specific affordable adaptations and to support it with new models and tools, to accommodate for the stepwise introduction of automated vehicles.
Relevant results for SHOW A8.1	The project defined Infrastructure Support Levels for Automated Driving (ISAD), of which Level E is defined as conventional infrastructure without digital information. Therefore, no explicit AV support can be provided. The vehicle has to rely on the on-board sensor system exclusively and has no redundant second source of information. Additionally, road geometry and road signs have to be recognised by automated vehicles on their own. The table below analyses the components on which AVs focus to recognise road geometry and signs (for motorways). [101][102]

Table 18 INFRAMIX ISAD Level E components

Class E / Conventional infrastructure	
AVs need to recognise road traffic signs; colours position	Information about the accurate road characteristics could prevent ADAS misuse
Signs with speed limits, road curvature and inclination	Accurate speed limit recognition facilitates the automated vehicle operation domain perception
Lane markings complied to regulations and standards on both sides	Safety-related automated functionalities need proper lane condition and recognition (supporting accurate localization, e.g. automated lane positioning, automated lane change)
Lane width based on standards	Change on lane width could pose safety related challenges even in conventional traffic
Working zone signalisation	Working zone signalization could prevent the misuse of automated functions in the specific road segment, and the human driver could timely take over
Partial CCTV coverage for real-time vehicle detection	Traffic detection through camera could reduce concerns related to the safety of mixed traffic flows in the near future

Project	TRANSAID [103]
Period	September 2017, 3.5 years
Funding	EU (H2020)
Website	https://www.transaid.eu/
Description	TransAID develops and demonstrates traffic management procedures and protocols to enable smooth coexistence of automated, connected, and conventional vehicles, especially at Transition Areas. A hierarchical approach is followed where control actions are implemented at different layers including centralised traffic management, infrastructure, and vehicles.
Relevant results for SHOW A8.1	The project deals with passenger vehicles on the motorway environment. The project results present only the digital infrastructure requirements (e.g. RSUs, V2X communication, vehicle detection through cameras, sensor data fusion).

Project	MAVEN [104]
Period	September 2016, 3 years
Funding	EU (H2020)
Website	http://www.maven-its.eu/
Description	The MAVEN project developed infrastructure-assisted platoon organisation and negotiation algorithms for such vehicle management at signalised intersections and corridors. It helped to extend and connect vehicle systems for trajectory and manoeuvre planning, as well as optimise traffic lights by adapting their signal timing. This facilitated the movement of organised platoons and make a better use of infrastructure capacity, thus reducing the vehicle delay and emissions.
Relevant results for SHOW A8.1	No data on physical road infrastructure requirements for automated vehicles was identified in the project deliverables, with the focus being on C-ITS infrastructure for V2I and I2V communication.

Project	Galileo4Mobility [105]
Period	November 2017, 3 years
Funding	EU (H2020)
Website	http://www.galileo4mobility.eu/
Description	Traditional GPS-based solutions have proven not to be a reliable solution due to low accuracy, especially in urban areas. GALILEO4Mobility, an EU-funded project, supports the introduction of GALILEO technology within the MaaS (Mobility as a Service) context by analysing the needs in terms of geolocation of the different stakeholders involved and demonstrating the benefits of GALILEO through five pilot demonstrators of shared mobility services.
Relevant results for SHOW A8.1	No public deliverables are available on the project website. From the publicly available results, no data on physical road infrastructure requirements for automation was identified.

Project	MANTRA [106]
Period	September 2018, 2 years
Funding	EU (CEDR)
Website	https://www.mantra-research.eu
Description	MANTRA responds to the questions of CEDR Automation Call 2017: How will automation change the core business of NRA's?" and "How will the current core business on operations & services, planning & building and ICT change in the future?" In detail this means finding out what are the influences of automation on the core business in relation to road safety, traffic efficiency, the environment, customer service, maintenance and construction processes.
Relevant results for SHOW A8.1	Based on the results of the MANTRA project, several observations regarding road infrastructure requirements could be extracted: • Decent quality and visibility (contrast) of lane markings • Clear visibility of road infrastructure for vehicle sensors and the driver – including road signs, speed limit signs, traffic signs indicating change of speed limits (maintenance to avoid coverage through bushes, or temporarily by snow, and are not clearly recognisable for vehicle systems at the required distance) • Allocation of dedicated lanes or areas where economically viable

- Enhanced winter maintenance is needed for instance to ensure that road markings and signs are visible and machine-readable, and road maintenance to react to appearance of roadbed damages and potholes, to maintain the condition of road markings, or to maintain the safe refuges and passenger pick-up and drop-off areas.

The project presents relevant ODD related requirements for several use cases in urban environment. [107]

Table 19 MANTRA ODD requirement effects on city streets

ODD Attribute	Year 2030	Year 2040
Roads covered	Main and collector streets in suburban areas as well as streets of major residential areas of cities with millions of inhabitants	Main and collector city streets as well as streets of major residential areas in most cities with more than 500.000 inhabitants
Shoulder or kerb	Roadside parking space, Passenger pickup/drop-off space at kerb beside public transport terminals, public service, shopping and recreation areas	Roadside parking space, Passenger pickup/ drop-off space at kerb beside in relevant locations
Road markings	Enhanced maintenance to ensure consistent and minimum quality of solid or dotted lines and symbols painted on the pavement	No enhanced maintenance due to automated vehicles
Traffic signs/signals	Enhanced maintenance to ensure traffic sign's and signal's machine-readable condition	Temporary regulatory and traffic management signs to be kept in machine-readable quality
Road equipment	Possible shelters and seats for passengers at the pick-up/drop-off points. Separated pedestrian/bicycle facilities along streets	Possible shelters and seats for passengers at the pick-up/drop-off points. Separated pedestrian/bicycle facilities along streets

Table 20 MANTRA ODD requirements for urban road for parameter road marking

Road markings			
Year	2020	2030	2040
Urban road/street	Consistent and minimum quality of solid or dotted lines and symbols painted on the pavement to distinguish lanes, shoulder, traffic regulations	Consistent and minimum quality of solid or dotted lines and symbols painted on the pavement to distinguish lanes, shoulder, traffic regulations	Perhaps not needed for automated driving

Table 21 MANTRA ODD related requirements for robot taxis (physical infrastructure)

Use Case "Commercial driverless vehicles as taxi services"	
Road	Urban road with not too complicated junctions; After year 2030: all urban roads including ring roads, motorways and any other road
Speed range	Up to 60 km/h; 2030 – up to 80 km/h and then 100 km/h
Shoulder or kerb	Roadside parking space on streets, wide shoulders or refuges on other roads with 500 m intervals; space needed for passenger hop-ons and -offs, likely clearly marked beside public transport terminals, public service, shopping and recreation areas and elsewhere in the cities at about 300 m intervals
Road markings	No specific requirements
Traffic signs	No specific requirements
Road equipment	Possible shelters and seats for passengers facilitating existing public transport stops where possible
Traffic	Separation of pedestrian/bicycle paths from the roads used
Time incl. light conditions	No specific requirements
Weather conditions	Precipitation <5mm/h, no ice nor snow on road, no fog/steam/smoke/dust hindering vision;

<table>
<tr><td>Project</td><td>SLAIN [108]</td></tr>
<tr><td>Period</td><td>April 2019, 3 years</td></tr>
<tr><td>Funding</td><td>EU</td></tr>
<tr><td>Website</td><td>https://eurorap.org/slain-project/</td></tr>
<tr><td>Description</td><td>Project SLAIN is a transnational project aiming to extend the skills and knowledge base of partners in performing network-wide road assessment. An assessment of road infrastructure readiness for improving road safety was performed.</td></tr>
<tr><td>Relevant results for SHOW A8.1</td><td>The SLAIN project investigated through literature search, stakeholder consultations and real-world collection of data, among others, the readiness of physical infrastructure for automation. The results are relevant for CAV vehicles.

Table 22 SLAIN Road infrastructure requirements for CAVs [109]
<table>
<tr><td>Road markings (incl. skid resistance)</td><td>Harmonisation of road markings at EU level is necessary;
For camera detection of 40m to 80m, 6-inch-wide road markings with adjacent 2-inch-wide contrast striping;
For camera detection < 40m, 1-inch wide contrast striping provides similar results to 2-inch-wide contrast striping;
Further research is needed to determine optimal retro-reflectivity level in case of poor weather conditions; detection of colour of lines; visibility of markings in tunnels;</td></tr>
<tr><td>Traffic signs</td><td>Research should focus on CAV readability of sign types, symbols used, shapes, heights, locations, influence of weather, visibility, noticeability, environmental conditions; AI algorithms for CAV readability training;</td></tr>
<tr><td>Shoulder and centreline rumble strips</td><td>Can significantly reduce risk of severe collisions for CAV vehicles;
Future research should focus on effects of centreline rumble strips in different types of in-vehicle systems and different types of road environment under varying weather conditions, noise and relationship with road markings.</td></tr>
<tr><td>Carriageway and number of lanes</td><td>CAV dedicated lanes have significant advantages in relation to traffic safety;</td></tr>
<tr><td>Lane width and paved shoulder width</td><td>A lane width of 2.72m was found to be the “critical” lane width for safe operation;
CAVs equipped with Lane Departure Warning (LDW) and Lane Keeping Aid (LKA) are dependent on roadway characteristics (markings, lane, shoulder width)</td></tr>
</table></td></tr>
</table>

	Median and side guard rails	Rumble strips or LKA, LDW systems can reduce unintentional lane drifting;
	Road condition	Poor road conditions influence the visibility of features such as road gradient, curvature, lane width, condition of road markings and traffic signs; Early detection of pavement distress can positively affect the reduction of crashes;
	Road grade	Bank angle and road slope can affect the trajectory tracking performance of CAV;
	Road curvature	Road curvature plays an important role for CAV operations, especially the type of curve and the interaction of speed, lateral position and safe cornering performance;
	Street lighting	Ensuring visibility of road markings, signals and signs for CAVs is necessary, requiring improved street lighting;
	Tunnels	CAV camera systems may suffer from reduced visibility or worse, due to quick changes in environmental illumination; Positioning is affected, due to GNSS inaccuracies in tunnels;
	Roadside objects and distance	Moving objects detection is still a challenge for CAVs; this can be solved mostly through HD maps;
	Intersections	Further research is needed in the sensing and perception of intersections and roundabouts for CAVs;
	Traffic lights	CAVs are able to recognise all traffic lights, however issues arise in understanding the context of the sign due to the dynamic nature of the traffic light; HD maps and V2X communication can aid in these challenges; Further research should focus on traffic light recognition in adverse conditions, early recognition (greater distances) and recognition in different illumination settings;
	Pedestrians, bicycles, powered two wheelers and facilities	Further research is needed to study the safe interaction between bicyclists, powered two wheelers, pedestrians and CAVs during different weather conditions, as well as on dynamic objects recognition;
	School zone warning	Future research on sensing and identification of school zone warnings as well as school zone warning supervisor should be undertaken;
	Vehicle parking	The presence of parking can be an obstruction to signs and road markings; Future research is needed in the detection of parking as an obstacle to sight distance under varying light conditions;
	Road works	Roadworks require CAVs to interpret real-time changes provided by temporary signs, markings and cones;

Project	AVINT [110]
Period	June 2018, 3 years
Funding	National (Greek)
Website	www.avint-project.eu
Description	In the AVINT project, participating partners will study the urban transport context in Trikala city and will implement a bus line supported by automated buses in a full integration mode with the city transport network. To accomplish this, AVINT will perform all the necessary tasks: feasibility study, implementation study, infrastructure adaptation, renting and adaptation of automated buses prior to coordination of pilot tests. The pilot results will be thoroughly analysed with regard to their impact on the Trikala traffic.

Relevant results for SHOW A8.1	Based on the available information, several observations regarding road infrastructure requirements could be extracted:
	• Slope of the whole route is less than 1%
	• To ensure smooth operation, some interventions such as parking ban and widening of the specific parts of the route will be proposed
	• The median road inclination is below 1%
	• Vertical markings on the route, including the placement of information and regulatory signs along the road;
	• The information boards mainly aim to provide (i) useful information for the simultaneous passage of the autonomous vehicle with the rest of the motorized traffic (bus traffic by flow) and not in a separate exclusive lane and (ii) early warning for the movement of an autonomous vehicle on the road;
	• The vertical information signage must meet the following requirements:
	  ○ To be easily seen and understood by both the Greek and the foreigner
	  ○ To be clear and uniform
	  ○ To be legible under the given vehicle speed conditions
	  ○ To be limited to the necessary information
	• A possibility for the delineation of the lanes is to be taken into consideration.
	• The possibility of safe movement of the autonomous vehicle within the roundabouts is to be examined.

<table>
<tr><td>Project</td><td>Via-AUTONOM [111]</td></tr>
<tr><td>Period</td><td>September 2016, 2 and ½ years</td></tr>
<tr><td>Funding</td><td>National (Austrian)</td></tr>
<tr><td>Website</td><td>-</td></tr>
<tr><td>Description</td><td>via-AUTONOM investigated future road infrastructure measures that have the highest effectiveness for supporting automated driving, and that fulfil the requirements of all road users regarding safety, efficiency and user comfort. Another objective was to develop a method to identify where on a road network those measures must be implemented.</td></tr>
<tr><td>Relevant results for SHOW A8.1</td><td>The physical infrastructure solutions are categorized into two groups, namely (1) road guidance systems and markings and (2) road geometry and structural adaptations. The first group comprises elements of road equipment such as road markings, traffic signs, delineation or reflectors. Solutions of the second group are constructional changes to the road such as the design of the road geometry and roadside. [112]
General remarks for physical infrastructure measures include:

Road markings characteristics: contrast, retro reflectivity, metal (for magnetic detection), temperature sensible
Safe exit stops, especially at roadworks
Separate lanes for AVs.

Table 23 VIA-AUTONOM Potential physical infrastructure solutions on selected hot spots for all road types
<table>
<tr><th>Hot Spots</th><th>Road guidance systems and markings</th><th>Road geometry and structural adaptations</th></tr>
<tr><td>Road work or other protected area</td><td>Protection and guidance through well visible delineation and markings, consistent design</td><td>Consistent design of chicanes, safe-exit bay before road work area</td></tr>
<tr><td>Tunnel area</td><td>Clearly visible lanes through markings and reflectors</td><td>Safe-exit bay before tunnel entrance</td></tr>
<tr><td>Ramp and merging lanes</td><td>Machine-readable signs (remaining length of lane or ramp), solid lines to avoid merging to 1st lane</td><td>Ensuring line of sight for merging vehicles, extension of the ramp length</td></tr>
<tr><td>Section with regularly poor weather conditions</td><td>Highly reflective markings, machine-readable signs to warn vehicles</td><td>Safe-exit bays</td></tr>
<tr><td>Toll gate area</td><td>Clear lane markings towards gates</td><td>Dedicated lane for CAV</td></tr>
</table>
</td></tr>
</table>

Accident black spot	Machine-readable signs to warn vehicles	Removal of risk factors
Section with poor road condition	Improvement of markings, machine-readable signs to warn vehicles	Improvement of surface condition
Curvy road section	Improvement of delineation, clearly visible lane edges and markings	Ensuring minimum sight distances by physical adaptations
Road junction	Clearly visible yield instructions or traffic lights	Ensuring line of sight to crossing road users
Roundabout	Locate stop lines where oncoming traffic is visible to sensors	Avoidance of multi-lane roundabouts, ensuring enough space for VRUs
Pedestrian and bicycle crossing	Machine-readable signs to warn vehicles	Ensuring line of sight to crossing road users
Railway crossing	Clearly visible signs, signals and markings, machine-readable signs to warn vehicles	Ensuring line of sight to crossing trains/trams, protection by gates
Narrow lane section	Markings, signs to warn vehicles	Extension of lane width, avoidance of narrow lanes, roadside lay-bys
Section with longitudinal bicycle lane	Clearly visible markings and delineation for separation	Physical separation by restraint systems, if necessary

Project	**SafeSign [113]**
Period	March 2020, 1 year
Funding	National (Austrian)
Website	-
Description	This project will investigate the influence of disturbance on deep learning based on traffic sign classification systems. Humans typically cannot judge if a sign can be perceived correctly by artificial intelligence. For example: a human driver approaches a tunnel. The variable traffic sign (based on LEDs) clearly shows "STOP" due to a height incident in the tunnel. The human driver stops the car. Due to disturbances (e.g. weather condition such as snow, ice, fog; defect of some LEDs) the automated system of the following car does not (or not correctly) perceive the sign. A crash happens.
Relevant results for SHOW A8.1	No deliverables are public yet.

3.5 Results of interviews with OEMs and other EU and national initiatives

As already described in chapter 2.2.1, it was decided to interview stakeholders in order to complement the literature review. Overall, data was collected from two OEMs, four projects (with several European pilot sites) and one national initiative. Due to the diversity of the projects, test sites and stakeholders, it was decided to present the results of the questionnaire per stakeholder group (*test site, project managers* and *shuttle manufacturers*). The respondents were as follows:

- Shuttle manufacturer EasyMile (partner in the SHOW project)
- Shuttle manufacturer NAVYA (partner in the SHOW project)
- The AVENUE project (May 2018, 4 years) aims to design and carry out full-scale demonstrations of urban transport automation by deploying, for the first time worldwide, fleets of autonomous minibuses in low to medium demand areas of 4 European demonstrator cities (Geneva, Lyon, Copenhagen and Luxembourg) and later on, of 3 replicator cities. The project employed Navya shuttles.
- The FABULOS project (January 2018, 3 years) [114] aims to establish and to deliver a systemic proof-of-concept on automated last mile public transport as part of existing transport systems of urban areas, based on the use of self-driving minibuses. The six partner cities of Helsinki in Finland, Tallinn in Estonia, Gjesdal in Norway, Helmond in the Netherlands, Lamia in Greece and Porto in Portugal are embracing this challenge by collectively procuring R&D for the prototyping and testing of smart systems that are capable of operating a fleet of self-driving minibuses in urban environments. The project employed GACHA, ISEAUTO, Navya and Sensible 4 shuttle buses.
- The Drive2thefuture project (May 2019, 3 years) [115] aims to prepare "drivers", travellers and vehicle operators of the future to accept and use connected, cooperative and automated transport modes and the industry of these technologies to understand and meet their needs and wants. The project employed Navya shuttles.
- The Sojhoa Baltic initiative (October 2017, 3 years) [116] researches, promotes and pilots automated driverless electric minibuses as part of the public transport chain, especially for the first/last mile connectivity. Sohjoa Baltic brings autonomous small buses to drive demo routes in six Baltic Sea Region cities. Demo sites include Helsinki, Tallinn, Kongsberg and Gdansk and Zemgale. The project employed Navya and EasyMile shuttles.
- The STOR - Ruter - SVV(NPRA) - BYM project (2019 - present) [117], a national initiative in Norway, gathering knowledge through a series of public transport trials with self-driving vehicles as part of the public transport chain in Akershusstranda, Kengens gate, Ormøya and Malmøya and Ski. The project employed Navya and Toyota vehicles.

Question 1: *How did you take into account the physical road infrastructure when preparing the pilot tests in your project (e.g. traffic signs, lane markings, junctions, sight distances, slope, road condition)?*

Test site, project managers:

In the Sojhoa pilots, the pilot area had to comply with the following characteristics: wide enough road, not too much traffic, speed limit preferably 30 km/h, not too steep slopes.

In the STOR project, three conditions were looked at when choosing the route for the test pilot: number of passengers (for evaluation of the provided service), traffic situation (the bus must handle the conditions), infrastructure. The bus should be able to handle normal traffic and road infrastructure, with none or minor adjustments to the road infrastructure. Regarding physical infrastructure, several factors were considered:

- Speed limit, so the buses can operate optimally according to their capability.
- Road surface has to be in good condition.
- Vegetation must be outside the bus's sensor area.
- Due to the buses' function and programming, traffic signs and road markings are not an influencing factor.
- Junctions and sight distances are not a big factor, due to the lower speed of the buses and altered safety/priority zones.
- Areas with higher slopes were avoided.

The majority of factors related to road infrastructure were taken into account when programming the route of the shuttle buses within the Drive2thefuture tests. They mentioned the following factors specifically and described their influence.

- Traffic signs and lane markings are not detected by the vehicle and are therefore irrelevant for the actions taken by the automation algorithm.
- Sight distances were a limiting factor especially on road junctions; therefore, the operator always has to confirm safety before the vehicle enters the junction. An improvement was sought by testing a system of cameras that detect traffic participants approaching one of the junctions, but this only ever delivered a visual signal to the operator and never directly influenced the shuttle's algorithms.
- Slopes and/or road condition were not an issue, as the chosen route was on flat terrain in a rather new district of Vienna, where the road condition was generally stable.

Within the AVENUE test pilots, the vehicle scans (through sensors such as LIDAR, video) the road and identifies different infrastructure elements, which can be used for increasing the localisation precision. The infrastructure is annotated after the initial road mapping, identifying fixed elements that can also serve as reference points to vehicle localisation. In the Lyon Site, a V2I system was installed and the vehicle can interact with the traffic lights.

A certain type of physical road infrastructure was not the number one priority when preparing the pilot test routes in FABULOS and was thus not taken into account to a large extent. The FABULOS cities believe that for autonomous shuttle solutions to be rolled out widely, they should be deployable anywhere without (too m)any infrastructural adaptations from the side of the cities. Several factors were taken into account when choosing the routes of the buses:

- The routes were predominantly chosen based on actual needs of the cities, regardless of potentially "difficult" infrastructural conditions. E.g. the Gjesdal route has a 8-10% slope, all routes have junctions, many have left turns and some do not have lane markings.
- Limitations from road authorities were taken into account: e.g. in the Netherlands the preferred route was on a stretch of a 50km/h road; however, when the road authorities did not approve a vehicle speed higher than 25 km/h, the route was changed to one with lower speeds.
- Preliminary information from the pilot routes and the infrastructure were gathered in the early phase of the project through city questionnaires and route descriptions provided by the pilot cities.

- Final decisions and actions regarding the infrastructure were made when the vehicles were deployed on the actual routes.

Question 2: ***What physical road infrastructure did you consider relevant for the planning of the pilot tests?***

Test site, project managers:

For the projects, the following infrastructure elements were considered relevant:

Sojhoa pilots: wide enough road, not too much traffic, speed limit preferably 30 km/h, not too steep slopes.

STOR project: speed limit (e.g., road design speed), segregated structured traffic (e.g., separate bike lanes), lower traffic volume.

Drive2thefuture:

- A precise GPS-signal and an immediate environment of the route that is as stable as possible is extremely important for the autonomous shuttle. As the vehicle takes its precise position from 3D-scanning its environment, even the walls of buildings up to several meters high along the road are an important factor for its orientation. Therefore, trees were a major concern, and especially the ones very close to the road.
- Building sites along the route.
- Other key information flows: traffic participants in and around junctions, speed limits and other traffic information.
- Constant environment along the route to avoid having to reprogram the vehicle regularly.
- A minimum of moving/growing objects along the route (plants, fields etc) would also be necessary, otherwise the vehicle will often be stuck and/or otherwise unable to continue on its own.

AVENUE: pedestrian crossings, bus stop installations.

FABULOS:

- Traffic lights (communication possibilities between the lights and pilot vehicles).
- Availability of storage and charging place for pilot vehicles (both daytime and overnight) considering the vehicles' dimensions.
- Quality of the intersections, e.g. number of lanes as well as speed and amount of general traffic at the intersections (and along the whole route).
- Width of the roads (the wider the better).
- Existence of uncontrolled roadside parking by the route (roadside parking should be completely prohibited by the pilot route or parking spaces should be at least clearly marked or located off the actual driveway). Possibility of prohibiting roadside parking with signs or other means if necessary.
- Availability of facilities near the route for local incident response team (acting on site in case of malfunctioning and other issues in the vehicles) as well as for onboard safety drivers/operators and remote-control centre.
- Available location (usually a roof of high building by the pilot route) for a fixed GNSS RTK reference station or availability of VRS RTK.
- Potential need for additional structures to improve (LiDAR) localization of the vehicle if no other fixed structures are available or usable.
- Need for lowering speed limits with additional traffic signs and other potential traffic signs to change the right of way in intersections and warning of other vehicles.
- Steepness of slopes.

- Arrangements for bus stops for the pilot vehicles, e.g. bus stop signs and reservation of parking spaces, if no otherwise space available.
- Availability and quality of 4G/5G mobile networks by the route and broadband connections in the remote-control centre facilities.
- Type and amount of vegetation next to the roadside.
- Existence of speed bumps.

Question 3: ***Did you use physical infrastructural elements to increase the level of awareness/safety for automated vehicles?***

Test site, project managers:

The following infrastructural element was deployed in the Sojhoa Baltic pilot to increase the level of awareness for AVs: custom signs at the robot bus stops.

In the STOR project, no infrastructural elements were deployed to increase the level of awareness/safety for the shuttle. Very minor adjustments were needed by the vehicle in the planning phase of the tests.

In Drive2thefuture, an attempt to monitor traffic participants at one junction via a system of video cameras and a detection software was performed. This delivered some remarkably positive results but was never used to directly influence the steering algorithms of the shuttle. Only four cameras were used. In order to really provide the shuttle with enough information to autonomously cross an intersection it would probably require several more.

In the AVENUE pilots, infrastructure markers were used to augment localisation.

The following infrastructural elements were deployed in the FABULOS pilots:

- Additional localization signs for improving the pilot vehicles' navigation were implemented next to the road in the Gjesdal pilot in Norway
- Warning signs of automated vehicles and informative signs were implemented at all three pilot sites
- Speed limitations were lowered with signs in some pilot routes (e.g. in Gjesdal a stretch of a few hundred metres was lowered from 40 to 30 km/h)
- Bus stop signs were deployed at the bus stops.

Question 4: ***How does the automated vehicle take into account the physical road infrastructure on the road?***

Shuttle manufacturers:

The EasyMile vehicle uses its available sensors to achieve this task. Infrastructure elements can be used by obstacle detection, localisation or navigation functions depending on the infrastructure element.

The physical road infrastructure is taken into account by the NAVYA vehicle through different ways: The first one is during the mapping of the predefined path – priorities are defined (pedestrian crossing, roundabout, turning signals, speed limitation, stations etc…) – and the second one is through the vehicle's sensors. The camera can read the traffic signs, and the lane markings for instance.

Test site, project managers:

In the Sojhoa Baltic pilots, the vehicle detects the infrastructure with the help of LIDAR sensors. Therefore, the road infrastructure should not change too much, or the route would need re-mapping.

The STOR pilots' manager commented that at the moment, the infrastructure of a city does not suit or support autonomous vehicles. For example, pedestrian crossings are quite narrow, therefore a bus would take a wider curve to avoid a "tourist" pedestrian (looking at things but not planning to cross the road), therefore showing a different intention than to surround a road user, when compared to a human-operated vehicle.

In the Drive2thefuture pilots, most physical infrastructure along the route is not considered beyond its physical appearance by the shuttle. For example a traffic light or a road sign would be scanned by the 3D Lidar and used in order to verify the position of the vehicle relative to it, but the vehicle would not classify objects that are scanned this way and therefore never know that the object is a traffic light or road sign, let alone whether the light is green or red or the traffic sign is a speed limit or a stop sign. The shuttle also extrapolates movement of physical objects in its immediate environment, and should this extrapolation yield a collision course it initiates countermeasures, such as breaking or giving an audio signal.

The FABULOS pilot manager remarked that the infrastructure was taken into account mainly by using it for navigation/localizing itself on the route. Physical infrastructure does not otherwise give much information for the automated vehicles used in the project. For instance, all intersections are programmed beforehand usually by using so called “priority zones” or similar, traffic rules cannot be programmed yet at least to vehicles that were used in FABULOS. If traffic lights and the vehicle are implemented with certain types of communication modules, they can communicate with each other.

Question 5: ***What infrastructure elements do the vehicle’s sensors (cameras, LIDAR, radar) detect/ need to detect in order to ensure operation? (e.g. lane markings, traffic signs)***

Shuttle manufacturers:

Some of the EasyMile shuttle’s driving functions require road markings, buildings, traffic lights, static urban furniture. Connected infrastructure is also used in some instances, for example for traffic lights.

Similarly, the lane markings and traffic signs can be detected by the camera of the NAVYA shuttle. They are also marked in the predefined path (e.g., pedestrian crossing).

Test site, project managers:

In the Sojhoa, STOR and Drive2thefuture pilots, none of the infrastructure elements are detected beyond their physical shape. Tomorrow’s road markings should support positioning in addition to GNSS. Traffic signs should be digital/programmed for AVs. Through V2I/V2X, AVs should communicate digitally with traffic signals.

The FABULOS project manager remarked that the vehicle needs to detect the surrounding buildings or other structures with LiDAR to localize itself on the path. If no buildings or other structures are near, additional infrastructure may be needed to improve localization of the vehicle. In some cases, navigation through satellites only (GNSS) may be also enough. Traffic lights need to communicate with the shuttle, in order for the vehicle to pass intersections automatically. Lane markings are not used by shuttles and traffic signs do not actually give any information to them as nearly all features and actions needed are programmed beforehand in the shuttles: trajectory of the route itself, speeds, intersections, zebra crossings, bus stops etc. The vehicle then adjusts its operation by taking into account other road users and other possible variables on its path, sometimes less successful (e.g. overtaking of obstacles not possible) increasing the number of operator’s interventions. Network connections are needed for navigation and communicating with the vehicle remotely.

Question 6: ***How could infrastructure elements impede the vehicle's operation? (e.g. traffic sign obscured by vegetation, road slope level)***

Shuttle manufacturers:

For the EasyMile vehicle, traffic signs are usually added in the vehicle's semantic map. Posts close to the AV lane could lead to a speed decrease. Also depending on the driving scenario, urban furniture could create blind spots, for example advertisement panels, bus stops etc.

For the NAVYA shuttle, vegetation is a real issue for the camera and also for the LIDAR localization. For an optimal LIDAR localization, the environment must be as constant as possible. LIDAR localization relies on several factors:

- number of physical objects in the field of view
- types of surfaces; the following surfaces are not suited for LIDAR localization:
- transparent surfaces
- mirrors (creates reflection)
- vegetation
- monotonous surfaces (tunnel-effect)
- light absorbent material (such as black surfaces)
- distance from the shuttle: ideally between 10m and 30m
- In addition, the road slope level can produce the following influences:
    - Shuttles can drive on slopes up to 8% permanently;
    - Shuttles can drive on slopes up to 12% for a duration of 3 minutes (at 3m/s), needing 5 minutes to cool down the electric motor before driving again.
    - Shuttles can drive on slopes up to 15% for a limited time, with a cooling time afterwards.

Test site, project managers:

The most common problem reported by the Sojhoa, STOR, FABULOS and Drive2thefuture pilots is the vegetation growing too close to the path of shuttle bus (or in the priority areas) causing unnecessary braking and stopping of the vehicle. Poor weather conditions, road surface standard and potholes as well as a steep slope causing overheating were also mentioned.

In addition, the FABULOS project reported the following infrastructure elements that could hinder a vehicle's operation:

- Vehicles parked to roadside or other objects on the shuttle's path can stop the automated vehicle, as an overtaking feature has not yet been demonstrated in open road pilots. The object does not necessarily have to be just in front of the shuttle. If the parameters for the safety distance are not met, the shuttle can stop anyway, even though there would be actually space to continue the ride directly on the programmed path. Issues with parked vehicles are highlighted on narrow two-way roads (width of the road around 6-7 m or under and width of a lane around 3-3,5 m or under) as there might be no space for programming the shuttle more to the left side of the lane which leads to a very small distance to the parked vehicles on the roadside.
- In the Helsinki pilot (Spring 2020), unexpected roadworks temporarily altered the infrastructure on the route and hindered the pilot. The route was narrowed and for a 100 metre stretch the safety driver had to take over operations manually.
- No availability for electricity and space for organizing charging and storage for vehicles near the route also impede the vehicle's operation.

Question 7: ***In case of lost GPS signal, how does the vehicle continue operation and how is it influenced by the physical infrastructure?***

Shuttle manufacturers:

For the EasyMile shuttle, GPS loss could impact the AV localisation function; however, the system relies on several independent modalities and it is resilient to the loss of one of them, which occurs especially in outdoor to indoor use cases.

In the case of the NAVYA, the vehicle continues operation through the 3D LIDAR localization, following the table below:

Table 24: NAVYA 3D LIDAR localization.

Urban environment: vertical walls in multiple directions, no vegetation	OK with 3D LIDAR localization
Irregular but stable environment: trimmed vegetation, irregular buildings	OK with 3D LIDAR localization, if one of the following conditions is fulfilled: Lateral LIDAR landmarks + straight line + low speed Lateral LIDAR landmarks + line localization assistance
Weak LIDAR environment: wild vegetation, evolving environment such as parking lots or construction area	Not OK
Empty LIDAR environment	Not OK

Test site, project managers:

In all the test pilots, the shuttle buses either stop if the GNSS signal is lost or continue based on LiDAR sensors alone, identifying fixed infrastructure elements or using HD maps. GNSS signal strength is influenced by high buildings, vegetation or geographical conditions.

Question 8: ***How do the following road infrastructure elements influence the vehicle's operation?***

- Visibility, reflectivity and detectability of lane markings (especially in adverse conditions)
- Traffic signs (consistency, standardization, detection)
- Quality, material, slope of road surface
- Sight distances and visibility at junctions (definition of minimal sight distances)
- Accessibility and safety of PT hubs and stations
- Temporary road works

Shuttle manufacturers:

The EasyMile manufacturer pointed out that lane markings can "disappear" under bad weather conditions and lead to localisation issues if such a function is used. Road has to be flat ideally and water evacuated to avoid creating a mirror like surface. Visibility in junctions has to be high enough to deal with other vehicles' speed. Temporary roadworks is still an issue as of today. Moreover, it could induce dust or particles that could degrade our sensors.

The NAVYA manufacturer commented that various road marks that have the same reflectivity as an actual lane marking can be interpreted by the vehicle for its relative position. A redundant perception system must be taken into account. As traffic signs differ from country to country, the camera software must learn them all (by learning step by step). In addition, the sensors have their limitations, and these are taken into account for the sight distances – for example, if sensors can be complementary (e.g., both short-range and long-range sensors), detection of different objects through radar/LIDAR/camera enables a fusion of data and redundancy. Stations and PT hubs are taken into account in the predefined path. Temporary road works are an issue and are taken into account before the public tests. A new mapping can be done if the road works or even building constructions can influence the LIDAR localization.

<u>Test site, project managers</u>:

The Sojhoa Baltic pilots reported that lane markings and traffic signs have no influence. Slopes can cause overheating, leading to potential problems during winter (due to the power distribution between wheels, at least in manual mode). Sight distances influence the overall feeling of safety and can cause dangerous situations with other road users. Public transport hubs and stations should be reached safely with the robot bus. Temporary road works are the most problematic issue, as they need to be driven around manually.

Similarly, the STOR project reported that lane markings and traffic signs have no influence. Road surface is usually optimised before starting the pilots. Slopes are avoided, due to mechanical issues and winter conditions (i.e. slippery road). Accessibility to PT hubs and stations is highly relevant, as it gives the route meaning, value, passengers. Minor adjustments could be needed, as new hubs could be installed for the pilots.

The Drive2thefuture pilots reported as well that lane markings and traffic signs have no influence, and neither does the road surface. Sight distances and visibility at junctions are relevant as it influences the vehicle's operation, however only as far as they also influence the operator's ability to assess a situation. Accessibility of PT hubs and stations are relevant for the programming of the route. Once they are considered, the only requirement for a stable operation is that their physical shapes remain rather constant. Temporary road works severely impact the shuttle's ability to navigate autonomously and will almost always make manual driving necessary.

The AVENUE manager commented that if driving in harsh roads (brick or granite pavement) the vehicle experiences strong vibrations that create issues to hardware connections (PC cables can be disconnected). For PT hubs and stations, there is required access for wheel chairs for public transportation. In the case of fixed routes, if the roadworks leave a space for the bus to pass, the vehicle will bypass them. Otherwise, the route and operation are blocked. In case of on-demand, door-to-door operations, if the road is not accessible for some reason, alternative paths are automatically identified.

The FABULOS project also pointed out that lane markings and traffic signs have no influence. Sandy road can raise dust from the ground which can be seen as an obstacle by the shuttles. If a slope of the road is too steep, it can affect the performance of the vehicle (not able to climb the slope at all) or cause difficulties at the top where the slope is levelling quickly, which makes detection of obstacles difficult. Icy conditions can be difficult for automated vehicles causing them to not be able to fully keep the programmed path due to slippery roads. Regarding sight distances, speed of other vehicles at an intersection might be a problem, as the radars and sensors of the automated vehicle cannot necessarily see far enough to determine safely whether it is safe to drive. Sometimes PT authorities do not allow shuttles to use PT hubs and stations as they can hinder the operation of normal PT buses. There might not be space for shuttles or the hubs can be located too far away from the operational route. Temporary road works are highly problematic, as the vehicle has to deviate from the programmed path, thus making operation impossible in automated mode. If the roadwork is controlled with traffic lights, V2X communication with the shuttle would be necessary to ensure automated passing.

Question 9: *What are the requirements that the current generation of vehicles set to the infrastructural environment?*

Shuttle manufacturers:

The EasyMile manufacturer remarked that besides connected traffic lights, the vehicles must be adapted to the existing infrastructure. In some cases, additional panels for localisation purposes could be added.

However, the NAVYA manufacturer pointed out that the Operational Design Domain of the shuttle defines where the shuttle can operate and in which conditions. There is a feasibility study on each site to determine if it is possible to operate on the site and the limitations and risks. These limitations and risks are usually related to the speed of other vehicles, a good localisation of the shuttle, road slopes, priorities etc. These risks can be mitigated by improving the localisation with LIDAR.

Test site, project managers:

The Sojhoa Baltic pilot specified that wide roads are a preferred requirement. Also, wide parking areas next to the route or preferably no parking on the route. Moreover, good road maintenance, especially during winter is paramount. Others include low speed limits and not too many vertical differences.

The STOR manager concluded that today's AVs can't operate in all traffic environments.

Stability was pointed out as the most important condition for the infrastructural environment by the Drive2thefuture pilot manager. Furthermore, the vehicle requires a certain number of buildings along the route. If it has to pass an open road e.g. between villages, this can cause issues as it will not recognize a sufficient fraction of its environment to ensure precise positioning.

The project AVENUE targets SAE L4 driving with the road fully mapped and using LIDAR as main scanning technology. As a result, the changes in road infrastructure need to be mapped as much as possible. Regular maintenance of streets is needed, due to potential issues with growing vegetation being recognized as obstacles.

The FABULOS manager remarked that the current automated vehicles are dependent on operating in an environment that is suitable for them. Having an unsuitable route and environment can heavily increase the operator's intervention during the operation and lower the safety level. Currently the problems and challenges in different environments can be circumvented as well as the amount of possible operational environments increased by implementing different (infrastructural) arrangements and accepting that the operator intervenes more in the operation. There is a threshold of accepted environmental changes and frequency of operator intervention, which varies from deployment to deployment. In cases where the number and magnitude of arrangements as well as frequency of intervention increases too high, the feasibility and viability of the deployment needs to be critically reconsidered. However, it needs to be noted that there are significant differences between various suppliers/vehicles.

Nevertheless, there are certain operational design domains that limit the operational capabilities. In case of infrastructure these limitations can be in relation to:

- Speed limit at maximum 30 km/h
- Amount of other traffic by the route (as minimum as possible)
- Type and level of difficulty of intersections
- Availability of internet connections, at least 4G speeds
- Availability of facilities for charging and storage, enough height and width (usually shuttles are around 3 meters high)
- Traffic lights with necessary communication modules
- Suitable bus stops (free of other vehicles during the operation and enough space to enter and leave from the stop, around 3 times the vehicle length)
- Limited/Wide enough lanes (at least 3 meters without roadside parking)
- Limited/No roadside parking (for having best experience of the operation and minimize the operator's intervention)
- Limited/No vegetation by the roadside
- Preferably no speed bumps.

Automated vehicles of the future should not require the environment being shaped by their demands, they should be able to adapt to the existing environment. Of course, some aspects can be added or be designed to already existing and newly built environments to ease the uptake. What "the current generation of automated vehicles" need from infrastructure is ambiguous.

4 Physical road infrastructure at SHOW pilot sites

Following the physical infrastructure requirements defined in chapter 3, the available physical infrastructure as well as planned or implemented adaptations at SHOW pilot sites are analysed in this chapter.

4.1 Evaluation of existing infrastructure at SHOW pilot sites

For the evaluation, a crosscutting analysis on a few general physical infrastructure components is carried out, followed by a detailed evaluation on the infrastructure components at the sites, based on a questionnaire, which was filled out by the pilot sites in February/March 2021. The general components derive from a spreadsheet which was developed by the work package leader and filled in by those responsible for the pilot sites until December 2020. Because of this due date the test site Gothenburg and the two test sites in Carinthia, Austria (Klagenfurt and Pörtschach), which are not in operation yet as their official approval is pending, are missing. Nevertheless, for a general overview data from 13 of 16 mega and satellite sites is considered enough.

4.1.1 Physical infrastructure overview based on area and road type

The area and road type give a first overview on the physical infrastructure (Figure 35 and Figure 36 – multiple answers were possible). In the SHOW project, most test sites are in residential or industrial/business areas. Four test sites have commercial areas, which might indicate higher pedestrian flows.

Higher pedestrian flows or other vulnerable road users could also be assumed depending on the road type. Almost half of the pilot sites have pedestrian streets or shared spaces along the route, and important for the physical infrastructure, these road types typically occur with no lane markings. Most of the pilot sites have residential roads, and a lot of vehicles drive in zones with lower speeds, like 30 km/h zones. Driving in lower speed zones was also recommended within other projects like AVENUE, FABULOS or the Sojhoa initiative (see Chapters 3.4 and 3.5).

Another important factor for automated driving is the traffic mix: is the AV separated from other traffic or does it operate within a mixed environment? The answer for this question can be derived from the SHOW use cases [185]: Use case 1.6 deals with mixed traffic flows, whereas use cases 1.1 “Automated passengers/cargo mobility in Cities under normal traffic & environmental conditions” and 1.2 “Automated passengers/cargo mobility in Cities under complex traffic & environmental conditions” are limited to dedicated or restricted AV lanes. Use case 1.6 applies to the majority of the SHOW test sites, only Graz, Turin, Tampere and Brainport do not address this use case. The Brainport pilot site also responded in the spreadsheet that they are only using bus lanes. Pedestrian areas and shared spaces, which occur at six test sites, indicate a mixed area with vulnerable road users. For the interaction with VRUs a specific use case, namely UC 1.3 “Interfacing non automated vehicles and travellers (including VRUs)”, exists, which applies to all pilot sites but Aachen and Tampere.

The terrain is flat in all areas except Salzburg, which claims hilly area. This is important to know, as the operational design domain of automated vehicles can be limited by the slope. As stated in Chapter 3.5 a too high slope can either be not manageable, or cause the vehicle to overheat, so pauses must follow to let the vehicle cool down.

Some physical infrastructure components make the driving situation more complex. These can be intersections (which will be addressed in the detailed analysis in chapter 4.1.2), having more than one lane in driving direction (possible overtaking and lane 1selection must be considered), the occurrence of merge lanes (estimating the gap to merge, calculating the other’s driving behaviours) and narrow roads with encounter possibilities (localization accuracy must be very high). The narrow roads were here defined with less than 5,5 m width, which makes up a width of 2,25 m per lane when there is encountering traffic. This is under the recommended width of 2,72 m as stated in the SLAIN project, or under 3 m as mentioned from the FABULOS project manager (see Chapters 3.4 and 3.5). At the SHOW test sites, these physical infrastructure components are present as shown in Table 25.

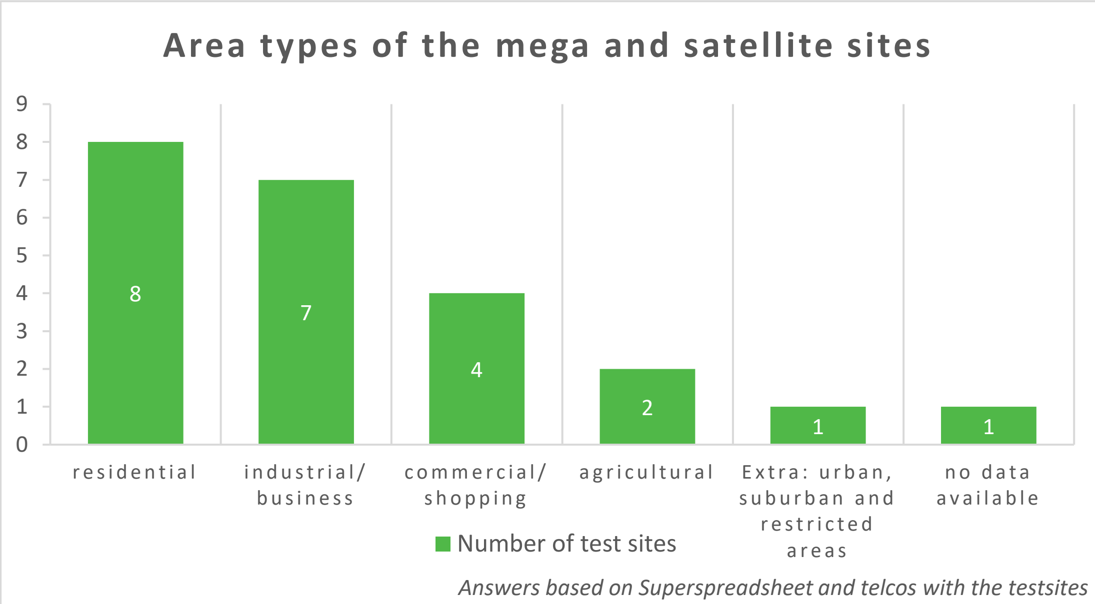


Figure 35: Area types at the Mega and Satellite sites within SHOW (status 12/2020).

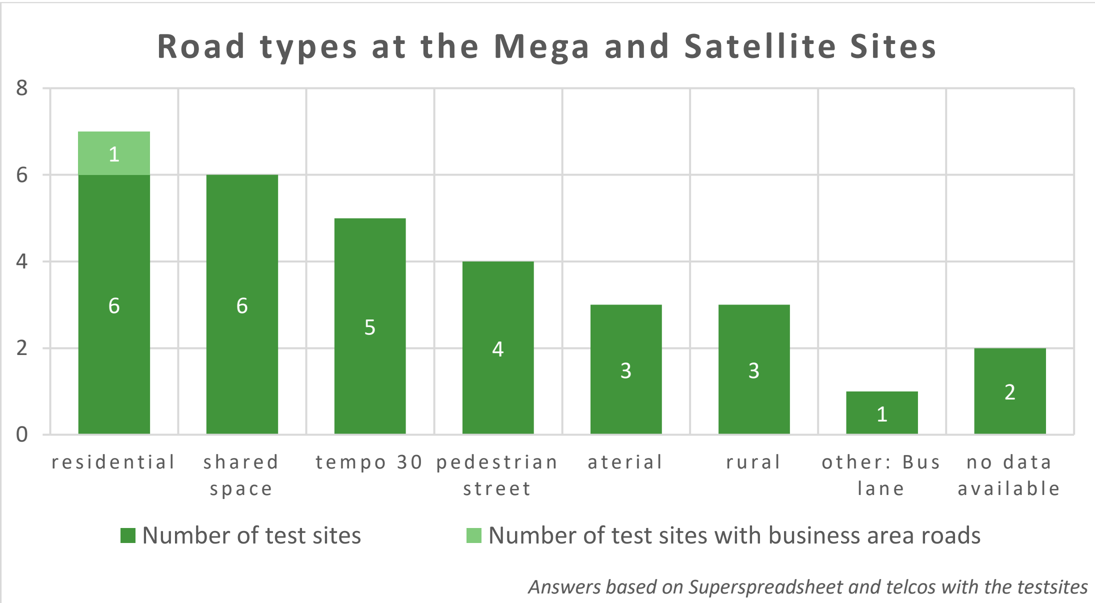


Figure 36: Road types at the Mega and Satellite sites within SHOW (status 12/2020).

Table 25: Occurrence of physical infrastructure components indicating complex driving situations at the SHOW test sites (status as of 12/2020).

Physical infrastructure component	Pilot site
Intersection	All pilot sites
> 1 lane in driving direction	Rouen (F), Copenhagen (DK), possibly Tampere (FI)
Merge lane along the route	Karlsruhe (DE), Salzburg (AT)
Narrow roads (< 5,5 m) with encountering traffic	Graz (AT), Salzburg (AT), Karlsruhe (DE), Trikala (GR)

4.1.2 Physical infrastructure elements in detail

In addition to the former analysis, a follow-up questionnaire was developed, focusing on information on lane markings, traffic signs, sight distances, public transport hubs and important components conceived from the desk research and interviews on physical infrastructure. The questionnaire can be found in the appendix. Answers were given by 15 SHOW mega and satellite sites and two follower sites. There were no answers given from Copenhagen, because the test site was not ready by the date of this deliverable to provide answers. The answers from the Brussels follower site are also missing, as they did not answer the questionnaire. Included are the answers from the pilot site in Klagenfurt and Pörtschach, both in Carinthia, Austria. These two sites are not in operation yet as their official approval is pending, but the answers could be given in advance.

The results are structured as follows: Grouped by thematic area the answers per pilot site are listed, followed by an overview of all SHOW test sites for each infrastructure component.

At the end of the evaluation there is a summary of the most important infrastructure components and gaps.

Road condition

The test sites were asked about the pavement conditions – material and quality. The road surface material can have effects on the detectability of road markings, as concrete surfaces are usually light-coloured. Also, harsh surfaces like bricks or granite can lead to vibrations, which might cause issues in the hardware of vehicles (disconnecting PC cables), as stated in Chapter 3.4 by a pilot site manager of AVENUE. Potholes can decrease driving comfort or be detected as an obstacle, which can cause problems.

Table 26: Road material and quality at the SHOW test sites (status as of 03/2021).

Test site	Road surface material (main)	Road surface material (other)	Quality
Madrid	Asphalt		Good conditions, potholes will be fixed.

Test site	Road surface material (main)	Road surface material (other)	Quality
Tampere	Asphalt		Good quality, some minor potholes and construction works. In winter snow, ice, ruts etc.
Aachen	Asphalt		Very good conditions
Brainport	Asphalt		
Gothenburg	Asphalt		Good quality.
Graz	Asphalt		Good conditions
Klagenfurt	Asphalt		Very good conditions
Turin	Asphalt		Some quality issues (cracks due to fatigue, bleeding, pumping), no potholes
Follower Thessaloniki	Asphalt		Quality varies, depending on road classification (major arterials better than local roads)
Rouen	Asphalt (but not relevant for AV)		Good to fair.
Salzburg	Asphalt	short section (turn place) gravel	
Pörtschach	Asphalt	short section (pedestrian square) concrete tiles	Very good conditions
Karlsruhe	Asphalt, other	Some parts cobblestone	Few potholes
Brno	Asphalt, paving stone		Good quality (mostly).
Linköping	Asphalt, road bricks		Good quality.
Trikala	Cement slabs	Cement (other)	Some potholes
Follower Geneva	Not answered.		Not answered.

Overview

Regarding the road surface, 15 out of 16 SHOW test sites have asphalt as material, mostly in good quality. Additionally, some test sites also have other materials: At one test sites gravel occurs, in Karlsruhe there is a part with cobblestone, and on three other test sites there are concrete tiles, road bricks or paving stones. Trikala is the only test site with cement as road surface and if detectability of lane markings is needed, they should make sure, that the contrast between road surface and road markings is as recommended in Chapter 3.3.1.

The road surface quality is mostly very good (see 8). A few potholes exist in Karlsruhe, Tampere, and Trikala. In Thessaloniki the road surface quality varies. Madrid will fix their potholes. Brainport and Salzburg did not mention their surface quality. For general road safety concerns and as poor road conditions influence the visibility of features such as road gradient, curvature, lane width the condition of road markings and traffic signs (mentioned in the SLAIN project referenced in Chapter 3.4), pothole cancellation would be recommended for all remaining sites.

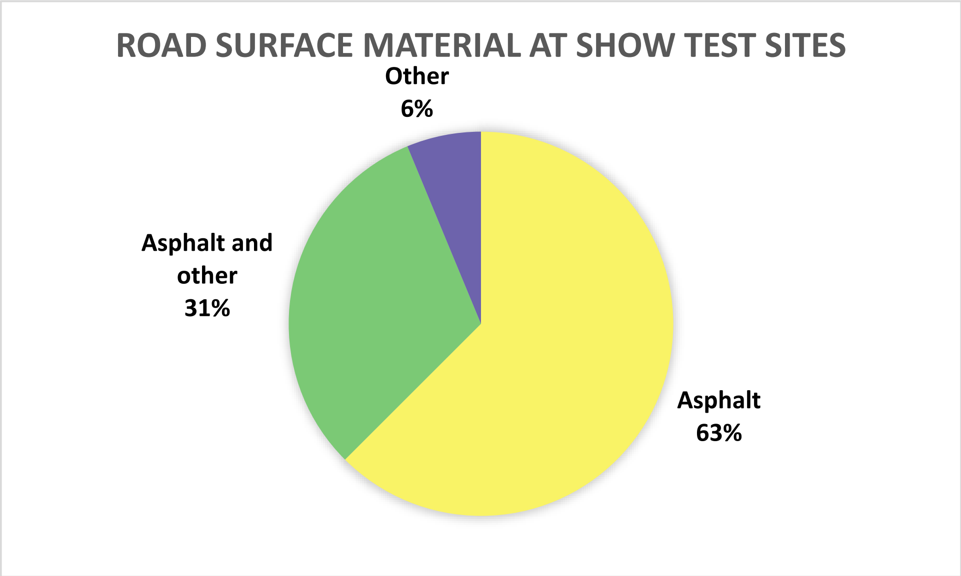


Figure 37: Road surface material at the SHOW test sites (status from 03/2020).

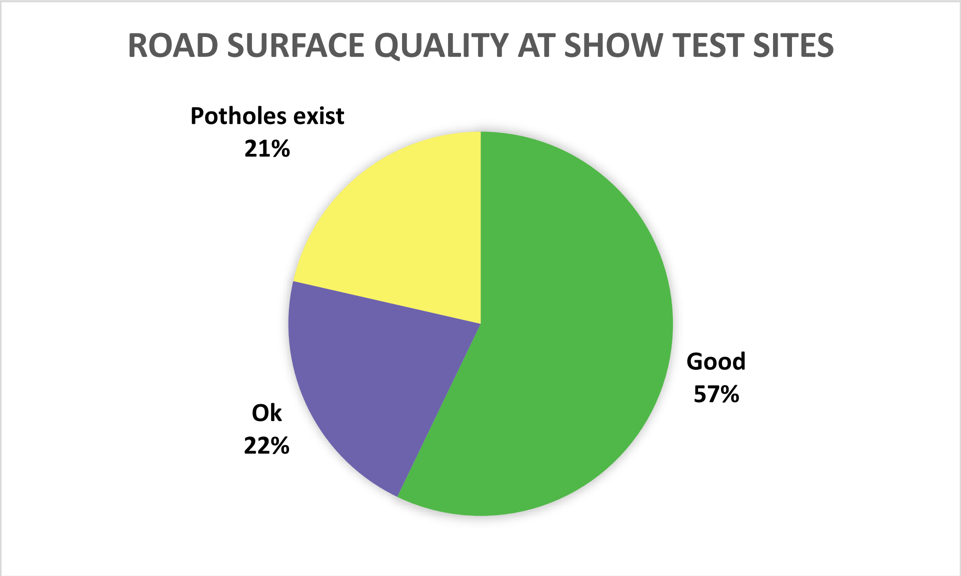


Figure 38: Road surface quality at the SHOW test sites (status from 03/2020).

Lane markings

To support various automated driving systems, including those which detect lane markings, the availability and quality of these are considered important. Following the findings on lane markings in Chapter 3.1.1 and 3.2.1, the test sites were asked about the availability of lane markings, structured into four classes (in percent intervals for the availability, see Appendix I) plus two additional classes for all route-long existing or none lane markings. For the road marking quality three categories were defined:

Good quality, Ok quality (being good, but bad in special conditions like rain), or poor quality (having fringed lines, etc.).

Table 27: Road marking availability and quality at the SHOW test sites (status as of 03/2021).

Test site	Road marking availability	Road marking quality	Other
Aachen	100%	Good	
Madrid Villaverde	100%	Good	
Rouen	100%	Good	
Brainport	81-100%	Good	
Tampere	81-100%	Ok, but bad during winter conditions (snow, ice, ruts, etc.)	
Trikala	81-100%	Ok, but bad in special conditions	
Turin	81-100%	Ok, shows some signs of wear.	Lane markings in most of the area, but not on smaller transversal roads (two-way streets)
Follower Thessaloniki	81-100%	Ok, but bad in special conditions	
Graz	61-80%	Good	
Pörtschach	61-80%	Differs from really poor to good along route	Good condition on the main street, rather bad condition (at the moment) on other parts of the route. Markings are not necessary on this site but a useful addition for autonomous driving.
Klagenfurt	41-60%	Good to ok (differs along route)	
Brno	41-60%	Good	
Madrid Carabanchel	Some	Ok, but bad in special conditions	
Salzburg	0-20%	Ok, but bad in special conditions (not very new)	No lane markings within municipality (strategy for road safety)
Gothenburg	0-20%	Good	
Follower Geneva	0-20%	Ok, but bad in special conditions	The pedestrian crossings are not in perfect conditions and some are barely visible.
Linköping	0-20%	Ok, but bad in special conditions	
Karlsruhe	0%	-	

Overview

The lane marking quality varies at the SHOW test sites from no lane markings at all to 100% lane markings in good quality (Figure 39). The quality is mostly good or ok (being bad in special weather conditions or have come into the years).

There are only three test sites having good quality lane markings along the whole route and one pilot site without any lane markings. The latter one obviously manages to operate a shuttle without them. As analysed in Chapter 3.1.1 and 3.2.1, lane markings should be available for automated driving at a certain quality. Even EasyMile and Navya mentioned to use them to a certain extent or are at least able to detect them (see Chapter 3.5). The interviews with the pilot site managers in Chapter 3.5 on the other hand showed, that lane markings have not been used at their test sites, although they said, in the future, lane markings might have a bigger influence and could support positioning. Those projects used certain vehicle technologies, which in the end define whether lane markings are needed for operating the AV or not. The MANTRA project (referred to in Chapter 3.4) guesses that by 2040 lane markings will possibly not be needed for automated driving, but by 2030 we will still need good contrast of lane markings.

In most of the test sites, there are parts with lane markings and without. But not only the availability, also the design can differ within the test site which is shown for example at the Turin test site: They have white longitudinal markings, being either solid or broken white, but also yellow lanes in one street to mark the priority bus lane.

According to the fact, that lane markings so far do not play a major role in automated driving in urban pilots and the future is unknown, there will be no recommendations made.

It was also asked, what standards exist regarding lane markings and the weather conditions. This could not be answered by a lot of test sites and was therefore not analysed.

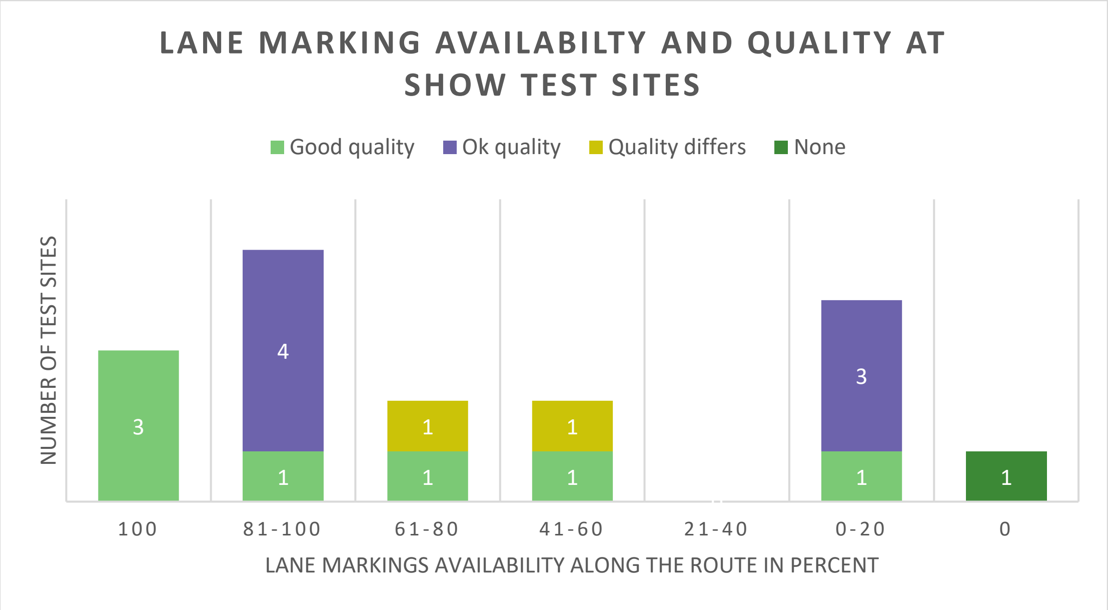


Figure 39: Lane markings availability and quality at the SHOW pilot sites.

Intersections

Automated driving along a straight stretch of road is much easier than managing intersections. These can be regulated differently, although the regulation with traffic lights can be seen as safest as the traffic lights give way to a group of road users at a time. At intersections with traffic signs, the automated vehicle can either have priority, thus having to focus less on the other traffic participants, or if the vehicle does not have priority, the vehicle has to check if the road is free to cross or join. This is always the case with unregulated crossings, which are actually regulated with priority to the right, and the perception system has to check in every case. Within SHOW, roundabouts are also categorized as complex conditions, this is why this special kind of intersection is listed here too.

Table 28: Number of intersections and their regulation at the SHOW test sites (status as of 03/2021).

Test site	Intersections regulated with				Sum	Comments
	traffic lights	traffic signs	Round-abouts	Priority to the right		
Madrid Carabanchel					0	No intersections at the moment, as this is the shuttle/bus depot.
Madrid Villaverde	2	1			3	Traffic lights: Intention is current light status should be sent to the AV by RSU and OBU.
Trikala	7		1		8	Intersections: 3 four-level, 4 T-shaped
Tampere			2	4	6	Roundabouts with signs & traffic lights
Aachen		4	1		5	4 stop signs
Karlsruhe		15		37	52	
Brainport	1				1	With C-ITS services
Brno		14				
Rouen	3		5	16	24	At the intersections without traffic lights the shuttle has priority If the traffic lights are not working the shuttle has the priority (signs in case of failure)
Turin	14	20			34	+ 3 "intersections" to driveways, garage
Gothenburg	No information on regulation				5	
Linköping	1		4		5	No interaction (X2V) with AV from traffic light.
Graz	2 (appr.)				2	Complex road layout, no typical intersections.

Test site	Intersections regulated with				Sum	Comments
	traffic lights	traffic signs	Round-abouts	Priority to the right		
						Combination of traffic lights & traffic signs
Salzburg		6			6	1 stop sign, 3 left turns with give ways, 2 right turns with give way sign. + 6 minor intersections.
Klagenfurt	5	2	1	7	14	1 intersection with traffic lights + stop sign Route not fixed and could be shortened
Pörtschach		4		5	9	1 intersection with stop sign, where the operator needs to double check and hit the GO button
Follower Thessaloniki (Egnatia)	13			31	44	
Follower Thessaloniki (Ethnikis Antistaseos)	32			50	82	
Follower Geneva				20	20	
Total	80	66	14	170	334	

Overview

In total, most of the intersections are unregulated or to be precise, priority to the right is applied. Almost a quarter of all intersections within SHOW are traffic lights regulated, some of them with communication services for the traffic light status (remark: communication services are not discussed here, as this is more digital than physical infrastructure). Six test sites have roundabouts (Aachen, Linköping, Rouen, Tampere, Trikala and Klagenfurt). The test site in Graz has a complex road layout (no typical intersection), that is regulated with traffic lights. This indicates that complex conditions are easier to handle with the occurrence of traffic lights. The test site in Rouen additionally mentioned the regulation in case the traffic lights do not work: the autonomous shuttle has priority. The test site in Pörtschach has one intersection, where an operator is still required. The intersection is equipped with a stop sign, and the operator has to double-check that there are no safety issues and allow the shuttle to go on manually. This should be fixed for operating AVs in the future – for example by better technology, better sight distances or change of priority at the intersection.

For junctions and roundabouts, there were recommendations made by the FABULOS project manager and the viaAutonom project (both presented in Chapters 3.4 and 3.5): For junctions, the potential need of changing the right of way should be considered, and for roundabouts stop lines, where oncoming traffic is visible to sensors should be located.

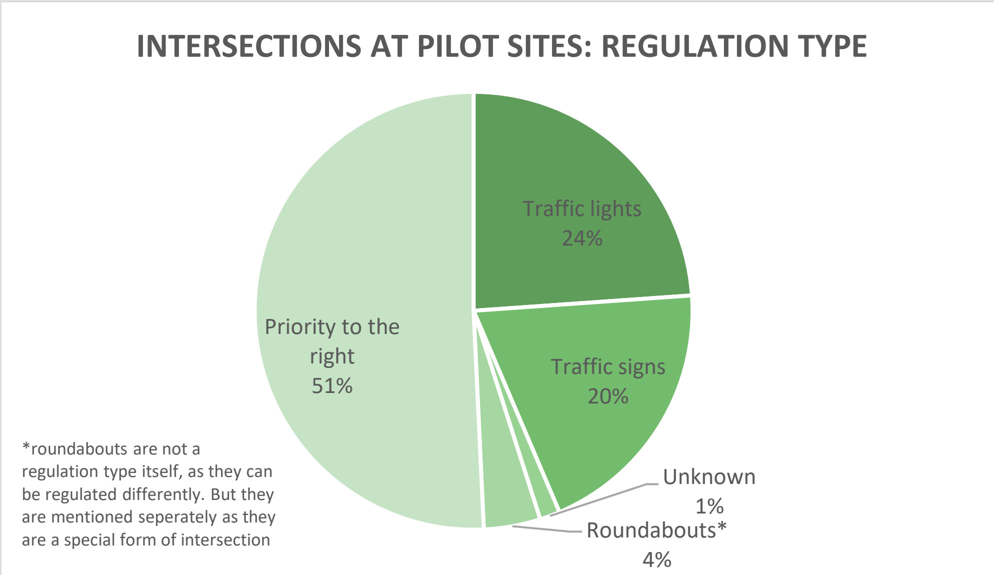


Figure 40: Distribution of regulation types for intersections at the SHOW pilot sites.

Pedestrian or cyclist crossings

The detection of vulnerable road users like pedestrians or cyclists is critical for assuring road safety. Traffic light regulated crossings ease the decision-making burden for the AV, as the right of way is clearly defined. If the crossing is unregulated, the AV has to identify many more potential issues, such as a pedestrian approaching a pedestrian crossing or a cyclist being in the process of crossing, without prior information. There was also an option given for other regulations or types for pedestrian or cyclist crossings, which are described in the comments.

Table 29: Number of pedestrian or cycle crossings and their regulations at the SHOW test sites (status as of 03/2021).

Test site	Total				Comments
	with traffic lights	Unreg-ulated	Other		
Madrid Carabanchel				0	Not at the moment, as this is the shuttle/bus depot.
Madrid Villaverde	2			2	
Trikala	5	8		13	Interventions planned, which might lead to having only 3 unregulated crossings
Tampere		24		24	
Aachen		5		5	
Karlsruhe		2		2	1 pedestrian crossing, 1 cycling crossing
Brainport	1			1	With C-ITS services
Brno		6	1	7	Route in pedestrian zone

Test site	Total				Comments
	with traffic lights	Unreg-ulated	Other		
Rouen	2	14		16	V2X infrastructure is used to reduce AV speed in case of large regroupment of pedestrians. Traffic lights are primarily designed for safe crossing of vehicles, not pedestrians.
Turin	56	51		107	
Gothenburg		4		4	
Linköping		6		6	Approximately.
Graz	1	1		2	
Salzburg		1		1	
Klagenfurt	5	3		8	The vehicle always stops as soon as it identifies pedestrians or objects on the road. There are programmed stop points in front of every crosswalk if needed.
Pörtschach		1		1	The AV is programmed to stop if it detects a pedestrian willing to cross the road"
Follower Thessaloniki (Egnatia)	13			13	
Follower Thessaloniki (Ethnikis Antistaseos)	32			32	
Follower Geneva			1	1	The site is mixed traffic streets with pedestrians etc sharing the same street.
Total	117	126	2	245	

<u>Overview</u>

Crossings regulated with traffic lights or unregulated are equally distributed in the sum of SHOW test sites (Figure 41). However, when looking at the test sites themselves, there are eight test sites having only unregulated crossings, whereas four only have crossings with traffic lights. In Trikala they plan to adapt the currently unregulated crossings and regulate five of them.

It will be seen in the pilot phase, whether the sites face challenges with detection of vulnerable road users at crossings or if traffic lights in fact reduce conflicts with vulnerable road users – as not following the traffic rules and pedestrians crossing at red lights could occur too.

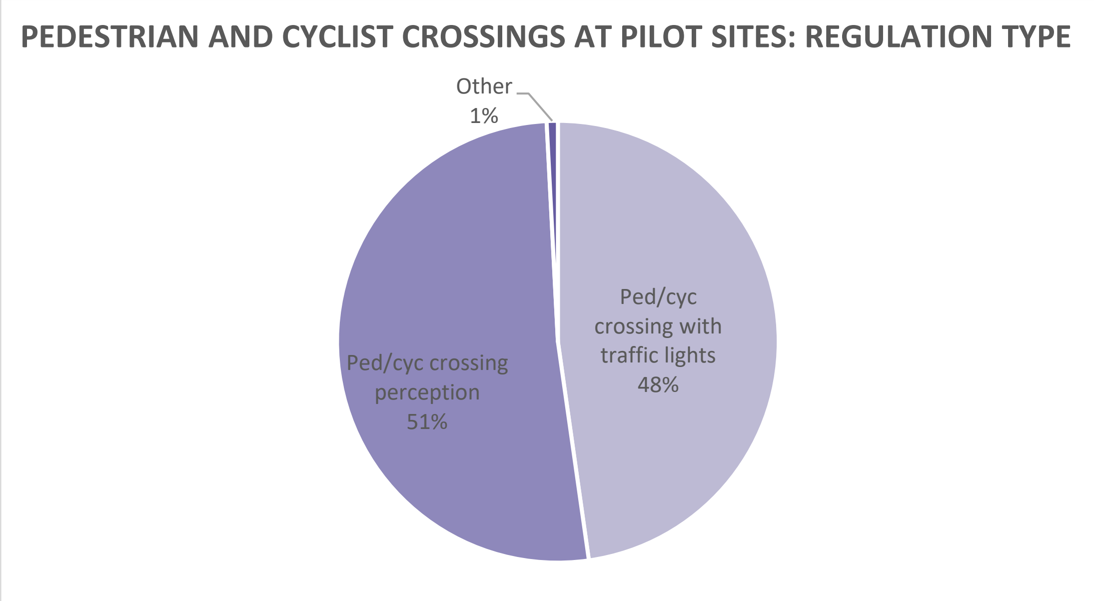


Figure 41: Distribution of regulation types for pedestrian or cyclist crossings at SHOW pilot sites.

Traffic signs

Traffic sign detection plays an important role in automated mobility, as explained in Chapter 3.1 But some signs might not be relevant for AVs but are still detected, which can lead to problems. Also abnormally located signs or shiny materials make it difficult to detect the signs. An alternative approach of not relying on traffic sign detection are the use of a map, which includes the traffic rules or the manual entry of the signs and meanings for the vehicle during a test drive – although the latter is only applicable for vehicles which operate on a fixed route.

Table 30: Traffic signs and possible confounding factors for their detectability at the SHOW test sites (status as of 03/2021).

Test site	Traffic signs	Only for pedes-trians	Abnor mally located	Shiny materials	Comments
Madrid Carabanchel	Not answered as this is the shuttle/bus depot.				
Madrid Villaverde	Yes	No	No	No	Traffic signs will be used for positioning in case of bad GPS signal
Trikala	Yes	Yes	No	No (will be checked later)	Signage not for the AV, but for other road users. Containing information about the AV sharing the lane, maybe additional speed limits or giving priority to the AV at

Test site	Traffic signs	Only for pedes-trians	Abnor mally located	Shiny materials	Comments
					intersections (where no traffic lights occur). Signs regarding pedestrians at all the pedestrian crossings (landmark indicators) (specified by the Greek regulation for road traffic).
Tampere	Yes	Yes	No	No	The AV needs to acknowledge and understand the signs. There are also signs for the pedestrians, mostly the signs are at intersections, but also along the road.
Aachen	Yes	No	No	Yes (3 glass building facades in >10m distance)	Route and behaviour along the route are preprogramed.
Karlsruhe	Not relevant for AV	No	No	No	No sign recognition, everything from map.
Brainport	No	No	No	No	
Brno	Yes	No	No	Yes (large windows)	Speed limit signs. The AV has to adjust its speed to them.
Rouen	Yes	No	No	Yes (bus stop glass, building windows)	Frequent traffic signs. The AV will respect the French highway code.
Turin	Yes	No	No	No	Mandatory road signs, pedestrian crossing signs; school, hospital warning signs.
Gothenburg	Yes	Yes	No	No	Stop signs, zebra crossing signs, bus stop signs, signs for information of the AV trials
Linköping	Yes	No	No	Yes	

Test site	Traffic signs	Only for pedes-trians	Abnormally located	Shiny materials	Comments
Graz	Yes, but not relevant for AV	No	No	No	The vehicle will not detect traffic signs. It will always know what to do according to its location.
Salzburg	Yes	No	Not known	No	Speed limit signs, stop signs, pedestrian crossing signs
Klagenfurt	Yes, but not relevant for AV	Not known	Not known	Yes (windows from buildings and parked cars)	Mostly stop signs, one way, priority signs and give way signs. But also, priority signs, parking, no overtaking, speed limits, crosswalks and signs for delivery traffic.
Pörtschach	Yes, but not relevant for AV	No	No	Yes (large windows from shops, reflections from parked cars)	Priority signs, parking, no overtaking, speed limits, crosswalks and signs for delivery traffic. Several signs were added (‘no entry’, ‘turning direction’, ‘one way’ and exceptions (periodic speed limits)).
Follower Thessaloniki (Egnatia)	Yes	Yes	Not known	Yes	
Follower Thessaloniki (Ethnikis Antistaseos)	Yes	Yes	Not known	Yes	
Follower Geneva	No role	No	No	No	
Total	15x Yes	5x Yes	0x Yes	8x Yes	

<u>Overview</u>

Traffic signs are present at almost all pilot sites. There are some sites, which have signs only dedicated to pedestrians, e.g. Trikala, Thessaloniki (both routes) and Tampere. The test site in Trikala also mentioned signs for other road users, e.g. to inform them about the AV sharing the lane. Shiny or reflective materials or any other that may cause disruption in traffic sign detection are present along the route of some test sites, mostly being windows of buildings close by or parked cars.

Traffic sign recognition was clearly stated as excluded at the pilot site in Pörtschach. The irrelevance of traffic signs was also confirmed by the test site managers interviewed in Chapter 3.5. Nevertheless, in order to provide adequate infrastructure for automated driving with a variety of technologies, the traffic signs at the test sites should allow automatic detection (reflections would have to be checked in detail). However, similar to the lane markings, it was referred to in Chapter 3.4 in the MANTRA project, that traffic signs should be machine-readable, but the information for all permanent signs will be available via connectivity by 2040. After that, the focus lies on temporary signs to be of sufficient quality.

Sight distances

For safe driving, sight distances are very important. For autonomous vehicles, they are even more relevant, as the sensors' view is more limited than the human eye. Road barriers, trees or bushes can limit sight distances, which are especially needed at intersections or crossings. Additionally, Trees and bushes can affect the positioning system, because seasonal changes in vegetation can lead to errors in LiDAR localization.

Table 31: Possible confounding factors for good line of sight at the SHOW test sites (status as of 03/2021).

Test site	Road barriers	Trees/ bushes	Comments
Madrid Carabanchel	Not answered as this is the shuttle/bus depot.		
Madrid Villaverde	No	Yes	Trees/bushes during 25% of the route, but we are studding to prune them.
Trikala	No	Yes	Trees are along the part of the route that is near the river at the edge of the sidewalks and a logical distance of the road. Small bushes along the other part of the route and scattered trees. No info if they are evergreens.
Tampere	No	Yes	Hundreds of trees along the route up 5 meters of road (in some places closer, < 2m). In winter, the deciduous trees do not have leaves, whereas coniferous trees are evergreen.
Aachen	No	No	
Karlsruhe	No	Yes	Trees in a distance ~4m away
Brainport	No	No	
Brno	Yes	No	Columns (1m tall) creating a barrier accessible only to pedestrians (~15% of the route).
Rouen	No	Yes	Pedestrian lane is separated by green spaces (bushes, trees and grass) on 50% of the route. Many, mostly deciduous trees, some of them are at close range (<2m).
Turin	No	Yes	A path segment is a road adjacent to a park □ trees are present for almost the entire route. Different types of trees: evergreens and no evergreens.

Test site	Road barriers	Trees/ bushes	Comments
Gothenburg	No	Yes	Some trees or bushes (some of them were pruned).
Linköping	No	Yes	20-40 trees, some bushes.
Graz	No	No	
Salzburg	Yes	Yes	Concrete wall for 20 meters. Trees or bushes, along ~20% of the route.
Klagenfurt	Not known	Yes	Large trees along the route (not directly on or right next the route on all parts of the route). There should be no problems with GPS reception. No evergreen vegetation or bushes that can protrude into the roadway.
Pörtschach	No	Yes	Different types of trees and bushes: Small bushes next to the path on the sidewalk need to be trimmed regularly especially in summertime. No evergreens. High amount of vegetation, especially trees along the second part or the route (Elisabethstraße/ Wahlissstraße/ Annastraße), which can lead to a lower GPS connection and should be kept in mind.
Follower Thessaloniki (Egnatia)	No	Yes	Trees planted on sidewalks.
Follower Thessaloniki (Ethnikis Antistaseos)	No	Yes	Trees planted on sidewalks.
Follower Geneva	No	Yes	Many trees/bushes, 1m away.
Total	2x Yes	14x Yes	

<u>Overview</u>

Road barriers are quite rare at the SHOW test sites. They exist at the Brno and Salzburg test sites, either in the form of 1m high columns between pedestrians and the rest of the traffic along 15% of the route, or in the form of concrete walls for about 20m. At almost all of the test sites trees and bushes exist alongside the route. Several test sites noted, that these trees and bushes have to be trimmed, for the vehicle to drive. As stated initially, the bushes can also limit the detection ranges of the AV's sensors.

Other physical infrastructure along the route

Here it was asked, whether the test sites have other infrastructure along the route that can either impede the AV (on-street parking) or support automated driving (landmarks). The existence of speed bumps was also part of the questionnaire, because their detection is not that easy, but needed as the AV has to adjust its speed in order to drive safely past them.

Table 32: Other infrastructure along the route (parking and landmarks) at the SHOW test sites (status as of 03/2021).

Test site	Parking	Effect of parking	Land-marks	Definition of landmarks
Madrid Carabanchel	Not answered as this is the shuttle/bus depot. Parking given as parking lots for buses.			
Madrid Villaverde	Yes	Does not affect AV.	Maybe	Under development.
Trikala	Yes	There are limited recesses in the street for parking and there is also the phenomenon of illegal parking on the road. We are planning to cooperate with the traffic police to solve this issue and to put additional and specific signs to inform regarding the AV.	Maybe	Still under investigation.
Tampere	Yes	Does not affect the AV. Some parking spaces are next to road and to some you have a separate road stretch.	No/ maybe	The operator may implement and use landmarks, if needed.
Aachen	No		Maybe	Not decided yet, if this is necessary in terms of increasing precision of localization.
Karlsruhe	Yes	Many parking areas; marked in the map.	No	
Brainport	No		No	
Brno	Yes	Does not affect AV.	No	
Rouen	No		No	
Turin	Yes	On street parking along all the pilot route, + two off-street parking areas. The former may affect AD since double-parked vehicles could be found on the road.	No	
Gothenburg	Yes	Does not affect AV.	Yes	Poles and gates
Linköping	No		Yes	Panels to help the LiDAR.
Graz	No		No	
Salzburg	Yes	3 parking areas aside of the road (in total	No	

Test site	Parking	Effect of parking	Land-marks	Definition of landmarks
		~100m). + several additional places where cars usually park along the road		
Klagenfurt	Yes	P+R between 1st & 2nd stop, but there should be no problems. Several parking facilities for cars right next to the route. In one section, separated by a bike lane. Cars not parked within the marked lines will cause the AV to stop manual intervention needed.	No	
Pörtschach	Yes	Several parking areas next to the path. Cars not parked within the marked lines will cause the AV to stop manual intervention needed.	Yes, but not needed	Several banners are available as reference points which are no longer necessary but still installed to provide information about the project to pedestrians.
Follower Thessaloniki (Egnatia)	No	There are illegally parked vehicles. Off-street parking facilities also exist along both routes.	No (not yet)	
Follower Thessaloniki (Ethnikis Antistaseos)	No			
Follower Geneva	Yes	Does not affect AV. The vehicle enters the parking areas to pick up passengers.	Yes	
Follower Brussels				
Total	11x Yes		3x Yes	

Speed bumps are not mentioned in the table as there are only three test sites which have them (Brno, Gothenburg and Rouen). In Brno and Rouen, they are marked with traffic signs, in Rouen also with markings. In Gothenburg no information on markings or signage for speed bumps is available.

Overview

At most of the test sites, parking along the street occurs, although it differs whether this affects the AV or not. Off-street parking seems to have no influence, whereas on-street parking might cause problems. This was also confirmed in Chapter 3.5. Also, illegal parking is an issue. Trikala tries to solve this with cooperation with the traffic police and additional signs for information about the AV being present. In Brno, Geneva, Gothenburg, Madrid Villaverde and Tampere parking will not affect the automated vehicle. It will be seen within the demonstrations whether on-street parking is still an issue or not.

Landmarks are so far present at three test sites: In Gothenburg, there are poles and gates, Linköping has panels to support the LiDAR, and Geneva also has landmarks. In Pörtschach there are banners that initially supported the vehicles' localization, which are no longer needed, because the vehicle technology evolved. They still exist as they provide information for the transport users. Several test sites have not yet decided about the use of landmarks (Aachen, Madrid, Trikala), say that they could be added (Tampere), or do not have them established yet (Thessaloniki).

Speed bumps occur at only a few test sites and seem to be marked well. For Gothenburg there was no statement on that, but adequate marking and signage would be recommended.

Public transport stations and terminals

For use case 3.4 "Automated services at bus stops" the physical infrastructure at the public transport stations is evaluated. The design of the stations was an item in the questionnaire to the test sites, as it is known, that stops on the lane are easier to handle than driving into a bus bay and then align with the traffic in the main lane again. The occurrence of other modes of transport was also asked, as this might affect the efficiency of automated driving, e.g. the shuttle being slowed down by high pedestrian traffic.

Table 33: PT station design/type and other existing modes of transport at the SHOW test sites (status as of 03/2021).

Test site	Bus bay	Stop on lane	Stop on bus lane	PT hub	Other	Modes of transport	Comments
Madrid Carabanchel	Test site is shuttle/bus depot.						
Madrid Villaverde	1			1		Regional buses Underground	
Trikala	8				2	At 6 Bus bays: Local buses, cars, bicycles 2 Bus bays are terminal/depot. Other: 2 PT stations under construction: Local buses, cars, bicycles	Bicycle lane on small part of the route.

Test site	Bus bay	Stop on lane	Stop on bus lane	PT hub	Other	Modes of transport	Comments
Tampere	8			1		PT hub: Tram, local buses, bicycles, pedestrians Bus stops: local buses, bicycles, pedestrians	Bicycle lanes and pedestrian lanes occur
Aachen		6				Local buses, cars, bicycles	Bicycle lane
Karlsruhe	4	13				1 bus stop with tram close by	
Brainport		2				Other PT (buses and cars)	
Brno					11	6 stops with local buses available	Other: Bus stop at the edge of the road
Rouen	3	5-7				Local buses, tram, TEOR (semi-automated BRT), bicycles, cars	Bus bay at the 2 terminals and Le Corbusier stop Bicycle lane
Turin	3	10	6			Stops on lane: Cars, local buses Dedicated bus lane: Local and regional buses, taxis	
Gothenburg	1	3				Cars, trucks, bicycles, pedestrians	
Linköping	3	5				At the bus bays: other local and regional buses, cars At the others: bicycles	Stops on lane are also within pedestrian zones, shared spaces.
Graz			1-2	1		PT hub: Tram, bus, train, taxi,	PT hub with 6 bus bays

Test site	Bus bay	Stop on lane	Stop on bus lane	PT hub	Other	Modes of transport	Comments
						park&ride car park	
Salzburg	4	1			1	Regional buses	Other: stop at turn place on gravel
Klagenfurt	7					Local buses, at one stop bicycle	Bicycle lane at one stop
Pörtschach	2	5				2 stations with local buses	5 stations AV-only
Follower Thessaloniki (Egnatia)			22			Cars, buses, taxis	
Follower Thessaloniki (Ethnikis Antistaseos)			17			Cars, buses, taxis	
Follower Geneva		4			65	None	65 Virtual bus stops
Follower Brussels							
Total	44	54-56	46-47	3	79		

Overview

The majority of public transport stations are simple stops on the lane. It is split half-half whether this is a normal lane or a dedicated bus lane. Almost a third of all PT stations is built as bus bays. When looking at Figure 42 the category “Other” takes up 35% as there are 65 bus stops in Geneva of this type. In Brno they have bus stops at the edge of the road, which can be considered as a mixture of a bus bay and a stop on the lane. The bus has to approach the stop, but leaving the stop is easier than in a bus bay. In Salzburg exists an end stop on the turning lane, which additionally has gravel as a road surface. A lot of test sites have bicycle lanes at the bus stops (5 mentions) and high pedestrian flows are expected at test sites with rapid transit e.g. Metro, train (Madrid, Graz) or tram (Tampere, Karlsruhe).

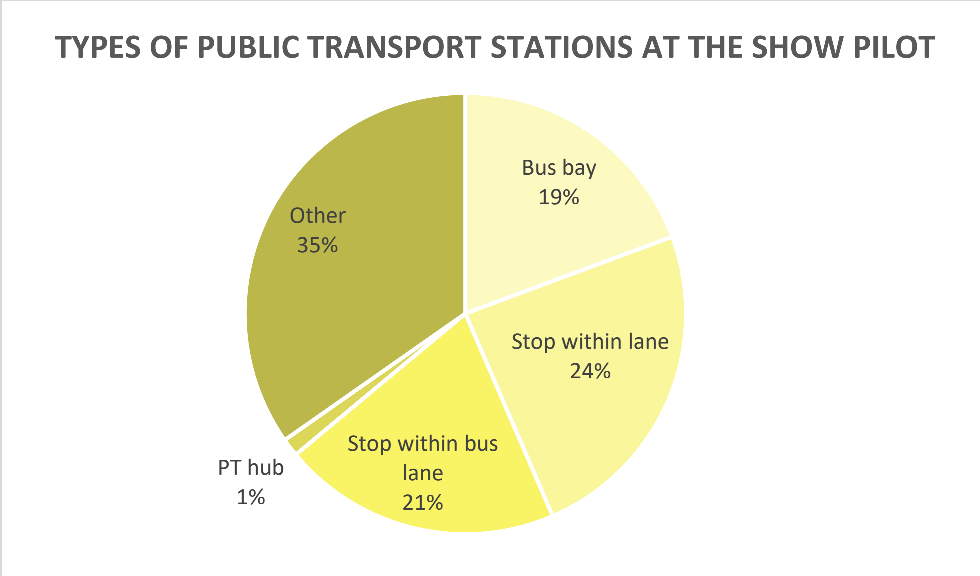


Figure 42: Distribution of public transport station types at the SHOW test sites (status as of 03/2021).

Thoughts on PT station design during planning phase and specific infrastructure

The pilot sites were asked about what they considered when choosing the PT station design and if they had (or will have) any specific infrastructure installed at the PT station. The answers are quite diverse, ranging from not really considering the design as the stations were already existing and will be used as they are, to focusing on passenger information or stops within the lane.

Table 34: Thought on PT station design and specific infrastructure at the PT stations at the SHOW test sites (status as of 03/2021).

Test site	Station design	Specific infrastructure
Madrid Carabanchel	Not answered as this is the shuttle/bus depot.	
Madrid Villaverde	Using existing stations	-
Trikala	Overall concept more important	Remote control centre at the terminal
Tampere	Using existing stations	-
Aachen	"Stop on lane" was preferred to give buses a higher priority (cars have to wait behind the buses, so buses can continue their journey quicker than with a bus bay)	-
Karlsruhe	AV-stop should not be an obstacle to other precipitants	-
Brainport	Not relevant, the focus is on using C-ITS technology to enable safe crossing of intersections	-
Brno	Using existing stations	-

Test site	Station design	Specific infrastructure
Rouen	Using existing stations Cateliers terminal needed to be regulated, decided for a bus bay	No, only for passengers
Turin	Using existing stations	Countdown displays at some bus stops
Gothenburg	-	Same signage etc. (PT system's corporate design)
Linköping	Only layout of the colours and icons to be used for visualization	Graphical design and signage to Indicate that this is an automated bus line
Graz	Using existing stations	Intelligent camera for recognition of road users and vehicles at bus terminal
Salzburg	Using existing stations	Established safe turn place at the end stop
Klagenfurt	Not fixed yet. Station should indicate the autonomous shuttle and its services, further information (shuttle location) should be quickly accessible for example via QR codes.	Information boards about the project, current timetable, test route, contact information. Possibly additional infrastructure to enable touchless travel (thermal image cameras for automatic fever screening, hand disinfection, etc.)
Pörtschach	Stop at train station: direct PT connection considered; shuttle shares the bus bay with local buses. One stop on a pedestrian square. Advantages of bus bays: the following vehicles can easily overtake here.	Information boards about the project, current timetable, test route, contact information. For new CoViD-19 use-case: thermal cameras for fever screenings, special information for behaviour and hand disinfection
Follower Thessaloniki (Egnatia)	Using existing stations	Most PT stations: real-time traveller information panels, informing about real-time ETA of buses
Follower Thessaloniki (Ethnikis Antistaseos)		
Follower Geneva	Using existing stations	-
Follower Brussels		
Total	9x using existing stations	5x passenger information

Overview

Most of the test sites stated that only the pre-existing PT stations were used along the route. Aachen chose to use the "stop on the lane" design, as this is easier to handle for the AV, whereas Rouen decided to set up a bus bay at the terminal. Pörtschach also has bus bays and mentioned a potential advantage: the following traffic can easily overtake the shuttle here. This comment is probably the result of the currently low shuttle speed, which can be experienced as a speed limiting factor for other motorized traffic participants. Passenger information or establishing a design that is clear for the users was also mentioned by a few test sites. Information infrastructure (as timetables, real-time information, project descriptions) was also mentioned as specifically installed infrastructure. Other specific infrastructure includes the installation of an intelligent camera in Graz, to recognize VRUs and other buses, or the occurrence of the remote-control centre at the terminal in Trikala. At both test sites in Carinthia, Austria, they will implement infrastructure to enable safe travel in times of CoVid-19 (thermal cameras, hygiene stations, etc.).

General

To find out more about the relevance of physical infrastructure, the test sites were asked to name the physical infrastructure characteristics that played part in the route planning. Some test sites named physical infrastructure, some also added digital infrastructure, or other factors that influenced route planning, like approaching certain points of interest. The listing of other factors, sometimes without naming physical infrastructure, indicates that physical infrastructure components do not always play a major role in route planning.

Table 35: (Physical) infrastructure components that played a role in route planning at the SHOW test sites (status as of 03/2021).

Test site	Physical infrastructure	Digital infrastructure	POIs	Other
Madrid Carabanchel	Not answered as this is the shuttle/bus depot.			
Madrid Villaverde	X		X	X
Trikala	X	X	X	X (demand and user acceptance)
Tampere		X		
Aachen	X			
Karlsruhe	No answer given			
Brainport		X		
Brno	X	X		
Rouen	X			
Turin				X (AV and municipality constraints)
Gothenburg	X			
Linköping	X			

<table>
<tr><th>Test site</th><th>Physical infrastructure</th><th>Digital infrastructure</th><th>POIs</th><th>Other</th></tr>
<tr><td>Salzburg</td><td>Adaptations made to fit</td><td></td><td></td><td>X
(existing route chosen)</td></tr>
<tr><td>Klagenfurt</td><td></td><td></td><td>X</td><td></td></tr>
<tr><td>Pörtschach</td><td>X</td><td></td><td>X</td><td></td></tr>
<tr><td>Follower Thessaloniki (Egnatia)</td><td rowspan="2">X</td><td rowspan="2">X</td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td>Follower Thessaloniki (Ethnikis Antistaseos)</td></tr>
<tr><td>Follower Geneva</td><td colspan="4">Not applicable –
They did not decide for a route, as all routes are covered with the virtual stops.</td></tr>
<tr><td>Follower Brussels</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Total</td><td>9 mentions</td><td>5 mentions, of which 2 are only DI</td><td>4 mentions</td><td>5 mentions</td></tr>
</table>

<u>Overview</u>

In eight pilot sites, there were physical infrastructure components that played a role in route planning. These components were:

- Physical infrastructure in terms of road geometry and/or road/area type:
  - Road quality and width, number of obstacles, radius of view, traffic density, amount of bus stops, average traffic speed (Aachen, DE)
  - Visibility, buildings for LiDAR localization, clean lane paintings, mostly flat ground (Rouen, FR)
  - Slope, charging, possibility of circular route (Brno, CZ)
  - Urban area with mixed traffic, but relatively easy to handle (low car intensity, road characteristics in good shape), distance to bus depot for charging, possibility to install RSUs (Madrid Villaverde, ES)
  - Urban arterials with more than 2 lanes (Thessaloniki, GR)
  - Shared space (Linköping, SE)
- Other
  - Avoid changes of physical infrastructure, use existing LiDAR markers (Gothenburg, SE)
  - Area with close distance between houses (Linköping, SE)
  - Sufficient space for passengers in waiting area, comfortable boarding and disembarking, also for wheelchair users. (Pörtschach, AT)

Besides the physical infrastructure, other aspects were also mentioned. These aspects were clustered into digital infrastructure, importance of points of interest and other. As these aspects were not asked for directly, a pilot sites not mentioning e.g. digital infrastructure here does not mean, it plays no role for the site. The answers provided only give a hint, on what is considered important besides physical infrastructure.

Four test sites mentioned the availability of digital infrastructure (4G/5G coverage, availability of C-ITS) as important for route planning, and four (also) mentioned the importance of certain points of interest (e.g. connecting the university to the metro lead to the chosen route).

The test site in Trikala considered a lot of different factors for route planning: the demand was estimated, route and operation scenarios have been formulated a traffic model was used to evaluate the feasibility and the effects on traffic. The optimal route was then determined by the operating characteristics like stops and timetables, and the route characteristics including necessary interventions. The ICT characteristics and the remote-control centre were also taken into account.

Constraints of the municipality e.g. AV maximum speed were mentioned by the Turin pilot site.

Summary

The physical infrastructure at the pilot sites is described in this chapter. The general setting was presented (mostly low-traffic and/or low-speed residential or industrial areas), followed by a more detailed analysis of lane markings, traffic signs, sight distances and public transport hubs and stations.

The analysis showed, that the physical infrastructure needs are different, from no need to certain requirements like detectability of traffic signs (marked important within the requirements analysis but seems not important at the test sites) or landmarks for localization. This is probably due to the fact, that in SHOW the routes are fixed, so physical infrastructure details can be assigned to the system during the test drive and are not only perceived via sensors during actual driving. Broader, open environment systems often rely more on lane marking or traffic sign recognition, which were described in more detail in Chapter 3. So, for the test sites to be ready to a wider range of automated mobility systems, meeting the requirements stated in this deliverable would be recommended. Fixing the pavement to ensure good quality should be done by all test sites to ensure safe driving. For the bus stops, there are a lot of different types existing across the test sites and it would be recommended to examine the safety and efficiency depending on the station type (stop within lane, bus bay, solutions for coping with large pedestrian flows at PT hubs).

4.2 Physical infrastructure adaptations and measures at pilot sites

4.2.1 Approach

This chapter largely builds upon the desk research and interviews conducted on the topic of physical road infrastructure regarding automated urban mobility described in Chapters 3.4 and 3.5 of this deliverable. Starting from statements of 6 interviews (3 of them covering projects also reviewed in the desk research) and from findings of 19 EU projects and 3 national projects, the most critical PI elements/conditions for automated driving (AD) were identified and used for assessing the role of PI at the SHOW test sites to be adapted for AD.

In depth-analysis of desk research results

For this chapter, an in-depth analysis of critical physical infrastructure (PI) elements for automated driving identified in the literature and interviews was undertaken and a list of relevant PI elements carrying a potential challenge or risk for AD was elaborated.

Table 36 shows PI elements that were analysed within the projects and mentioned in the interviews. The number in the third column indicates in how many different projects and interviews they were raised.

Table 36: Identified PI elements relevant for AD mentioned in 22 projects and 6 interviews.

PI element	Relevant PI elements mentioned in projects/interviews	Ranking
Traffic lights	8	1
Slope/inclination	7	2
Traffic signs	7	
Parking	6	3
Road side vegetation	6	
Road works	6	
Junctions (often in combination with sight distances)	5	4
Lane markings (important for AD)	5	
Lane markings (no influence on AD)	5	
Terminals/stations	5	
Traffic signs irrelevant	4	5
Lane width/narrow road/lane	4	
Separate lanes	4	
PI for localisation/reference points	4	
Road condition	3	6
Pothole (cancellation)	3	
Bicycle lanes	3	
Pedestrian crossings	3	
Tram crossing	2	7
Pavement type	2	
Surface	2	
Road geometry	2	
Pedestrian facilities	2	
Speed bumps	1	8
Tram line	1	
Railway crossing	1	
Left turn	1	
Curbs	1	

PI element	Relevant PI elements mentioned in projects/interviews	Ranking
Ramp and merging lanes	1	
Tunnel area	1	
Sensitive areas as schools and hospitals, VRUs	1	
Accident hot spots	1	

Although some PI elements were mentioned by more projects/OEMs/initiatives than others (see ranking in Table 36), we classified all of them relevant for AD. Different test sites have specific conditions and some PI elements might not be relevant for one test site but could be for others. This will be further investigated when evaluating the SHOW test sites (please see Chapter 4.2.2.2).

Preparation of SHOW survey on PI adaptations and measures at SHOW test sites:

In a further step, all PI elements (listed in Table 36) were merged into a spread sheet, which was created for a specific survey on adaptations and measures at SHOW test sites. These were enriched by ten additional elements, which were rated relevant for AD operations by several SHOW experts:

1. Terminals/stations interchange areas
2. Shuttle depots
3. Road condition maintenance
4. Buildings along the road (blind spots due to bill board, trees, bus stops, etc.)
5. Parking in second lane
6. Sight distances and visibility at junctions
7. Roundabouts
8. Road safety barriers
9. Bridges
10. Areas of schools, hospitals, etc.

Test site managers could also add other relevant PI elements to provide additional test-site specific information.

To further structure the survey, all PI elements in the table were thematically clustered as follows:

- Road
    - Road condition
    - Lanes
    - Crossings
- Roadside
- Public transport terminals and stations
- Hot spots

The survey was designed to be as straightforward as possible, to ease completion and encourage participation. Three questions were formulated for each PI element with possible answers, while a column for comments was also inserted. For a better understanding of the spreadsheet, an example entry was provided. The survey was sent to 19 SHOW test sites and 3 follower sites, with the following questions:

1. Have you made or are you planning to make any infrastructure adaptations related to the following element/condition… (Yes, No, Not applicable (= does not occur at the test site))
2. If yes, please describe the adaptation. What is the intention of the measure? E.g. increase safety, optimize communication with other traffic participants, improve localization
3. Is this a necessary adaptation or a nice to have adaptation?

SHOW D8.1 Chapter 4 Efficient infrastructure adaptations and measures at test sites				
Test Site Name XY (please fill in)				
Infrastructure element/condition	Have you made or are you planning to make any infrastructure adaptations related to the following element/condition… (Yes, No, Not applicable (=does not occur at the test site))	If yes, please describe the adaptation. What is the intention of the measure? E.g. increase safety, optimize communication with other traffic participants, improve localization	Is this a necessary adaptation or a nice to have adaptation?	comments
Example Entry for slope/inclination				
Road condition				
slope/inclination	yes	a traffic sign limiting access for AVs just on dry road (no rain, no	this is a necessary adaption due to safety reasons	
slope/inclination	no			with increased slope, we do not need any measures as it is within
slope/inclination	not applicable			Our terrain is flat.
Road				
Road condition				
pavement type/road condition				
to weather events (icy/snowy roads, standing water, etc.)				
pothole cancellation				
slope/inclination				
road geometry				
speed bumps				
Lanes				
width of road/lane width (also on				
separate lane for AVs,				
lane marking quality (e.g. with				
street side parking				
bicycle lanes				

Figure 43: Extract from the spreadsheet which was sent to 19 SHOW test sites and 3 SHOW follower sites (full spreadsheet see in Appendix II).

4.2.2 Analysis

4.2.2.1 *Desk research and stakeholder interviews results*

The desk research showed that out of more than 60 projects initially screened, just 22 projects were considered relevant for A8.1 of WP8 and taken forward for a more in-depth investigation. While the literature review revealed several relevant insights regarding the physical infrastructure requirements and adaptations for automated vehicles (see Chapter 3.4), the stakeholder interviews (see Chapter 3.5) allowed for a more comprehensive and practical examination of these elements.

The analysis of physical road infrastructure requirements and adaptations through both literature reviews and stakeholder consultations revealed that a certain type of physical infrastructure is not the number one priority when preparing pilot test routes for testing automated vehicles and therefore is not taken into account to a large extent. The overall conclusion is that autonomous shuttle solutions should be deployable anywhere, without critical infrastructural adaptations or investments by cities. However, at the moment, the infrastructure of a city does not necessarily support a wide deployment of autonomous vehicles; hence, the infrastructure was taken into account mainly by using it for navigation/localization on the route (i.e. the vehicles' sensors detect the physical shape of the infrastructure elements).

Nevertheless, the pilot test routes were selected, through feasibility studies, looking at the limitations and risks and taking into account several infrastructure-related factors that would possibly influence the optimum operation of the vehicle during the tests (among also the needs of cities and limitations from road authorities). Below, a synthesis of the most relevant physical infrastructure (PI) elements requirements and suggested/implemented adaptations are presented.

Traffic lights

Traffic lights should be detected and recognised by the AVs. While in some pilots, the vehicles detect the traffic light, they do not interpret the significance of the light (red/yellow/green). Therefore, V2X systems should be implemented to allow communication between the vehicles and the traffic lights, allowing the vehicle to navigate an intersection or other challenging traffic situations, such as roadworks that need signalisation measures.

Slope/Inclination

Areas with higher slopes were avoided when choosing the location of the test pilots, as slopes higher than 8% would impede the vehicle's operation (e.g. overheating leading to vehicle stop for a cool down period, potential mechanical issues in winter conditions due to the power distribution between the wheels). Shuttles are able to drive on slopes up to 8% permanently.

Traffic signs

While the literature states that traffic signs should be recognised by AVs (position, colour, shape, height, interpretation) and maintenance should be employed to ensure readability, interviews reveal that in practice, traffic signs are not detected by the vehicle and are usually digitally programmed for AVs beforehand (HD maps). Traffic signs differ from country to country, meaning that the sensors' algorithms must learn all of them. Therefore, they are mostly considered to have no influence on the vehicle's operation.

Parking

While most road infrastructure elements are digitally programmed for the vehicles beforehand (via HD maps), parking was considered an obstacle for the automated vehicle's operation, as the presence of parking can be an obstruction to traffic signs and road markings. Moreover, parked vehicles on narrow two-way roads can stop the vehicle. Uncontrolled parking by the route of the AV should be completely prohibited, or at least clearly marked or located off the actual driveway.

Roadside vegetation

Roadside vegetation (trees, plants etc) was considered a highly relevant obstacle for a vehicle's operation and should be trimmed through regular maintenance or be situated completely outside the AVs sensor area, as it poses an issue for the cameras, GPS signal strength as well as for the LIDAR localisation, causing unnecessary braking and stopping of the vehicle.

Roadworks

Temporary roadworks require AVs to interpret real-time changes in the environment provided by temporary traffic signs, markings and cones. Therefore, they are considered to severely impact the shuttle's ability to navigate autonomously, as the vehicle must deviate from the programmed path, needing manual intervention (ODDbreakdown). If the roadwork is controlled with traffic lights, V2X communication with the shuttle would be necessary to ensure automated and scheduled passing.

An additional issue mentioned was the dust/particles caused by the roadworks that could degrade the vehicle's sensors.

Junctions (incl. sight distances)

Generally, junctions and sight distances are not considered of high influence, due to the current lower operating speeds of shuttle buses and altered safety/priority zones. Nevertheless, sight distances were considered a relevant limiting factor at road junctions, as a human operator would always have to confirm it is safe for the vehicle to enter a junction. Furthermore, the sight distance influences the overall feeling of safety, as the AVs sensors cannot determine speed of other vehicles at an intersection in a reliable way. Higher vehicle speeds may increase the influence of this infrastructure element.

Lane markings

Visibility, reflectivity and detectability of lane markings were evidenced as relevant for AVs in the literature for optimum operation of AVs. However, similar to traffic signs, lane markings are considered to have no influence on the vehicle's operation in practice. While the vehicle's sensors detect the markings, they are mostly programmed in vehicle's path (HD maps). A potential issue highlighted by a shuttle manufacturer is that various road marks have the same retro-reflectivity as an actual lane marking, leading to potential confusion of sensors.

Terminals/stations

Accessibility to PT hubs and stations is considered highly relevant, as it gives the vehicle's route meaning, value, passengers. Therefore, PT hubs and stations should be safely reached by the shuttle bus and are included in the vehicle's predefined path. Required access for wheel chairs for public transportation is necessary.

Lane width, Narrow road/lane

Narrow lane sections should be generally avoided, as they would impede the vehicle's operation. Narrow two-way roads or lane widths of 3-3.5 meters or under are not considered suitable, especially in combination with side parking. Wider lanes allow for optimum vehicle operation.

Separate lanes

The general recommendation is to have separate driving lanes for AVs. However, in practice, separate lanes were not a perquisite for choosing pilot sites for deploying shuttle buses, as long as other requirements were fulfilled.

PI for localization/reference points

The use of physical infrastructure structures to improve LIDAR localization was evidenced as being necessary for optimum operation. The infrastructure is annotated after the initial road mapping, identifying fixed elements that can also serve as reference points to the vehicle localization. Moreover, the installation of additional landmarks/signs for the improvement of the vehicle's navigation (if no buildings or other structures are near) was mentioned at multiple test sites and by shuttle manufacturers.

Road surface, condition

Poor road conditions influence the visibility of features such as road gradient, curvature, lane width, condition of road markings and traffic signs, as mentioned in the literature. Transparent, wet (mirror like surface), monotonous and light absorbent material surfaces could impede LIDAR localization. Sandy roads can raise dust from the ground which can be detected as an obstacle by the shuttles. In practice, the road condition and surface were optimised before starting the pilots, therefore they were not an influencing factor in the vehicle's operation.

Potholes

Pothole cancellation and regular road maintenance should be a part of pilot preparation processes, before starting the public test with AVs.

Bicycle lanes

Separation of bicycle lanes and facilities from the road used by the AVs is considered a priority, either through lane markings and delineation for separation or clearly defined on a HD map used by the vehicle.

Pedestrian crossings/facilities

Generally, pedestrian crossings are included during the mapping of the predefined path of the vehicle. Pedestrian paths and facilities should be separated as much as possible from the paths used by the AVs.

Tram lines/crossing

The literature indicates that operating AVs on streets with tram lines would be suitable, however crossing tram lines and railway crossing would be challenging (e.g., field of vision, detection of oncoming trams/trains). Clear visible signs, signals and markings should be employed, as well as ensuring line of sight to crossing trains/trams; V2X communication and inclusion of this infrastructure element in a HD map would be a priority.

Pavement type

Driving on brick or granite pavement leads to strong vibrations that could cause hardware issues to vehicles (e.g. cables can be disconnected). Asphalt was highlighted as the preferred road surface. In practice, the pilot routes were generally chosen as such that pavement type was not an influencing factor in the vehicle's operation.

Road geometry

While literature indicates that the road geometry should be detected and recognised by the AVs themselves, in practice, the geometry is programmed in the predefined path of the vehicle.

Other relevant elements mentioned include additional traffic signs to signalise bus stops, to indicate lowering speed limits, to inform pedestrians of the pilot tests; speed limitations imposed by the city authorities; the stability of the environment and road infrastructure; the presence of high buildings; V2X as a method for communication with traffic lights and signals; good road maintenance, especially during winter; no speed bumps.

4.2.2.2 *Results from the survey on PI adaptations and measures at SHOW test sites*

This sub-chapter presents the results of the survey on PI adaptations and measures at SHOW test sites. The survey has been sent to the 19 SHOW test sites and 3 SHOW follower test sites. 19 responses and 18 completed survey spreadsheets were received. No input came from Copenhagen, because the test site was not ready by the date of this deliverable. The test site in Braunschweig was thought to replace Mannheim, however, the decision was still pending at the date of this survey. Similar is true for the test site in Rennes which had to struggle with some difficulties and were not ready to answer the survey. From the Brussels follower site, we did not receive any answer.

Table 37 below details the results per test site.

Table 37: Indicated adaptions and measures of PI by SHOW test sites.

Adaptations and measures of PI at SHOW test sites																				
Countries			ES		GR	FI	GER		NL	CZ	FR	IT	SE		AT				GR	CH
Ranking	PI element	No of test sites adapting PI element	Madrid Carabanchel	Madrid Villaverde	Trikala	Tampere	Aachen	Karlsruhe	Eindhoven Brainport	Brno	Rouen	Turin	Gothenburg	Linköping	Graz	Salzburg	Klagenfurt	Pörtschach	Follower Thessaloniki	Follower Geneva
1	road/traffic signs (bus stop signs, warning signs of automated vehicles and informative signs, etc.)	9		y	y	y				y		y	y			y	y	y		
2	shuttle depots	8				y		y			y		y	y			y	y		y
3	terminals/stations (layout, design, waiting areas, platforms, etc.)	7		y							y		y	y		y	y	y		
4	lane marking quality (e.g. with reflective paintings)	5	y	y	y								y					y		
	road side vegetation	5		y									y	Y		y	y			
	road junctions	5	y	y	y				y									y		
	traffic lights	5		y	y			y	y		y									
5	temporary road works	4	y			y							y	Y						
	fixed infrastructure elements as reference points for localisation of the vehicle/Static urban furniture	4	y			y							y					y		
	road condition maintenance due to weather events (icy/snowy roads, standing water, etc.)	4			y	y								y						y
6	street side parking	3	y	y	y															
	pedestrian and bicycle crossings	3	y		y				y											
	terminals/stations interchange areas	3									y		y					y		
7	buildings along the road (blind spots due to bill board, trees, bus stops, etc.)	2											y					y		
8	pavement type/road condition (asphalt, cobblestone, etc.)	1		y																
	pothole cancellation	1			y															
	separate lane for AVs, safety/priority zones	1											y							
	narrow lane sections	1											y							
	tram track and railway crossings	1													y					
	curbs	1		y																
	accident hot spots	1											y							
	sight distances and visibility at junctions	1																y		
	working area	1	y																	
no adaptation/not applicable	slope/inclination																			
	road geometry																			
	speed bumps																			
	width of road/lane width (also on parts)																			
	bicycle lanes																			
	longitudinal tram tracks																			
	parking in second lane																			
	left turn lanes																			
	roundabouts																			
	road safety barriers																			
	ramp and merging lanes																			
	tunnel area																			
	bridges																			
	areas of schools, hospitals, etc.																			

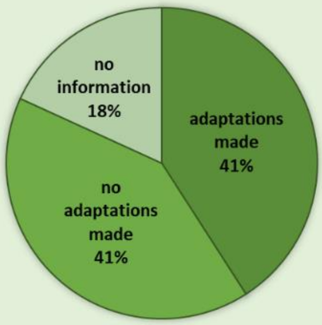
Table 37 presents all the PI adaptations made by the SHOW test sites by the end of March 2021. The responses indicate that out of 37 selectable PI elements/conditions, for 23 of them adaptations had already been made or were planned. The ranking according to the number of test sites which will undertake/undertook adaptations for single PI elements could give a first estimation on the importance of PI requirements for automated driving. In addition, Table 38 below shows the number of PI modifications at the single test sites, of which Gothenburg undertook the most adaptations, whereas Aachen and Thessaloniki test sites left the physical infrastructure as it was.

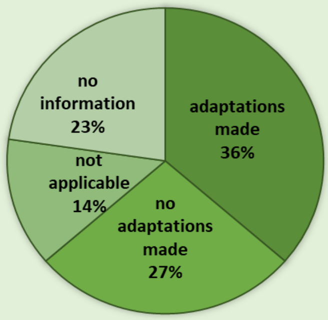
Table 38: Number of adaptations per test site

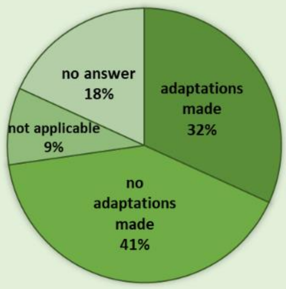
Test Site	Number of adaptations
Gothenburg	12
Madrid Villaverde	9
Pörtschach	9
Trikala	8
Madrid Carabanchel	7
Tampere	5
Linköping	5
Rouen	4
Klagenfurt	4
Eindhoven Brainport	3
Salzburg	3
Karlsruhe	2
Follower Geneva	2
Brno	1
Turin	1
Graz	1
Aachen	0
Follower Thessaloniki	0

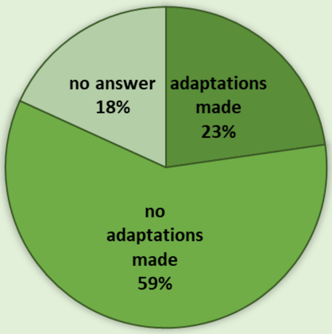
Detailed SHOW test site survey results on adaptations per PI element

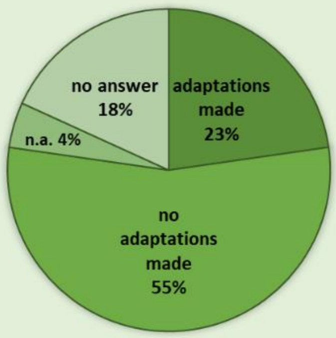
The following boxes detail the specific adaptations undertaken by the SHOW test sites (and follower sites) by the end of March 2021, per physical road infrastructure element, in the order of rank.

Rank 1: Adaptations on road/traffic signs (9 test sites)	
Madrid Villaverde	Tree branches covering some signs are cut back
Trikala	Vertical signs will be installed specifically for AVs
Tampere	Temporary warning signs will be installed for warning automated shuttles
Brno	There will be signs to mark stops of autonomous shuttles; these signs are informative, but also partially safety related; for a shuttle service with fixed routes, this adaptation is necessary
Torino	The route will be equipped with traffic signs (warning/informative signs) to warn the public about the presence of an AV; about 70-80 new traffic signs
Gothenburg	Information sign on poles that an autonomous bus is running in the area
Salzburg	Warning sign on automated vehicle test track; speed limit of 50km/h (outside municipality)
Klagenfurt	Information signs will be installed, bus signs for stations and waiting areas will be set up; information about the project and autonomous driving leads to a higher acceptance.
Pörtschach	It is a necessary adaptation that information signs (test area for autonomous driving) were installed and bus stations were set up
No adaptations on road/traffic signs (9 test sites)	
Madrid Carabanchel, Thessaloniki, Aachen, Eindhoven Brainport, Karlsruhe, Linköping, Rouen (existing bus stop signs and warning signs of automated vehicles will be used), Geneva, Graz	
No information (4 test sites)	
Braunschweig, Copenhagen, Rennes, Brussels	
Conclusion road/traffic signs	
Traffic signs on the route of automated shuttles serve in the first instance for information and warning purposes of the presence of AVs for all other road users. Informative and warning signs are also important at bus stations indicating where the automated bus will stop. The readability of traffic signs by sensors does not seem to be a criterion for the AV itself. 9 test sites report no adaptations on road/traffic signs.	

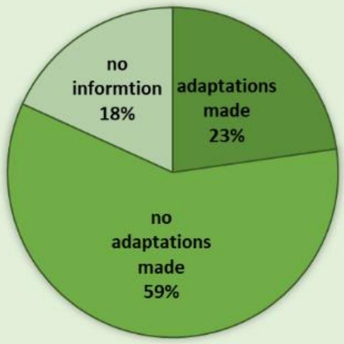
Rank 2: Adaptations on shuttle depots (8 test sites)	
Tampere	It is a necessity that the operator together with the city authorities will find a depot for vehicles.
Karlsruhe	There is a mobile depot for AV available which is rented from the Testfeld Autonomes Fahren BW
Rouen	Will be using an existing workshop close to the test site, adapting it to their needs
Gothenburg	Using a depot or garage very close to the operated route
Linköping	It was necessary to add a charging station for the AV
Klagenfurt	It is necessary that a garage will be set up
Pörtschach	Up to now a tent garage was used (not suitable for cold weather conditions); it is not yet decided how the shuttle depot will look like, but it will be necessary to find a solution
Geneva	It is necessary to build a 3 mini-bus depot
No adaptations on shuttle depots (6 test sites)	
Trikala (it is under investigation the design of the terminal and the depot. No major adaptations are however expected.), Thessaloniki, Aachen, Brno, Torino, Graz	
Not applicable (3 test sites)	
Madrid Villaverde, Madrid Carabanchel, Eindhoven Brainport (not applicable, no operational service, only tests at intersections)	
No information (5 test sites)	
Braunschweig, Copenhagen, Rennes, Salzburg, Brussels	
Conclusion traffic shuttle depots	
For 8 test sites appropriate equipped shuttle depots (if possible in the vicinity of test sites) are a necessity for automated shuttles. No information was given on the requirements of such depots for automated parking of the shuttles which is why one may assume the shuttles will be parked manually. At 6 test sites no adaptations were reported. 3 test sites do not need shuttle depots.	

Rank 3: Adaptations on terminals/stations (layout, design, waiting areas, platforms, etc.) (7 test sites)	
Madrid Villaverde	Book some area to stop the busses
Rouen	It is necessary that a new platform to the Zenith terminal and a bus bay at Cateliers terminal will be added
Gothenburg	Simple bus stop with poles and signs and possibly bus shelters
Linköping	New stations had to be installed along the AV bus route; they have their own special design
Salzburg	It is necessary that a safe turn place has been established
Klagenfurt	There will be adaptations, but it is not yet decided of which kind
Pörtschach	It is necessary that stops are clearly visible for passengers (autonomous driving signs)
No adaptations on terminals/stations (9 test sites)	
Trikala (the design of the terminal and the depot is under investigation, bus stops will be redesigned where necessary to meet AV needs, no major adaptations are however expected), Tampere (existing infrastructure will be used), Thessaloniki, Aachen, Brno (there is no need for this adaptation), Karlsruhe, Torino, Geneva, Graz	
Not applicable (2 test sites)	
Madrid Carabanchel, Eindhoven Brainport (no operational service, only tests at intersections)	
No information (4 test sites)	
Braunschweig, Copenhagen, Rennes, Brussels	
Conclusion terminals/stations	
The situation at the SHOW test sites is different. 7 test sites redesign existing stations upgrading them with additional signs and information on automated shuttle service. 9 test sites reported no adaptations. 2 test sites install new stations and terminals, 2 test sites do not have any terminals/stations.	

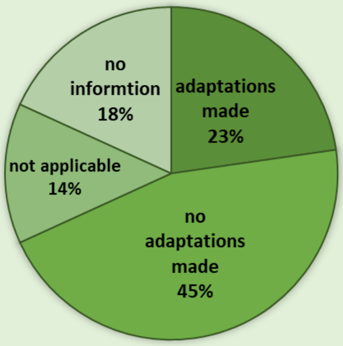
Rank 4: Adaptations on lane marking quality (e.g. with reflective paintings) (5 test sites)	
Madrid Carabanchel	We repaint new lines in the workplaces, repaint the workplaces for a better perception
Madrid Villaverde	We repaint new lines in the street, repaint the street for a better perception
Trikala	Lane marking will be enhanced according to the standards and national legislation
Gothenburg	could be added
Pörtschach	Lane markings on some part of the roads were renewed; does not matter for this kind of autonomous vehicle technology
No adaptations on lane marking quality (13 test sites)	
Tampere (can be done, if needed, but at the moment no plans), Thessaloniki, Aachen, Eindhoven Brainport, Brno (the aim is to make a vehicle to work under available conditions, not vice versa) Karlsruhe, Klagenfurt, Linköping, Rouen, Torino, Geneva, Graz, Salzburg	
No information (4 test sites)	
Braunschweig, Copenhagen, Rennes, Brussels	
Conclusion terminals/stations	
5 test sites indicate that lane markings will be (partly) renewed; the other 13 test sites do not see a need to refurbish them. Lane markings do not seem to have high importance for AD at the SHOW test sites.	

Rank 4: Adaptations on road side vegetation (5 test sites)	
Madrid Villaverde	Prune some vegetation
Gothenburg	To be pruned if needed
Linköping	It was necessary to trim bushes and trees for better LIDAR performance
Salzburg	It was necessary to cut branches and grass
Klagenfurt	It is necessary to trim trees and bushes also next to the bath regularly, otherwise shuttle would detect branches as obstacles
No adaptations on road side vegetation (12 test sites)	
Trikala, Tampere, Aachen, Karlsruhe, Eindhoven Brainport, Brno, Rouen (unless vegetation is going wild but it is common maintenance of green areas done by the city), Torino, Graz, Pörtschach, Thessaloniki, Geneva	
Not applicable (1 test site)	
Madrid Madrid Carabanchel	
No information (4 test sites)	
Braunschweig, Copenhagen, Rennes, Brussels	
Conclusion terminals/stations	
5 test sites indicate that they have pruned vegetation and will have to do so also in the future. Vegetation protruding into the road could be detected as an obstacle by the sensors. For the other 13 test sites, road side vegetation does not need special attention.	

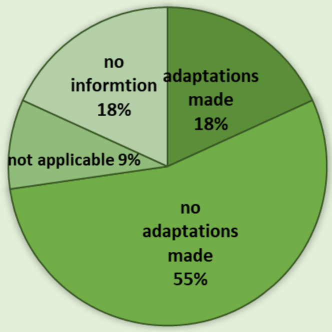
Rank 4: Adaptations on road junctions (5 test sites)	
Madrid Carabanchel	HD mapping and high perception
Madrid Villaverde	Improving traffic light communication
Trikala	Several complex junctions e.g. four-way intersection, left turns, right turns which will have different interventions e.g. converted into a level sign-shaped junction -T, level signpost cross junction, traffic lights are very important, one light signalization only works when the AV crosses; at smaller junctions, priority of AVs will be emphasized with appropriate signage, speed bumps

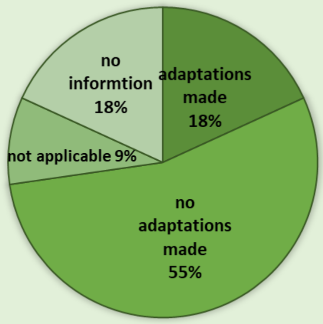
Eindhoven Brainport	Virtual road junctions need to be added for test purposes, safety relevant scenarios staged with virtual crossing traffic
Pörtschach	It was necessary to set up stop signs, speed limits and one-way signs to increase safety; specifications will come from shuttle manufacturer
No adaptations on road junctions (13 test sites)	
Tampere (existing infrastructure will be used), Aachen, Karlsruhe, Brno (this kind of modification is not in the scope of the project), Rouen, Torino, Gothenburg, Linköping, Graz, Salzburg, Klagenfurt (not yet decided), Thessaloniki, Geneva	
No information (4 test sites)	
Braunschweig, Copenhagen, Rennes, Brussels	
Conclusion road junctions	
5 test sides deemed it relevant to take measures and adaptations at road junctions. These are digital interventions (HD maps, virtual tests, communication technologies with traffic lights) as well as classical interventions to make junctions safer (traffic lights, speed limits, appropriate signage, one-way regulation). Interestingly 13 test sites do not plan any interventions at junctions.	

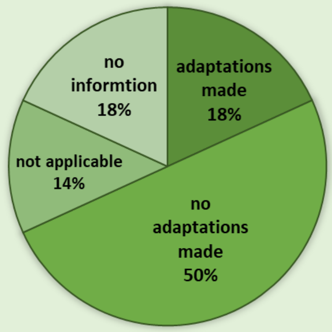
Rank 4: Adaptations on traffic lights (5 test sites)	
Madrid Villaverde	Improve communication
Trikala	It is under investigation how to give green wave for the AV; install relevant controllers and V2X communication to improve performance of AD and safety of all road users
Karlsruhe	No camera detection in AV, status of traffic light has to be transmitted to the AV
Eindhoven Brainport	It is necessary to install C-ITS equipment as C-ITS services provide safety enhancement functions
Rouen	It is necessary to add a traffic light to increase safety on a limited visibility crossing
No adaptations on traffic lights (10 test sites)	
Tampere (existing infrastructure will be used), Aachen, Brno (this kind of modification is not in the scope of the project), Torino, Gothenburg, Linköping, Graz (potentially upgrade traffic light at intersection, currently a dedicated traffic light for buses is available; potentially this traffic light can be upgraded with C-ITS for operation with the shuttles; it would be a nice to have), Klagenfurt (not yet decided, negotiations currently underway with Siemens), Thessaloniki, Geneva	
Not applicable (3 test sites)	

	Madrid Carabanchel, Salzburg, Pörtschach
No information (4 test sites)	
	Braunschweig, Copenhagen, Rennes, Brussels
Conclusion traffic lights	
5 test sites plan adaptations on traffic lights. Most of these interventions are on the level of communication and signals will be transmitted to the vehicle (V2X communication). Also, from the test sites who do not plan currently any adaptations some think of adaptations in terms of C-ITS installations. 8 test sites report no adaptations. At 3 test sites no traffic lights are on the route.	

Rank 5: Adaptations on temporary road works (4 test sites)		
	Madrid Carabanchel	They are a daily challenge and managers will try to adapt depending on the specific situation; if appropriate adaptations are not possible, AVs will stop and wait for help
	Tampere	In case of construction areas, it will be necessary that the operator will plan an alternative route
	Gothenburg	Could occur, it is under discussion with constructors how to minimize the impact
	Linköping	It was necessary to reroute the AV for ongoing constructions
No adaptations on temporary road works (12 test sites)		
	Madrid Villaverde train, Aachen, Eindhoven Brainport, Brno, Rouen, Torino, Graz, Salzburg, Klagenfurt, Pörtschach, Thessaloniki, Geneva	
Not applicable (2 test site)		
	Trikala, Karlsruhe	
No information (4 test sites)		
	Braunschweig, Copenhagen, Rennes, Brussels	
Conclusion temporary road works		

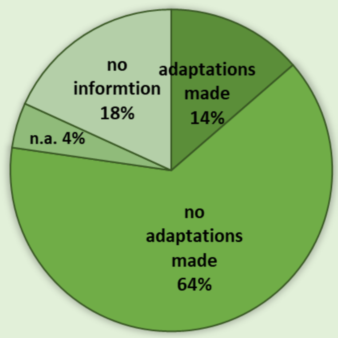
Rank 5: Adaptations on temporary road works (4 test sites)	
Temporary road works are a big challenge for AVs as planned routes could become partly or wholly unusable. 2 test sites would reroute the AV, two are still looking for solutions. 12 test sites do not take any measures as they maybe do not expect any road works at their test sites in the near future. 2 test sites explicitly indicated that temporary road works will not occur.	

Rank 5: Adaptations on fixed infrastructure elements as reference points for localisation of the vehicle/Static urban furniture (4 test sites)	
Madrid Carabanchel	Furniture will be used for geo-localization if the GPS fails using SLAM; if fixed furniture cannot be used as reference, the AV will stop and wait for help
Tampere	If natural landmarks are not sufficiently visible, there might be some reference points to ensure positioning of the vehicle; can be done by the operator, if needed
Gothenburg	LIDAR markers to be added such as fixed dustbins etc.
Pörtschach	This is already adapted and will be put up again; this is a nice-to have but also provides additional information for road users
No adaptations on fixed infrastructure elements (12 test sites)	
Madrid Villaverde train, Trikala (it is under investigation), Aachen, Eindhoven Brainport, Brno (this would be nice to have, but we prefer to have vehicles that work in the environment without any changes), Rouen, Torino, Linköping, Graz, Salzburg, Thessaloniki, Geneva	
Not applicable (2 test site)	
Karlsruhe, Klagenfurt (nice to have)	
No information (4 test sites)	
Braunschweig, Copenhagen, Rennes, Brussels	
Conclusion fixed infrastructure elements	
4 test sites consider fixed infrastructure elements as reference points for AV positioning to be useful. 3 test sites think that measures in this concern would be helpful. 11 do not take this adaption into consideration.	

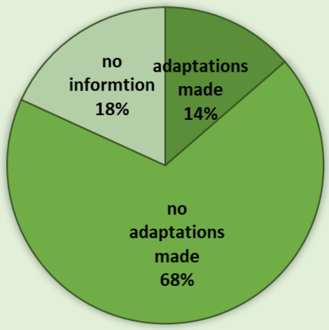
Rank 5: Adaptations on road condition maintenance due to weather events (4 test sites)	
Trikala	If needed it would be necessary, that the asphalt will be fixed during the pre-demo phase or due to bad weather
Tampere	Winter maintenance is necessary in winter
Linköping	It was necessary to order more rigorous removal of snow piles; the internal LIDAR maps could not adapt to the new snowy landscape.
Geneva	Trimming tree branches and hay
No adaptations on road condition maintenance (11 test sites)	
Madrid Villaverde train, Aachen, Karlsruhe (AV is not allowed to drive in heavy rain, snow, fog) Brno (this kind of modification is not in the scope of the project.), Rouen (nice to have, the test will be stopped if weather conditions are not adapted to our safety standards), Torino, Gothenburg (roads are winter maintained), Graz, Salzburg (due to the limitations related to the maximum slope of 8%, an operation during the winter months is not possible), Pörtschach, Thessaloniki	
Not applicable (3 test site)	
Madrid Carabanchel, Eindhoven Brainport (tests will only take place in dry conditions), Klagenfurt	
No information (4 test sites)	
Braunschweig, Copenhagen, Rennes, Brussels	
Conclusion road condition maintenance	
3 test sites explicitly mention that winter maintenance is very important. From those who do not have additional (to normal) winter maintenance interventions 4 indicated that operation will be stopped in case of adverse weather conditions. 11 test sites report no adaptations.	

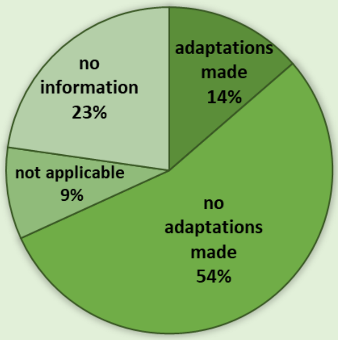
Rank 6: Adaptations on street side parking (3 test sites)	
Madrid Carabanchel	Normal elements that exits in a bus depot will be detected, improve detection of different vehicles parked like busses, lorries and cars
Madrid Villaverde	Cars wrongly parked, improve detection of different vehicles parked like buses, lorries and cars, focus on the place that there will be wrongly parked
Trikala	Traffic police will regulate illegal parking and dedicated vertical signs for the AV will be placed wherever is needed
No adaptations on street side parking (14 test sites)	

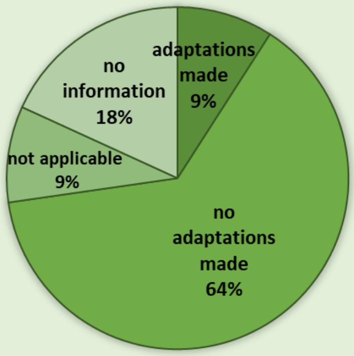
Rank 6: Adaptations on street side parking (3 test sites)
Tampere (street side parking is and will be allowed), Aachen, Karlsruhe, Brno (our aim is to make a vehicle to work under available conditions, not vice versa), Rouen, Torino, Gothenburg, Linköping, Graz, Salzburg, Klagenfurt, Pörtschach (given situation, can occur over several parts along the road, no additional signs are needed), Thessaloniki, Geneva
Not applicable (1 test site)
Eindhoven Brainport
No information (4 test sites)
Braunschweig, Copenhagen, Rennes, Brussels
Conclusion street side parking
2 test sites say that detection systems of the car itself have to be improved to detect wrongly parked cars. One test site leaves this problem to the police who will regulate these cases. 14 test sites do not consider parking as an obstacle for operation.



Rank 6: Adaptations on pedestrian and bicycle crossings (3 test sites)	
Madrid Carabanchel	Pedestrians crossing line detection, try to improve safety
Trikala	Some pedestrian crossings will be regulated by traffic lights
Eindhoven Brainport	Crossings may be added for test purposes, need to have, safety relevant scenarios staged with virtual crossing traffic
No adaptations on pedestrian and bicycle crossings (15 test sites)	
Madrid Villaverde (VRU detection, try to improve safety), Tampere, Aachen, Karlsruhe, Brno (this kind of modification is not in the scope of the project), Rouen, Torino, Gothenburg, Linköping, Graz, Salzburg, Klagenfurt (no changes needed, additional information for road users can be provided), Pörtschach, Thessaloniki, Geneva	
No information (4 test sites)	
Braunschweig, Copenhagen, Rennes, Brussels	
Conclusion pedestrian and bicycle crossings	

Rank 6: Adaptations on pedestrian and bicycle crossings (3 test sites)	
Only minor adaptations (i.e. additional traffic lights) will be taken by 3 test sites on pedestrian and bicycle crossings. One of these test sites will add pedestrian crossings for testing purposes. 15 test sites do not deem any adaptations necessary.	

Rank 6: Adaptations on terminals/stations interchange areas (3 test sites)	
Rouen	Adding a new platform to the Zenith terminal and a bus bay at Cateliers terminal
Gothenburg	Using the current ones as much as possible
Pörtschach	Stations are clearly signposted for automated vehicles, which is necessary; users get more information about autonomous driving and the project; no additional safety features are needed
No adaptations on terminals/stations interchange areas (12 test sites)	
Madrid Villaverde (there is one zone to stop), Trikala (the design of the terminal and depot is under investigation; no major adaptations are however expected), Tampere (existing infrastructure will be used), Aachen, Karlsruhe, Brno (there is no need for this adaptation), Torino, Linköping, Graz, Klagenfurt (not yet decided), Thessaloniki, Geneva	
Not applicable (2 test sites)	
Madrid Carabanchel, Eindhoven Brainport (no operational service, only tests at intersections),	
No information (5 test sites)	
Braunschweig, Copenhagen, Rennes, Brussels, Salzburg	
Conclusion terminals/stations interchange areas	
There is just one major adaptation, 2 test sites refurbish stations to automated shuttle operations mostly by informative features for the passengers. For the others mostly, the existing infrastructure is used. For two test sites the use case shuttle bus is not applicable.	

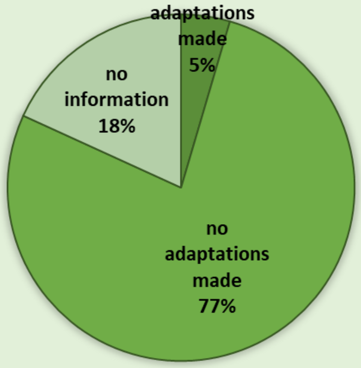
Rank 7: Adaptations on buildings along the road (blind spots) (2 test sites)	
Gothenburg	There will be digital priority zones, and lower speeds
Pörtschach	Mirror to increase sight for the operator, operator needs to double check if there are approaching road users and therewith increase additionally safety; the same is the case on the intersections with STOP signs
No adaptations on buildings along the road (14 test sites)	
Madrid Carabanchel (one building in the centre; no adaptations required), Madrid Villaverde (some trees around the trip without interaction), Trikala (not at the moment but it will be checked) Tampere, Aachen, Brno, Rouen, Torino, Linköping, Graz, Salzburg, Klagenfurt, Thessaloniki, Geneva	
Not applicable (2 test sites)	
Karlsruhe, Eindhoven Brainport	
No information (4 test sites)	
Braunschweig, Copenhagen, Rennes, Brussels	
Conclusion buildings along the road	
Blind spots along the routes of the SHOW test sites are not considered to be an obstacle for operation.	

Rank 8: Adaptations on pavement type/road condition (asphalt, cobblestone, etc.) (1 test site)	
Madrid Villaverde	Asphalt in bad conditions, the issues will be fixed
No adaptations on pavement type/road condition (asphalt, cobblestone, etc.) (17 test sites)	
Madrid Carabanchel, Trikala (if needed during the pre-demo phase or due to bad weather asphalt will be fixed, no need at the moment), Tampere (asphalt, some 100 m of stone paved road), Aachen, Karlsruhe, Eindhoven Brainport, Brno (this kind of modification is not in the scope of the project), Rouen, Torino, Gothenburg, Linköping, Graz, Salzburg , Klagenfurt (asphalt all along the route in very good condition), Pörtschach (concrete plates on a short part of the route in very good condition) Thessaloniki, Geneva	
No information (4 test sites)	
Braunschweig, Copenhagen, Rennes, Brussels	

Rank 8: Adaptations on pavement type/road condition (asphalt, cobblestone, etc.) (1 test site)

Conclusion pavement type/road condition (asphalt, cobblestone, etc.)

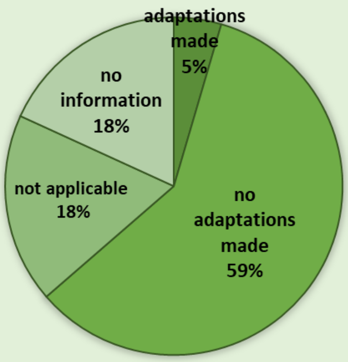
Only at one test site, the pavement is not in good condition. All others currently see no need for any maintenance work in this concern.

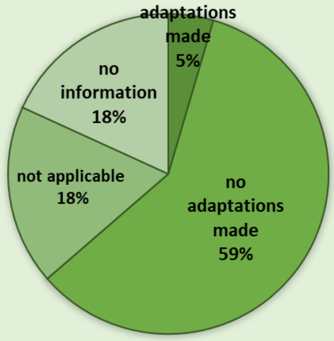


Rank 8: Adaptations on pothole cancellation (1 test site)	
Trikala	The road will be checked, and roadworks will be performed for all the potholes on the route, necessary
No adaptations on pothole cancellation (13 test sites)	
Madrid Carabanchel (no adaptation planned for it), Madrid Villaverde (no adaptation planned for it), Tampere, Aachen, Karlsruhe, Eindhoven Brainport, Brno (this kind of modification is not in the scope of the project), Gothenburg, Linköping, Graz, Salzburg, Thessaloniki, Geneva	
Not applicable (4 test sites)	
Rouen (no pothole on the test site; if it may occur, the city will do the road maintenance), Torino (no potholes), Klagenfurt, Pörtschach	
No information (4 test sites)	
Braunschweig, Copenhagen, Rennes, Brussels	

Conclusion pothole cancellation

All routes seem to be in very good condition in terms of road surface. One test site will monitor the possible occurrence of potholes.

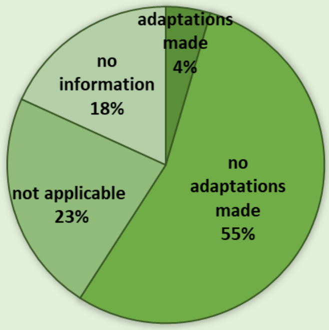


Rank 8: Adaptations on separate lane for AVs, safety/priority zones (1 test site)	
Gothenburg	Priority zones are digital in the AV system
No adaptations on (13 test sites)	
Madrid Villaverde, Trikala, Tampere (existing infrastructure will be used), Aachen, Eindhoven Brainport, Brno (our aim is to make a vehicle to work under available conditions, not vice versa), Rouen, Torino (there is a priority bus lane, which might be used by the AV of the pilot) Linköping, Graz, Salzburg, Thessaloniki, Geneva	
Not applicable (4 test sites)	
Madrid Carabanchel, Karlsruhe (AV drives on public roads), Klagenfurt, Pörtschach	
No information (4 test sites)	
Braunschweig, Copenhagen, Rennes, Brussels	
Conclusion	
There are no priority zones currently foreseen for AVs at the SHOW test sites. Shuttles will use existing lanes and should adapt to the current situation of road conditions and traffic.	

Rank 8: Adaptations on narrow lane sections (1 test site)	
Gothenburg	Digital priority zones, in order to increase traffic safety
No adaptations on narrow lane sections (12 test sites)	
Trikala, Tampere (existing infrastructure will be used), Aachen, Karlsruhe, Brno (our aim is to make a vehicle to work under available conditions, not vice versa), Rouen, Torino, Linköping, Graz, Pörtschach (narrow point but one-way road), Thessaloniki, Geneva	
Not applicable (5 test sites)	
Madrid Carabanchel, Madrid Villaverde, Eindhoven Brainport, Salzburg, Klagenfurt	
No information (4 test sites)	
Braunschweig, Copenhagen, Rennes, Brussels	
Conclusion narrow lane sections	

Rank 8: Adaptations on narrow lane sections (1 test site)

There will be almost no adaptations to narrow lane sections. One test site indicates such a section as one-way street. Most of the other test sites did not comment on this PI element.



Rank 8: Adaptations on tram track and railway crossings (1 test site)

Graz	Currently a yellow warning light is present for buses crossing the tram track; the AV shuttle may re-use an upgraded traffic light with C-ITS; decision and detailed planning has not yet been made

No adaptations on tram track and railway crossings (5 test sites)

Tampere (existing infrastructure will be used), Aachen, Karlsruhe, Rouen, Geneva

Not applicable (12 test sites)

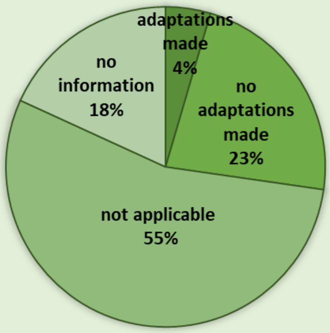
Madrid Carabanchel, Madrid Villaverde, Trikala, Eindhoven Brainport, Brno, Torino, Gothenburg, Linköping, Salzburg, Klagenfurt, Pörtschach, Thessaloniki

No information (4 test sites)

Braunschweig, Copenhagen, Rennes, Brussels

Conclusion tram track and railway crossings

One test site uses a yellow warning light but will possibly upgrade it with C-ITS. 5 test sites do not take any measures and 12 test sites do not have tram or railway crossings on their routes.

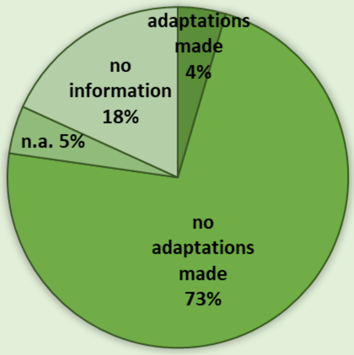


Rank 8: Adaptations on curbs (1 test site)

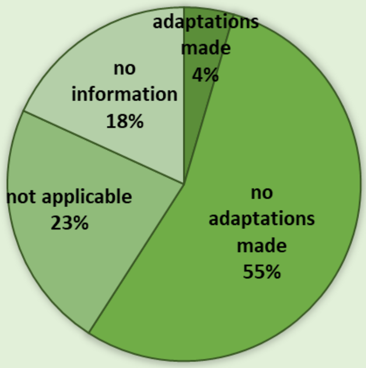
Madrid Villaverde	Paint of yellow to avoid illegal parking in some places

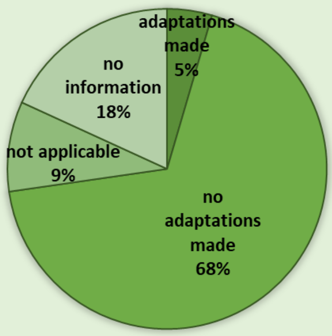
No adaptations on curbs (16 test sites)

Madrid Carabanchel (detection with a Lidar, curbs are around the depot; sensor fusion between LIDAR and HD maps), Trikala, Tampere (existing infrastructure will be used),

Rank 8: Adaptations on curbs (1 test site)	
Aachen, Karlsruhe, Brno (this kind of modification is not in the scope of the project), Rouen, Torino, Gothenburg, Linköping, Graz, Salzburg, Klagenfurt, Pörtschach, Thessaloniki, Geneva	
Not applicable (1 test site)	
Eindhoven Brainport	
No information (4 test sites)	
Braunschweig, Copenhagen, Rennes, Brussels	
Conclusion curbs	
Curb side management does not seem to be an issue at the SHOW test sites.	

Rank 8: Adaptations on accident hot spots (1 test site)	
Gothenburg	Digital priority zones
No adaptations on accident hot spots (12 test sites)	
Trikala (under investigation especially regarding illegal parking on the road side and high speed of the other cars on a specific part of the road), Tampere, Aachen, Karlsruhe, Brno, Rouen, Graz, Salzburg, Klagenfurt (not yet decided), Pörtschach, Thessaloniki, Geneva	
Not applicable (5 test sites)	
Madrid Carabanchel, Madrid Villaverde, Eindhoven Brainport, Torino, Linköping	
No information (4 test sites)	
Braunschweig, Copenhagen, Rennes, Brussels	
Conclusion accident hot spots	

Rank 8: Adaptations on accident hot spots (1 test site)	
The routes of the SHOW test sites seem to have been chosen in safe areas of the cities.	

Rank 8: Adaptations on sight distances and visibility at junctions (1 test site)	
Pörtschach	A mirror was installed to increase visibility for the operator at one intersection, increases safety for all road users
No adaptations on sight distances and visibility at junctions (15 test sites)	
Madrid Carabanchel (better communication between vehicles), Madrid Villaverde, Trikala, Tampere, Aachen, Karlsruhe, Brno (this kind of modification is not in the scope of the project), Rouen, Torino, Gothenburg, Linköping, Graz, Salzburg, Thessaloniki, Geneva	
Not applicable (2 test sites)	
Eindhoven Brainport, Klagenfurt (good sight an all parts of the route)	
No information (4 test sites)	
Braunschweig, Copenhagen, Rennes, Brussels	
Conclusion sight distances and visibility at junctions	
No adaptation on sight distances and visibility at junctions has been taken. One test site mentions in this concern that the communication between vehicles should be improved to solve priority at junctions.	

Rank 0: no adaptation/not applicable

The following 14 PI elements/conditions were either considered as not relevant for AD adaptations or were not existent at the SHOW test sites:

- Slope/inclination
- Road geometry
- Speed bumps

- Width of road/lane width (also on parts)
- Bicycle lanes
- Longitudinal tram tracks
- Parking in second lane
- Left turn lanes
- Roundabouts
- Road safety barriers
- Ramp and merging lanes
- Tunnel area
- Bridges
- Areas of schools, hospitals, etc.

4.2.3 Conclusions and outlook

The survey of the SHOW test sites confirmed the results of the desk research and stakeholder consultations – namely that physical infrastructure and its requirements do not play a major role for automated driving, in the current state of development. Most adaptations were indicated for road/traffic signs, shuttle depots, terminals/stations, lane marking quality, roadside vegetation, road junctions and traffic lights. Even so, adaptations for these PI elements were undertaken just by a minority of the test sites. Infrastructure adaptations and measures often serve information purposes e.g. new traffic signs (sometimes also denoted as warning (!) signs) for other road users to make them aware of automated driving pilots in the area. Critical points in terms of traffic safety on the route as for instance junctions and different kinds of crossings are mostly mentioned by the SHOW test sites in connection with HD maps, C-ITS, V2X communication, and digital transmission of information to the vehicle. Physical infrastructure mostly serves as a reference point (landmarks) for the localisation of the vehicle (through LiDAR), if the GNSS fails.

As a conclusion, it can be stated that physical infrastructure is currently of moderate importance for automated driving in an urban environment, which may have the following reasons:

- The choice of current test routes avoids difficult conditions and complex situations and therefore can use the existing physical infrastructure as is
- Automated shuttles still drive at low speeds in urban environments
- Highly sensitive sensors installed in the vehicle and navigation systems using highly precise HD maps with physical reference points on the infrastructure enable automated driving without any adaptations to the physical road infrastructure. This makes AD feasible in different environments and saves costs for municipalities and road operators.

Nevertheless, real world traffic is highly complex and often does not operate according to plan:

- Automated vehicles will drive at higher speeds in future
- Events such as temporary road works, illegal parking, accidents or other spontaneous and unpredictable occurrences remain critical challenges for AD
- Vulnerable road users are not currently connected and require special attention and protection that cannot end in banning them from the streets
- Over time, road damages will occur and road monitoring and damage maintenance will be important services for infrastructure operators.

Whether physical infrastructure needs to be adapted for special situations in real world traffic has to be investigated in large-scale demonstrations for AD in the future.

5 Segmentation of roads (harmonized sections) for the assessment regarding traffic safety at pilot sites

According to [118], several road elements have an influence on traffic safety. Main rural roads for example, which are designed and operated by higher standards than those for secondary rural roads, are usually safer in terms of accidents per vehicle-km. On any given road, the safety level is not constant, either. Accident densities are generally lower on links than at nodes, due to differences in the number of traffic conflicts. At nodes, T-intersections are considered safer than + intersections for this very same reason.

Consequently, distinct reference populations can be defined to help determine what constitutes a representative safety level for a given type of site. Such populations are defined by taking into account the main road features having an impact on safety. For example, a reference population may be defined for two-lane four-way intersections in urban areas with stops on the minor legs, another population for T-intersections on similar roads, and so on (see Figure 44).

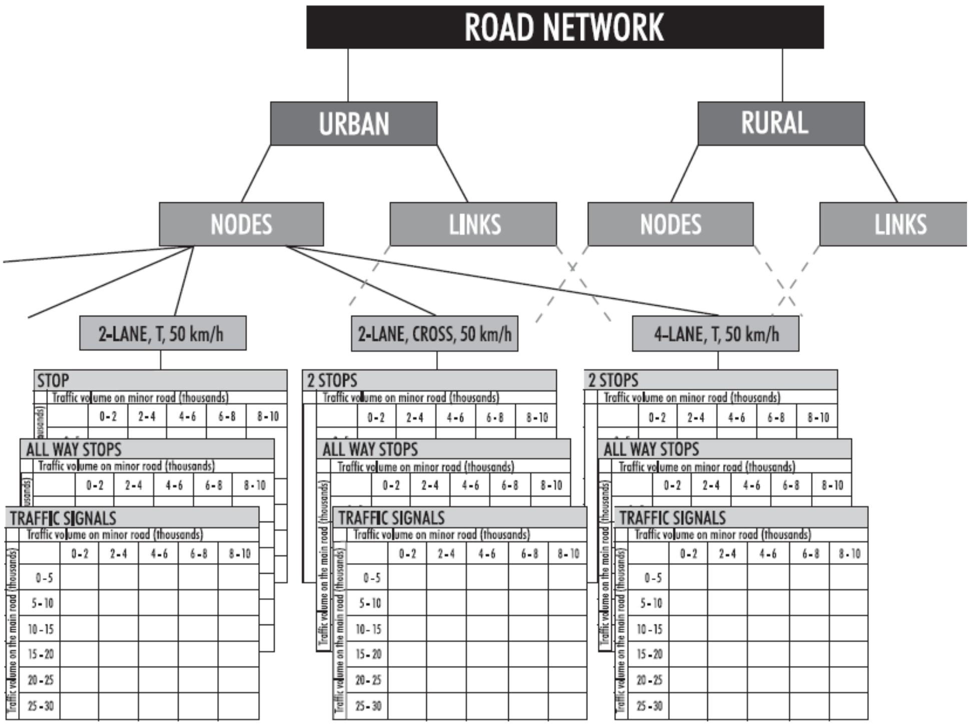


Figure 44: Examples of reference populations for site evaluation [8].

Such a classification technique for traffic site evaluation can also be used to investigate different road segments at SHOW pilot sites for their AV assessment and safety-related confounding factors. State-of-the-art driver assistance systems (ADAS) such as lane-departure warning (LDW) and lane-keeping assistance (LKA) typically use machine-vision technology in the form of cameras to detect various physical infrastructure components such as lane markings or traffic signs [10].

In the case of LDW, the machine vision algorithms do not only detect the lane itself but also extract other important data from the detected lanes. Double- or continuous boundaries that separate the direction of traffic, discontinuous boundaries that separate lane markings in the same direction, and merge-type markings (dense, discontinuous markings) that separate the road from the roadside parking area are only a few examples of such additional information that these algorithms need to be provided with for proper functionality [8], [119].

Hence, collecting information on the currently available physical infrastructure is of major importance for the SHOW pilot sites to evaluate if the PI needs to be improved for automated urban mobility to function seamlessly. For this reason, scientists of the Austrian Institute of Technology have developed a software tool to classify different road elements due to specific site characteristics and provide site representatives with a methodology for a quick-scan road safety assessment concerning lane markings, traffic signs and sight distances.

The SHOW segmentation tool (see Figure 45) works similar to modern routing mapping systems, i.e. the user scrolls through a digital map to move the display window to the area of interest (see also "Segmentation Tool Manual" in the Appendix III). For the sake of convenience, different base maps can be chosen from:

- Open Street Map
- Google Maps
- Google Maps Satellite

Figure 45: Segmentation tool for physical infrastructure appraisal.

Using the segmentation tool at pilot sites usually results in a large number of repetitive digitalisation routines, i.e. each road element has to be redrawn in a digital map and evaluated afterwards (see Chapter 7). To reduce the mental payload of the respective site manager during the evaluation process, only those road elements should be used in the tool which are also visible in the real-world. Since such a detailed classification amounts to major software programming efforts, a low-level classification regime was chosen instead.

The segmentation process starts with the selection of one of the following SHOW use cases [120] most relevant for Physical infrastructure evaluation:

<u>Use case 1.1</u>: Automated passengers/cargo mobility in cities under **normal traffic** & environmental conditions

Road elements to be assessed within this use case are:

- Pedestrian crossing
- Cyclist crossing
- Signalized intersection
- Unsignalized intersection
- Roundabout
- Straight section
- Smooth curve
- Sharp curve/turn

<u>Use case 1.2</u>: Automated passengers/cargo mobility in cities under **complex traffic** & environmental conditions

This use case contains all the road elements of SHOW use case 1.1 plus additional features for specific urban driving scenarios:

- Level crossings
- Ramps/junctions/exits
- Tunnels
- Bridges

<u>Use case 3.4</u>: Automated service at a bus stop

One of the most common use cases at SHOW pilot sites. According to [121], such a use case consists of an automated shuttle driving along a predetermined route with speeds well below 20 km/h. At dedicated route locations, the automated vehicle automatically decreases its speed and either turns into a bus bay or stops directly at the road for passenger deboarding.

Road elements to be assessed within this use case are:

- Bus stop – Midblock
- Bus bay – Midblock
- Bus bay – Intersection

A bus bay is a designated spot on the side of a road where buses may pull out of the flow of traffic to pick up and drop off passengers. It is often indented into the sidewalk or other pedestrian areas.

A bus bay is, in a way, the opposite of a bus stop. With a bus stop, the point is to save the bus the time needed to merge out of and back into moving traffic, at the cost of temporarily blocking that traffic while making a stop. With a bus bay, the goal is to not block traffic while the bus is stopped, but at the cost of the time necessary to merge back into flowing traffic. Bus bays, therefore, will generally produce longer dwell times than bus stops.

Midblock bus stops or bus bays are located in the middle of a city block, i.e. between adjacent intersections. In contrast, bus bays at intersections are usually situated before (un-)signalized crossroads to provide passengers easy access to road crossing points.

6 Simulation Framework: Public Transport Hubs and Stations

Due to the current status of automated vehicles in public transit, current research focuses on small fleets of automated vehicles in Public transit. Thus, little practical experience of the inclusion of AVs in Public Transport Hub environments was gained. The functionality of transit hubs can only be tested in practice once certain levels of vehicles and passengers are available at these hubs. As a result, the research in this area concentrates on simulation studies. The research into the state of the art on PT hubs described in 3.2.4 and 3.2.5 delivered some first guidelines into the design of PT-hubs but also a series of questions that was not answered so far was extracted. In this section we describe a simulation setup and the questions that will be answered in WP10.

<u>General questions for PT hub infrastructure and influence of AVs</u>

When operating autonomous vehicles as public transport, the following problem areas regarding public transfer hubs need to be analysed in detail:

1) Due to the **layout** and structural conditions of the station, arrival and departure of the AV may be delayed. Potential conflicts with other road users are exaggerated by the fact that all of them have nearly the same priority within the area of a public transport hub. Following aspects could have a particularly negative effect on the operation of AVs:
    - Crossing pedestrian flows resulting from transfer operations
    - Conventional public transport vehicles serving other routes, such as buses and trams
    - Delays when the AV tries to get in lane with the passing traffic at the station exit. Especially, at times when trains arrive at the railway station which induces an increased traffic of private vehicles.
2) **Passenger exchange** processes at autonomous vehicles are more time-consuming for safety reasons and therefore can lead to delays in the departure of the vehicle:
    - All passengers using a public AV must have a seat in the vehicle. However, if there are more people boarding than there are seats available, there will be delays until they have disembarked.
    - Additional communication with waiting passengers is therefore required to minimize these delays. This can be done acoustically or visually and informs the passengers about the expected number of passengers who are allowed to board.
    - Furthermore, the station layout must be designed in such a way that waiting passengers who have not found a place in the vehicle can return to an area where they do not hinder the departure of the vehicle.
    - Within the nationally funded project "autobus:Seestadt" passenger exchange experiments with an autonomously driving bus from the “Navia“ company were conducted. The results of these experiments have not yet been published but can already be used for the investigations within this project.

Simulation setup for PT hub infrastructure simulations under the influence of AVs

To investigate all these issues and the effectiveness of possible solutions in advance, simulation studies are carried out using the AIT's simulation framework and the Graz-Puntigam transport hub as a test site, which is part of the SHOW pilot site in Graz. This public transport hub consists of a railway station, a tram station and bus stations of several bus lines. It is planned to operate an AV as a public shuttle to transport passengers from the station to a near shopping mall (see the figure below). The simulation setup is a combination of AIT's Simulate tool [122], [123] that was applied to the analysis of PT hubs in several projects (e.g. [124]) and simulation of automated vehicles done by Virtual Vehicle Research GmbH.

Figure 46: Simulation area in the Graz Mega Site that will be used as a base for the simulation scenarios in WP 10.

The simulation includes the pedestrian flows of arriving, changing and departing passengers as well as the movements of all private and public vehicles passing through and by the station. This allows the interactions of all traffic participants to be modelled and the resulting problem fields to be analysed. For the evaluation of the station's performance, KPIs are defined to enable the comparability of the simulation results of the different scenarios. For this purpose, the following scenarios for the analysis of the public transport hub are examined:

- **Scenario 0 "Base scenario"**: Simulation of the selected public transport hub in the current situation and determination of the baseline of the station performance.
- **Scenario 1 "Base scenario + AV"**: On one bus line the conventional vehicles are replaced by AVs while the station layout and the transport processes remain the same. Due to the problem fields described above, it can be expected that the performance of the station in general and the passenger exchange times on the AV-line will decrease. This decline will be quantified by the simulation.
- **Scenario 2 "Scenario 1 + optimisation of the AV's passenger exchange processes"**: This scenario consists of several sub-scenarios which are used

to quantify the effectiveness of certain measures to accelerate passenger exchange processes and finally to determine the optimal mix of measures.

- **Scenario 3 "Scenario 2 + station layout adaptations"**: Similar to the previous scenario, a number of measures concerning changes in station layout are examined here. The goal is to evaluate their potential for improvement in order to ensure the most efficient operation of the AVs.

7 Digital Dynamic Maps for urban automated Driving

7.1 Desk research and interview results

The desk research on how to acquire and manage the different data sources of digital dynamic maps (DDM) focused on a broad literature review and the expertise of the partners involved in the work package. In addition to this theoretical approach, the SHOW pilot sites were surveyed on their approaches on digital (dynamic) maps to gain information from practice.

In Chapter 7.1.1, the desk research results on DDM are presented. Different definitions for digital dynamic maps were reviewed to adapt the initial one defined in SHOW in case something was missing, and the usages of digital dynamic maps are explained. Existing data formats and standards are described to show how the maps can be managed. Also, as the environment is not fully static, updates are discussed.

Chapter 7.1.2 deals with the implementation of digital dynamic maps at the SHOW pilot sites. Therefore, a questionnaire was developed (see Chapter 2.2.2) and answered by the pilot sites.

7.1.1 Desk research results

In contrast to standard digital maps, or so-called navigation maps being used for vehicle navigation for nearly three decades, digital maps for automated driving – so called high definition (HD) maps – represent a precise digital twin of the physical driving environment. In a recent survey paper, Liu et al. [125] sketch the development of HD maps from paper maps (1930) to digital maps (1990) and enhanced maps for Advanced Driver Assistance Systems - ADAS (2000) to high definition (HD) maps (2010) for automated driving. While digital maps are intended to support human drivers in their navigation task, enhanced digital maps and HD maps are mainly intended to support ADAS-enhanced and highly automated vehicles (HAVs) and not human drivers.

Digital dynamic maps definitions

There are several approaches on how to define a digital dynamic map or HD map. For the desk research, we started with the following definition:

A digital dynamic map refers to a digital map, that is designed for automated driving and therefore must have a higher accuracy and can include more elements than simple maps. The elements can be divided into four layers (based on the definition from the viaAutonom project [126], pp. 24–49], where the former two are mandatory:

- *Static information:* Road model (for routing), lane model (detailed information on lanes in general and especially at intersections and in case of bad road conditions, roadworks, bus stops), landmarks for positioning, Addresses and POIs.
- *Traffic regulations:* Semantic information on (virtual) lanes (including the meaning for AVs) like speed limits, give way, stop lines, crossings, traffic light existence, use of lane, restrictions (e.g., no overtaking)
- *Quality information:* road surface material, road surface quality, lane marking quality, state regarding traffic signs.
- *Dynamic real-time information:* Weather data or other data on the environment, roadworks (where, how long, effects), real-time traffic data (traffic jams, tolls, traffic light data/circuits, PT-information etc.), predicted traffic information (e.g., latencies), operational infrastructure (available parking or charging

infrastructure), information on connectivity. Information can be shared between vehicles, can be communicated by TMC, RSU (Roadside Units, mostly available in case of highways), infrastructure (in case of existing sensors), traffic lights or even Traffic Signs with codes (which transmit latest information).

It is not specified whether a digital dynamic map is 2D or 3D as the usages are similar. Also, the map is considered as a planar map, while point cloud maps can be an addition.

As this definition was not comprehensive, we looked at other definitions to reveal the missing pieces.

According to Liu et al. [125], HD maps are typically composed of three layers, namely

1. Road Model,
2. HD Lane Model and
3. HD Localization Model.

While the Road Model layer provides a navigation view to the automated vehicle and is widely comparable with a traditional navigation map, the HD Lane Model supports the HAV in planning and executing automated driving manoeuvres such as lane changes. The HD localization model represents the enhanced driving environment such as buildings or road furniture and therefore supports the HAV in accurate lane-level positioning. This map definition is also used by the company HERE maps [127, pp. 1–2].

From an automated manoeuvre planning and executing perspective, the HD Lane Model is the most important part of an HD map. The HD Lane Model (2) typically consists of the following parts [125]:

- Highly accurate geometries of physical road features
- Lane attributes
- Traffic regulations, road furniture and parking
- Lane connectivity.

To connect the road level with the lane level layer for route planning, in [128] an additional intermediate layer for linking those two was proposed.

Hausler & Milford [129, pp. 13–15] follow another approach for defining a HD map: They consider a 3D representation of the world in the HD map mandatory, all other maps that support automated driving or ADAS are called enhanced digital maps. The 3D representation can be generated by LiDAR, radar or cameras. Also, information from Apollo software and DeepMap's U.S. patent were combined resulting in a HD map description with the following contents: lane positions and widths, road sign positions (the exact 3D position relative to the map and vehicle is considered important), special road features (such as pedestrian crossings, school zones, bicycle lanes), occupancy map (required for localization).

The map provider TomTom [130] also includes a 3D representation of the environment in their so-called RoadDNA on top of their HD map. The 3D point cloud data of the roadside patterns is compressed into a 2D version.

These layers so far contain static information. For a dynamic HD map, additional dynamic layers are added on top of these static layers of a HD map. The dynamic layers represent dynamic or semi-dynamic map features, e.g. features that change continuously, e.g. during short time spans. But dynamic layers can also contain knowledge which is derived from real-time data over longer time periods, so called map priors.

Figure 47 represents a 5-layer model for dynamic maps which has been adapted from the 5-layer model proposed by Lyft [131]. The first three layers (bottom-up) represent the static layers of the HD map, i.e. the road model, the HD geometries (including the lane and the localization model) and the HD Semantics (including lane topologies and driving rules). The additional two layers on top are of semi-dynamic or dynamic nature. The Map Priors layer represents knowledge which has been derived from dynamic data (e.g. driving behaviour) over time. This layer is of semi-dynamic nature, i.e. it has to be updated regularly, but not in real-time. The real-time layer contains frequently changing attributes of map features, such as traffic signal states, road conditions or lane closures.

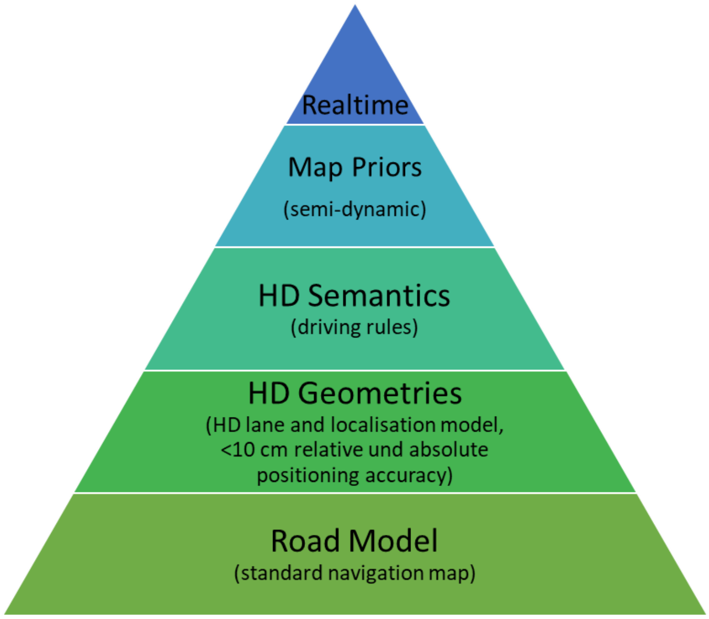


Figure 47: 5-layer model for Dynamic HD Maps, adapted from Lyft.

The provider “HERE maps” has such a real-time layer within their product of HERE Real-Time Traffic [132], containing data on traffic, deriving from vehicle sensor data, fixed sensors, government sources and historical traffic records.

In [133] a map concept containing static and dynamic data is proposed. It is a seven-layer map, mainly for route planning on lane level. Layer 1, 3 and 4 can be considered as layers containing static data and layers 3, 5, 6 and 7 contain dynamic information:

1. Road layer: for static mission planning
2. Traffic information layer: includes global traffic dynamic data, for dynamic mission planning
3. Road-lane connection layer: for lane-level route planning
4. Lane layer: for reference trajectory planning and adjustments
5. Map feature layer: for enhanced localization and perception
6. Dynamic objects container layer: for dynamic local trajectory planning
7. Intelligent decision support layer: filled with decision knowledge layer, for fully autonomous driving.

Like Liu et al. [133] they propose a layer that links the road and lane level layer (road-lane connection layer). Within the study, route planning was tested with the first four layers, while the information from layers five to seven was not used. Therefore, there are no insights on those layers available.

The approaches so far have described the layers by their contents. Another approach is to define layer categories based on how static or dynamic the data is, like Maiouak & Taleb [134] did with the following layer concept:

- Permanent static: Static information provided by geographic information systems (GIS) and map providers. It includes intersections, points of interest (POIs), and roads.
- Transient static: This layer contains information like lane data, static ITS stations, traffic data, and landmarks.
- Transient dynamic: In this layer we have the semi-dynamic data like road, weather, and traffic conditions or light signal phases.
- Highly dynamic: This indicates data like vehicles' locations and pedestrians' positions and trajectories.

The European Automobile Manufacturers' Association (ACEA) [135, p. 6] categorized the layers with a similar system, with different features in the layers including e.g. dynamic driving recommendations such as lane change, distance gap and speed.

Definition of digital dynamic maps within SHOW

After reviewing this literature, the definition of digital dynamic maps/HD maps was adapted as follows. The four-layer-structure defined initially, where only the first two are mandatory, stays the same, with some adaptations:

Within the static information, we acknowledge that there is a road and lane model, and depending on the specific map format and usage, an intermediate layer linking these models might be needed. The geometry of the lane model is defined in the static information layer, whereas the semantics are on top in the traffic regulations layer. The representation is mainly a 2D map, although the 3D representation of the surrounding area in the form of a point cloud map can be added. For the dynamic data, we focus on dynamic information which changes over time, not changes in space, like communicating positions of individual vehicles or pedestrians.

- *Static information*: Road model (for routing), lane model (detailed lane geometry in general, and especially at intersections and in case of bad road conditions, roadworks, bus stops), landmarks for positioning, addresses and POIs.
- *Traffic regulations*: Semantic information on (virtual) lanes (including the meaning for AVs) like speed limits, give way, stop lines, crossings, traffic light existence, use of lane, restrictions (e.g., no overtaking), lane connections
- *Quality information*: road surface material, road surface quality, lane marking quality, state regarding traffic signs, accident hot spots (potentially dependent on additional criteria e.g. weather conditions/bad visibility/slippery road, or even time of day (blinding sunlight can be temporarily dangerous e.g. during bad weather conditions)), driving dynamics, map priors.
- *Dynamic real-time information*: Weather data or other data on the environment available on a small scale, roadworks (where, how long, effects), real-time traffic data (traffic jams, tolls, traffic light data/circuits, PT-information etc.), predicted traffic information (e.g., latencies), operational infrastructure (available parking or charging infrastructure), information on connectivity (GNSS, 5G, etc).

If one wanted to categorize the layers depending on how dynamic the data is, we would say the static information and traffic regulations are static data, quality information is medium-dynamic and dynamic real-time information is dynamic data.

Concerning accuracy requirements of HD maps, Liu et al. [125] provide the following overview (Table 39). Especially for the HD lane model, an absolute accuracy of 10-20 cm will be necessary. A considerable difference to traditional navigation maps is that the HD map has to provide an accurate elevation model as well. Especially for accurate lane level positioning on roads with incline, a 3D lane level model is important.

Table 39: Accuracy requirements of a HD lane model according to Liu et al. [125].

Category	Content	Accuracy Requirement
Geometry	Superelevation	0·5%
	Heading	0·05°
	Lane centre lines	10–20 cm
	Lane marking width	10 cm
	Lane boundary geometry	10–20 cm
Lane connectivity	Relations between lanes and lane groups	10–20 cm
Road furniture	Traffic signs	50 cm
	Poles	50 cm
	Information sign	100 cm
	Toll booth	500 cm
	Tunnel and Bridge	100 cm

Digital dynamic maps: Usage

A digital dynamic map can support automated driving in different tasks. In [136] for example "understanding its precise positioning, plan beyond sensor range, possess contextual awareness of the environment and local knowledge of the road rules" are listed. According to the literature found, we inspected the following areas further:

- Route planning and navigation
- Perception, behaviour generation and planning beyond sensor range
- Localization and positioning
- Simulation

The different areas will be described in more detail in the following sections.

We want to acknowledge that non-map alternatives would need to process considerably more information in real time for the above stated first three purposes. To reduce the amount of processing, one could drive in a more restricted manner (possibly along a fixed route/grid).

Route planning and navigation

From classic maps used for route planning and navigation for a human driver, the digital dynamic map includes enough detailed information on how to support automated vehicles in these tasks.

For providing a route accurate enough for an automated vehicle, this information for example must include where lane changing is possible or mandatory, which lane leads to a turning lane or what restrictions apply on a lane (e.g. only to use for buses), as well as the lane connections [137, pp. 1672–167]. At intersections, virtual lanes including virtual stop lines are needed to plan a trajectory, as there are in general no lane markings present at intersections [138, pp. 33–34]. An intersection model was for example created within the MAVEN project [138] and is shown in Figure 48.

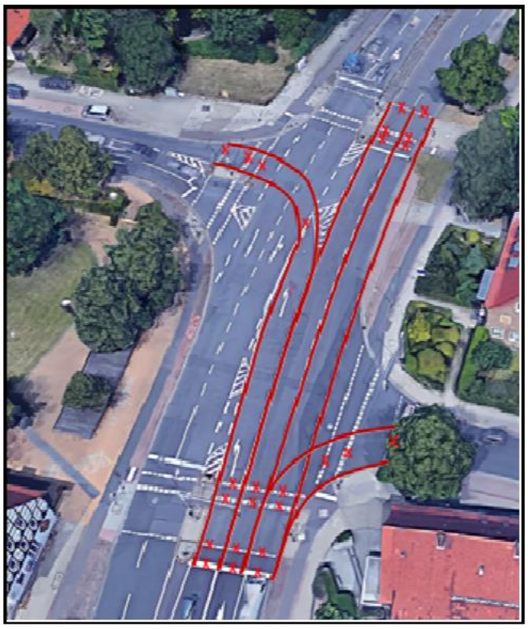


Figure 48: Ideal MAVEN intersection corridor representation (visualized on GoogleMaps). Source: [138, p. 34]

For route planning and navigation, Poggenhans et al. [137, p. 1674] propose that the lanes should be mapped completely with their left and right borders, not only with a centre line. When driving in urban areas, the AV might need to avoid obstacles such as parked vehicles and it is possible to do that while staying within the lane but having to leave the centre line. For this trajectory adjustment, the vehicle has to know how wide the lane is, and in context of maps: "What is the tolerated distance from the centre line without leaving the lane?" This could be implemented with fully mapping the left and right borders of each lane. Also, knowing the traffic rules on lane-level (e.g. speed limits, driving direction, right of way) is important for accurate route planning.

Navigation could be done on road-level (without a HD map) and on lane-level according to [133, p. 306]. On road-level the driving instructions are given, while on lane-level a specific trajectory that the autonomous vehicle can follow could be calculated. As shown in Figure 49, with a lane-model, the computation burden while driving (for perception and decision making) is therefore a lot lower: The trajectory does not have to be calculated in real-time according to the dynamic environment, it is instead only adjusted constantly. The computational burden for the provision of the trajectory might be higher within the lane-model, but Jiang et al. [133, pp. 311–314] propose a hierarchical planning algorithm which is more efficient. First road-level routing is done, then the lane-level nodes based on this route are selected. With these, the path on lane-level is found using their proposed travel cost model. The use of road-level routing before lane-level routing is convenient, because there are many algorithms available for road-level route planning, as research on this topic has been going on for decades. But, with this proposed algorithm, there is an intermediate layer necessary, which connects the road- and lane-model.

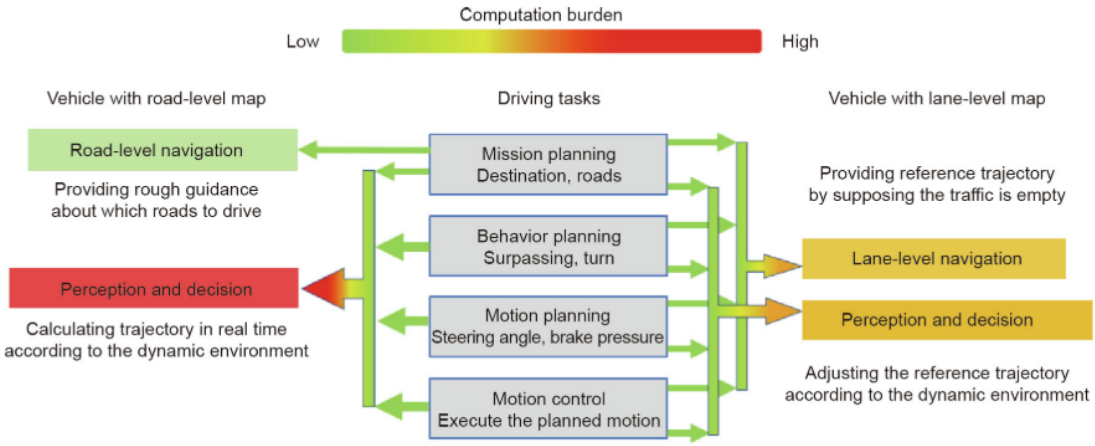


Figure 49: Strategies for autonomous driving with road- or lane-level navigation. Source: [133, p. 306].

For autonomous vehicle navigation and routing, there are also publications which question the need of digital dynamic maps, focusing on road-level route planning and navigation with sensor-based perception. For example, in [139] such "mapless" driving in rural areas was investigated. First, global navigation is done with a road-level map, then a local navigation goal is set within the sensor view. This goal is a waypoint leading towards the global goal. To reach the waypoint, a feasible trajectory is calculated and updated. This allows reliable navigation at high speeds without the use of HD maps.

Artunedo et al. [140, pp. 1645–1646] propose a routing and navigation architecture based on OpenStreetMap (OSM) because, according to them, detailed maps in urban environment are neither cost-efficient nor completely reliable. Not so detailed maps are more stable. They use OSM for obtaining a global route and generating driving corridors. As OSM is openly accessible, this is convenient to use but also a possible source of data inaccuracy. Therefore, the driving corridors are updated with a vision-based lane detection algorithm. To consider for the localization uncertainty, a grid-based approach is applied. With the corridors, a local planner then generates trajectories for the vehicle to follow.

<u>Perception, behaviour generation and planning beyond sensor range</u>

HD maps include detailed information on the road geometry, traffic rules and surroundings to support the autonomous vehicle's perception and behaviour generation system: the mapped roadway elements (lanes, lane markings, signage etc.) can serve as a prior for the perception system [141, p. 3] as the vehicle knows where to expect what. If other road users are detected, the map also helps the automated vehicle with generating the behaviour of these, as the set of possible manoeuvres can be determined with the rules (that they should follow) stored in the map [137, p. 1674]. Therefore, not only the traffic rules for the automated vehicle, but for all road users should be integrated in the map.

Also, with the map, the inadequacies of the sensors can be compensated and the vehicle can "see", even if objects are occluded, beyond sensor range or are not extractable from sensor information [135, p. 8]. For example, road works or street eligibility are known beforehand.

<u>Localization and positioning</u>

Commonly, Global Navigation Satellite Systems (GNSS) are used for the localization of vehicles. Combining these systems with an inertial measurement unit (IMU) and real-time-kinematics (RTK) can already lead to centimetre-level accuracy, according to [142, p. 220]. But, especially in urban areas, they say, satellite-based systems cannot reach this level of accuracy, so landmark-based positioning systems can be used in these areas to enable automated driving within a short period of the lost or bad GNSS signal and therefore extend the ODD. Landmarks can be defined as static features that can be recognized by sensors and are stored within the HD map, such as traffic signs, lanes, walls, poles, trees or traffic lights [143, p.3].

Huang [144] considers localization as the main function of a digital dynamic map. For this kind of localization, data provided by the perception module is needed to match with the map. There are different approaches:

- Yu Huang [144] proposed a method which uses a combination of low-cost sensors (camera, consumer level GPS and IMU) together with the HD map: Visual (inertial) odometry, lane/road marking and landmarks (traffic signs and traffic lights) detection are run and HD map matching is done, following a multiple sensor fusion in a particle filter.
- Wilbers et al. [142, pp. 220–223] investigated landmark-based positioning systems, focusing on pole-like objects (traffic signs, lamp posts, trees). Besides the semantic landmark-map, they used LiDAR, IMU and a low-cost GNSS-receiver. They consider that the main advantage of matching with semantic landmark maps in comparison to raw sensor data maps (like point cloud maps) is that they are faster to process because they require smaller storage and are easier to inspect for correctness.
- In [145] a low-cost GPS, vision-based sensors and radar were used for localization on expressways. With camera and radar road features such as lane markings and road boundaries were identified and used for map matching.
- In the EU-project “inLane” [146, pp. 7–8] they used GNSS, IMU, visual odometry and vision-based map matching for positioning, focusing in the latter on lane and traffic sign detection.

These sources along with Poggenhans et al. [137, p. 1674] indicate that for the HD map to be usable for localization of vehicles with different sensor setups, a variety of elements that can be observed by as many sensors as possible (e.g. lane markings, crash barriers, roadsides) is needed. Also, the density of such elements must be sufficient to allow precise localization.

As physical objects referenced with GPS are not robust against environmental changes like continental drift, [137, p. 1674] recommend using a locally fixed reference frame instead to provide a stable localization option.

As stated initially, if the system does not rely on such landmark-based localization, a HD map as defined here might not be needed. In [141], p. 13] it was stated, that “the a-priori surface reflectivity and/or 3D occupancy map or LiDAR point cloud of the intended driving environment” can be used instead. In general, GNSS can support LiDAR-based localization, especially during bad weather conditions, while LiDAR is used when GNSS signal quality is low. In the project “inLane” [147] GNSS signal quality was tested, leading to good results (0,5 m accuracy) on highways. In urban environments and especially in tunnels, where GNSS signal is lost for a longer time period, other localization approaches have to be added. But even if the localization system relies heavily on GNSS signal, we would assume that the signal quality could be included in the map so vehicles without landmark-based positioning systems can choose routes only with good signal quality.

<u>Simulation</u>

Testing plays a significant role in vehicle development. HD Maps are used for these simulations to provide real circumstances through a copy of the reality [148, p. 367]. Such copies are also known under the term “digital twins”.

Standardization progress of digital dynamic maps

Currently, there is no single standard for HD maps but several standardization attempts. The International Standardization Organisation (ISO) recently extended the GDF (Geographic Data File) standard to support HD map features for automated driving [149]. For Barsi et al. [148, p. 365] GDF is not a physical file format itself, but can be seen as an “exchange map data format”, to transform information from one physical format to another without data loss. It is supported by various map providers, like HERE, TomTom, Mapscape BV or NavInfo [150].

There are also several industry/government consortia working on the standardization of HD maps. The most common ones are Navigation Data Standard (NDS) and ASAM OpenDRIVE [151]. The NDS format is divided into so called building blocks e.g. for basic map display, for points of interest, or traffic information [148, pp. 365–366]. It also has a route buildings block for route calculation and guidance, as well as a lane building block (including lane geometry, boundaries, directions, road markings, lane-changing possibilities). The HERE Live HD map is for example provided in NDS format (or via protocol buffer format) [127] and TomTom’s HD map, which is initially in its own format, can be transformed directly into NDS format [138, p. 90]. But, these two organisations (TomTom Maps and HERE maps within the OneMap Alliance), as well as the Japanese initiative sip-adus are also trying to build a data standard out of their own [136], p. 24].

For simulations, ASAM OpenDRIVE has been established as de-facto standard [148, p. 366], [150, pp. 40-41]. The format is organized in nodes with quite strict syntax but can be extended by user-defined data [138] [148]. For creating maps in this format, “Road2Simulation” is a generic guide on how to pre-process and store road data for simulation, oriented towards OpenDRIVE [152, p. 4].

Another format, which should be mentioned, is Lanelet2, as for expressing real-world HD maps, there are some drawbacks of the simulation targeted ASAM OpenDRIVE format. Furthermore, Lanelet2 is an open HD map format as it extends the OpenStreetMap data format, which opens the path to edit the HD map data with existing open source software tools such as JOSM (https://josm.openstreetmap.de/) – which is a significant advantage in comparison to NDS and OpenDRIVE formats [137].

This list cannot be considered complete, as there are AV manufacturers which use their own formats for their self-developed maps.

When speaking of standards, there are also some working groups dealing with the contents of a digital dynamic map. For example, for EU-EIP 2018 [136, pp. 23–24] static data includes the road model with road width, geometry, gradients and junctions, the road classification, the lane model with the number of lanes and linked attributes (access conditions and restrictions, speed limits, other traffic regulations, the direction of travel) and a HD localization model with beacons and landmarks, as well as locations of PT stops, parking, charging (although HD map providers may choose to provide this information within a basic or premium version). Zenzic UK Ltd. [153] lists the following features that a HD map can include: Street furniture including PT stops, road markings, junctions, road lanes, pedestrian crossings, traffic islands taxi stands, parking locations, vegetation, road network, buildings (might be helpful for positioning) – in their Appendix they also provide a non-complete list of elements.

Digital traffic regulations are currently displayed via physical infrastructure. The EU-EIP [154, pp. 21–22] refers to Malone et al. 2019, saying this could either remain standard, or the regulations could be provided by the implementing authority – via bidirectional communication with the service providers, or via a trusted digital regulation access point.

The ACEA [135, p. 7] also mentions other information that should be shared: the geofencing status, constantly updated static and dynamic traffic rules or road health (current physical data of the road infrastructure). The data must be in an electronically readable format and have clear interpretation tools.

Managing dynamic data in maps

So far, we focused on the standardization approaches of static data within HD maps. The Open AutoDrive Forum (OADF), a cross-domain platform driving standardizations in the area of autonomous driving, has proposed the automated driving data chain and ecosystem combining static and dynamic data (Figure 50).

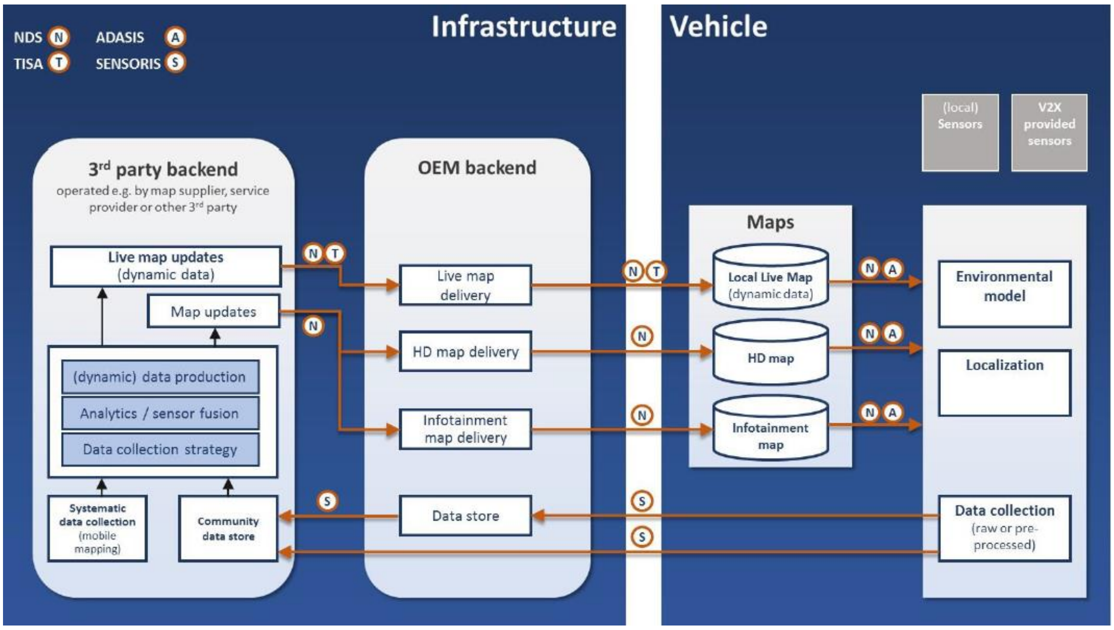


Figure 50: Open AutoDrive Forum (OADF) automated driving data chain and ecosystem. [164 p. 4]

Figure 50 shows how the different industry standards NDS, ADASIS (https://adasis.org/), SENSORIS (https://sensoris.org/) and TN-ITS (https://tn-its.eu/) complement each other in order to build an automated driving data ecosystem. While ADASIS specifies the in-vehicle interface for ADAS data providers, SENSORIS specifies the interface for vehicle data being transferred to the backend (cloud). NDS represents the general map format and the TN-ITS interface specifies the channel for transferring map updates to the vehicle. TISA TPEG™ (https://tisa.org/technologies/tpeg/) can be used to describe and transfer dynamic traffic data such as traffic events. Also, the Japanese SIP-adus dynamic map platform (https://en.sip-adus.go.jp/) is part of the OADF platform. Although OADF sketches a whole industry-driven data ecosystem, it is unclear how the automated driving data ecosystem will look like in the future. As can be seen in Figure 50, the role of road infrastructure operators or public authorities is undefined at the moment. However, some of the dynamic data will be issued by road operators or public authorities since these stakeholders are the only ones to have the permission to do so. On the other hand, especially when it comes to traffic management strategies, issuing and activating these is also under the responsibility of road operators.

Within the DIRIZON project [136, pp. 20–22], there was a process flow developed, for who provides and how to manage the different data sources (static data and traffic regulations, as well as updates) within a map (Figure 51). There are different parties involved: Road operators and authorized authorities, HD map providers and service providers. The road operators provide data via a national access point, which can also include a trusted digital regulation access point with a trusted party connection to the HD map providers (a trusted party connection could also be used only). They use the data (which includes the road and lane model, as well as data for localization (signs, beacons, landmarks) and certified digital traffic regulations), to create maps. The created map is then provided to the service providers which use it in their vehicles. There is also a feedback process proposed, where the service providers get feedback from their vehicles/users and communicate it back to the map providers, which pass it to the National Access Point, where it is available for the road operators.

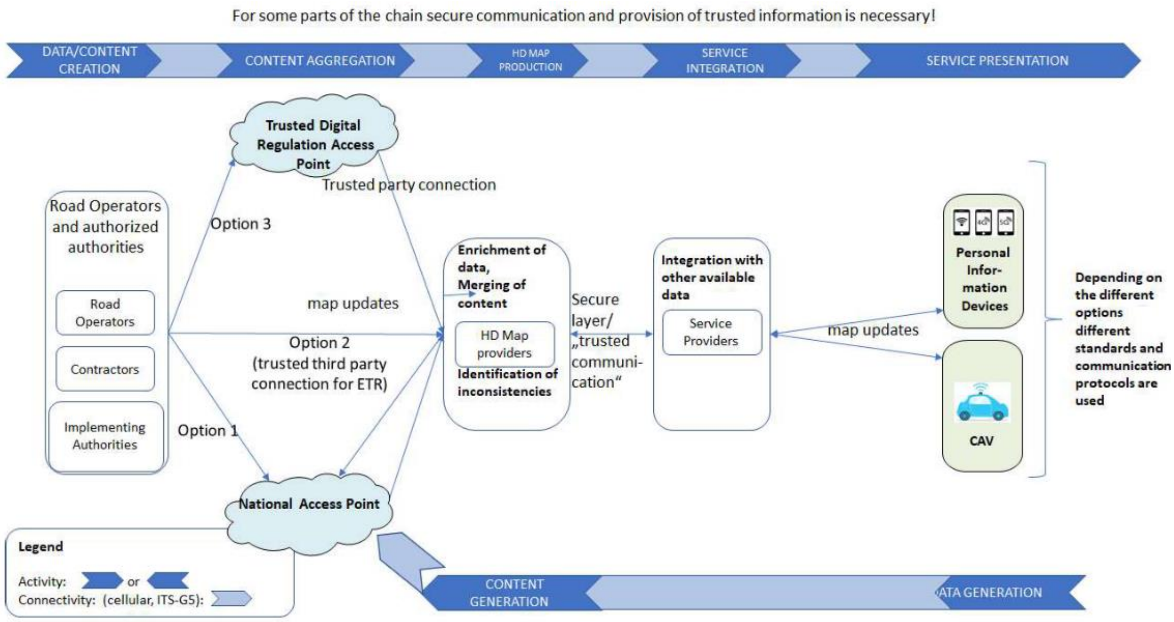


Figure 2: Process Flow diagram for Provision of High-Definition maps for automated mobility

Figure 51: Process flow diagram for provision of digital dynamic maps developed within the DIRIZON project. [136, p. 21]

Another open issue in the data ecosystem is related to the role of C-ITS standards. While the OADF simply ignores C-ITS (as well as the EU-driven DATEX II standard for data exchange), some vehicle manufacturers such as Volkswagen [155] already equip their new vehicles with ETSI ITS-G5 technology. Although the EU delegated regulation for making ETSI ITS-G5 mandatory for all new vehicles has not been adopted by the European Commission, the technology will play a certain role, either as ETSI ITS-G5 or as C-V2X. In the DIRIZON project [136] either cellular or ITS-G5 connection are included for map data communication (see Figure 51).

Map generation techniques

There are different techniques available to generate maps when focusing on how to map the area and the further data processing. It is important for the resulting maps that the accuracy reaches a certain level and the effort and costs also play a role. According to [148, pp. 364–365] satellite imagery, aerial mapping, field surveying, terrestrial laser scanning or mobile laser scanning can be used:

- Satellite imagery can reach an accuracy up to submeter level, with 0,34 m from GeoEye or 0,31 m from Worldview while having small production efforts. The obtained recognition accuracy with multispectral imaging is 80-90% on average. This accuracy might be enough for road furniture, but for the road geometry and lane geometry a 10-20 cm accuracy is necessary (see accuracy requirements in Table 39). Moreover, with satellite imagery comes a strong dependency on cloud coverage.

- Aerial mapping is based on photographs from airplanes, helicopters or balloons, and nowadays also unmanned aerial vehicles. For deriving digital orthophotos, which are not distorted by the perspective and height effects, aerial laser scanning can be used additionally during data capturing. In research and technology, the goal is to generate homogenous high accuracy maps with minimal fieldwork using photogrammetry. Drones are very flexible for capturing the area, but are also depending on weather, and shadows can occur. They can also be used to detect the road quality. The geometric resolution of photogrammetry is at cm-dm level.
- Field surveying is a technology, where maps are drawn by surveyors with the use of measuring distances and GNSS. The resulting maps are the most precise (reaching cm to mm level accuracy), but the data acquisition is very slow and also costly. Field surveying is therefore not a suitable method for HD mapping.
- Laser scanning uses LiDAR instruments for capturing the world around in a point cloud. With terrestrial laser scanning, one or more fixed position LiDAR instruments are used, reaching mm resolution and cm-dm absolute accuracy (absolute: on the whole Earth). The more common mobile mapping uses vehicles equipped with LiDAR, positioning systems (GNSS, IMU, odometer) and cameras for mobile laser scanning. This is considered the most efficient way, concerning data capturing capability, accuracy and cost. But still, a lot of data is generated, which leads to challenges in storage and data processing and also the equipment is costly.

As mobile laser scanning is the most usual data acquisition method [133, p. 317], we describe a couple of approaches in more detail:

In [156] a method for generating horizontally curved driving lines with point cloud data from mobile laser scanning was proposed. First the road surface is extracted, followed by a road marking extraction and then the driving line generation. This results in a map containing the road geometry and driving lines, where the driving lines (limited to circular horizontal curves, no complex and spiral curves as they occur at intersections) reach a 15 cm level localization accuracy. The dependency on good road markings is high.

In [157], already published in 2015, LiDAR was combined with prior maps to reduce the time for mapping as roads only have to be scanned once, instead of once per lane. They reached an accuracy with a mean error of 0,06 m and a maximum error of 0,22-0,38 m (depending on the filtering method).

Joanneum Research [158] published their approach of mobile mapping, which also only needs one test drive (per direction). To avoid shading due to other vehicles, they used escort vehicles which hindered other participants from overtaking (their test track was on a highway). With the proposed method they estimate reaching an optimum accuracy of +/- 2 cm, while with bad GNSS signal the accuracy might exceed +/- 10 cm (e.g. in urban stop and go traffic with shading and multipath because of buildings). For processing the data and generating the map, they propose the following workflow: First the trajectory of the mapping vehicle must be calculated, then the mobile mapping data is georeferenced, followed by a definition for a data structure scheme. They chose to follow the Road2Simulation guidelines. The point cloud is then evaluated semi-automatically with the software ORBIT GT Feature Extractor, which for example allows to extract lane markings automatically with a manually defined starting point.

Overall, the process of ground mapping consists of three steps: data acquisition (surveying the environment), data processing (mainly feature extraction) and database management (for map access and management). [143, p. 3]

The high cost of generating maps with LiDAR instruments also lead to other mapping solutions. In [159] a method was investigated, which uses low-cost sensors like cameras instead of LiDAR instruments. However, they still experienced errors up to 0,4 m when comparing their synthetical orthographic image to the manually labelled ground truth, which is not accurate enough for HD maps.

For the future, Jiang et al. [133, p. 317] conclude that the information will be extracted from user data with AI, and therefore reduce the construction costs of HD maps.

<u>Examples of creating HD maps within SHOW</u>

Within the SHOW project, two partners provided a detailed view of their workflow of creating a digital dynamic map, for Salzburg in Austria and Karlsruhe in Germany. A broader but less detailed overview of HD maps within the SHOW pilot sites is presented in Chapter 7.1.2.

Pre-information on the Lanelet format

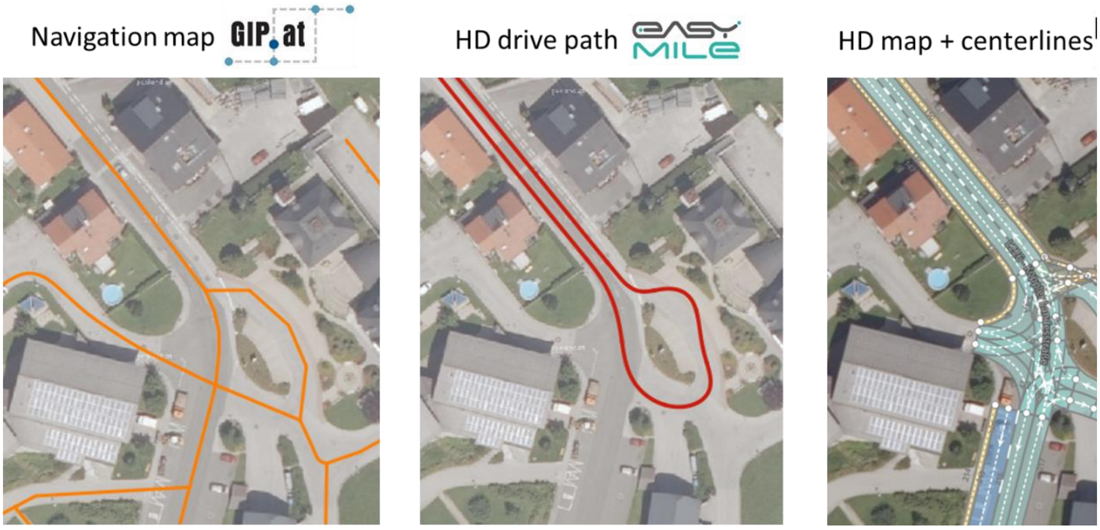
Both SHOW test sites use the Lanelet format, so a more detailed description is given before going into the generation techniques.

Lanelets are atomic, interconnected drivable road segments which may be annotated with additional data. A Lanelet describes an atomic lane segment which is characterized by its left and right boundary. Furthermore, traffic rules are considered static within a Lanelet. The boundaries of a Lanelet are modelled using polylines, which allows an arbitrary precise approximation of lane geometries. By specifying the role of a boundary (left or right) possible driving directions can be assigned. To model traffic rules like traffic signs, the right of way or traffic lights the concept of regulatory elements is used. The general idea is to conceive those elements as own relations which are linked to specific Lanelets. The relations store all information needed to describe the situation. Regulatory elements provide two types of information. On one hand, they provide a rule or a manoeuvre name. On the other hand, they provide all the static information or parameters to obey this rule. At a traffic light, for example, the rule may be stop at the stop line if one of the lights signals a red light and the parameters may be the stop line and the positions of the relevant lights. Other important regulatory elements are traffic rules at intersections without lights. Driving in such situations has to be planned in a way that obstructs other traffic participants as little as possible if they have the right of way.

For the Lanelet format there is C++-Opensource-API available. This API provides direct access to the primitives like Lanelets, Lanelets-boundaries and the regulatory elements. Therefore, the access to the attributes is also given. Furthermore, the API provides useful tools like routing, shortest-path or query by bounding-box. Through the source-code availability for public use special needs could be implemented.

HD map of Digibus® Austria, a project started prior to SHOW at the Salzburg test site

In the Digibus® Austria project (https://www.digibus.at), the Austrian flagship project for automated driving in public transport, one of the main research goals was to specify and optimize the process for generating a HD map for automated passenger shuttles. Automated passenger shuttles such as the EasyMile EZ10 passenger shuttle (for more information see https://easymile.com/vehicle-solutions/ez10-passenger-shuttle) are built to drive along a highly accurate driving path, being annotated with additional attributes for initiating and controlling driving manoeuvres (e.g. speeds, stop points). The usual way to generate this driving path is to start with a manual data collection drive at the beginning of a shuttle deployment, followed by a manual map editing process using a proprietary map editor. The resulting driving path has to be iteratively optimized with several test drives until a satisfying quality level has been achieved. Besides the resource consuming trial-and-error process of optimizing the driving path, the resulting path does not represent common features of an HD map (only the centreline) and due to the proprietary format, cannot be shared between passenger shuttles of different suppliers. The goal in the Digibus® Austria project was to develop and evaluate an alternative way to automatically generate the driving path out of an HD map (e.g. the HD lane model, the HD connectivity model and the traffic regulations).



(a) (b) (c)

Figure 52: Comparison of different digital maps used in the Digibus® Austria: (a) Standard navigation map from Austria's Graph Integration Platform (GIP.AT); (b) HD drive path generated manually by EasyMile; (c) HD map and centrelines being semi-automatically generated by project partners AIT, Prisma solutions and Salzburg Research.

For generating the HD map, a generation process was set up, including the following steps: (1) specification of a feature catalogue, (2) HD data collection, (3) geographic feature extraction, (4) semantic annotation and (5) export of the HD map and drive path (Figure 53). The HD map is exported as OpenDRIVE or Lanlelet2 format (the OpenDRIVE file can also be automatically converted to Lanelet2) containing the driving path as centrelines. Additionally, the driving path alone can be exported as GPX or GeoJSON file with attribute extensions. The resulting driving path can be directly imported to the map editor of the EZ10 passenger shuttle. Beside the standard format, the main benefit of the process is that not only the driving path, but the whole road network is represented as HD map paving the way for executing more enhanced driving manoeuvres (e.g. lane changes).

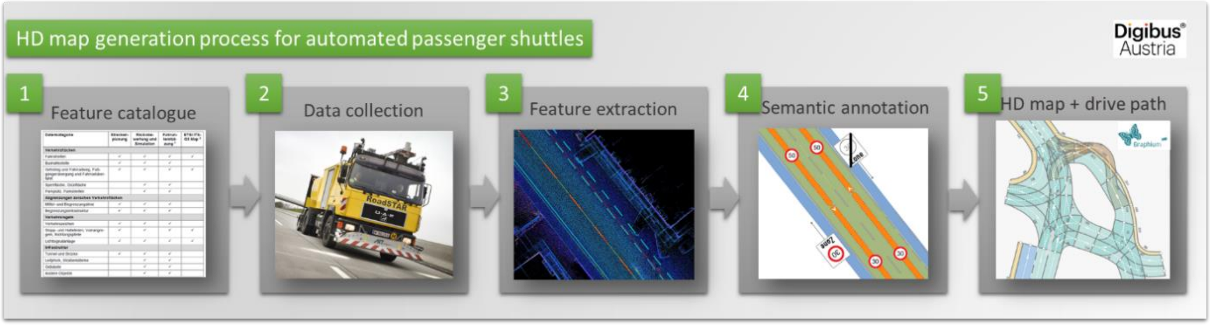
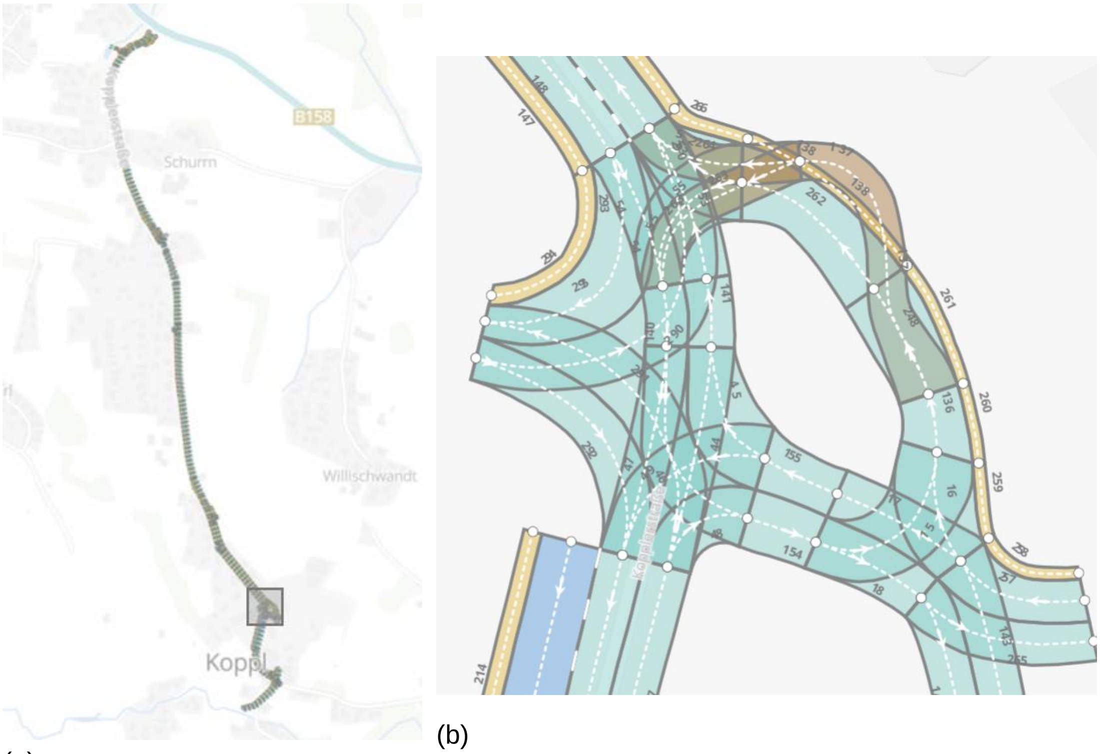


Figure 53: Semi-automated processing pipeline for generating the driving path for an automated shuttle bus out of a HD map

The HD lane model of the HD map consists of highly accurate geometries (<10 cm absolute accuracies of lane markings and lane boundaries) including physical road features along the test track. These features have been extracted from GNSS-referenced LIDAR data being collected with the RoadSTAR vehicle from the project partner Austrian Institute of Technology (AIT) (for more information see https://www.ait.ac.at/en/research-topics/road-condition-monitoring-assessments/road-condition-evaluation). The highly accurate lane model, the lane attributes, the regulatory elements as well as the lane connectivity model have been composed using the MODAL-X software package (for more information see https://www.prisma-solutions.com/en/infrastruktur/) of the project partner Prisma solutions. After composition, the HD map has been exported to the ASAM OpenDRIVE format. Since this format is mainly intended for describing synthetic road networks for simulation, expressing highly accurate geometries of real-world road networks is challenging. Moreover, since OpenDRIVE files at the time of writing can only be edited with commercial software tools, an alternative open format for HD maps was chosen. The Lanelet2 format [137] provides the necessary openness, as well as support for accurate geometries and since the format is based on the well-known OpenStreetMap data format, it can be easily adapted to new requirements and edited with open source editors such as JOSM. Therefore, the Lanelet2 format is increasingly adopted by the automated driving community, e.g. being integrated into the open source automated driving software Autoware.AI (https://www.autoware.ai/) or LGSVL simulator (https://www.lgsvlsimulator.com/)). In the Digibus® Austria project, they converted the OpenDRIVE file with the open source OpenDRIVE2Lanelet-Converter (https://pypi.org/project/opendrive2Lanelet/) implemented by the Technical University of Munich [160]. Although at the time of writing, the converter does not support all elements from ASAM OpenDRIVE, the conversion was successful. The resulting HD map in Lanelet2 format could then be successfully imported into the open source graph management software Graphium (https://github.com/graphium-project/graphium) by Salzburg Research. Within the Digibus® Austria project, Graphium has been extended to manage HD road graphs, being read from Lanelet2 files. Figure 54 shows parts of the HD map generated in Digibus® Austria. The HD map consists of a HD lane model, a HD lane connectivity model (which makes it fully routable) and a HD centreline (white dotted lines) for each Lanelet. These centrelines are automatically generated during import. In order to generate the driving path, the HD route from the start bus stop to the destination bus stop is calculated. The driving path consists of all centrelines of all connected Lanelets which have to be traversed along the route.



(a) (b)

Figure 54: (a) 2 kilometers long HD map of the Digibus® Austria test track in the village of Koppl (near the City of Salzburg) represented in the Lanelet2 format, visualized with Graphium Viewer. (b) Map extent around Kopple Village center. Color codes: turquoise: roads; yellow: sidewalks and walkways; brown: bus lane or bus stop; blue: parking area; dotted white lines: centerlines

HD map generation at the test site in Karlsruhe

For the HAD function at the Karlsruhe test site a high-precision map is needed. Because the commercially available maps were not precise enough, the FZI had to create their own maps. To do this, the map format should be considered.

For describing the static parts of a driving scene, the FZI decided to use the Lanelet format, which represents the drivable environment under both geometrical and topological aspects.

The second format, that the FZI considered switching to, was the OpenDrive format since it is also capable of an accurate geometrical and topological approximation of the street layout. One big challenge of the OpenDrive format is the lack of suitable editors. Also, there is a Python library for converting the OpenDrive format into the Lanelet format (https://pypi.org/project/opendrive2Lanelet/).

For creating the map, the only company providing precise maps using Lanelets that the FZI knows was the start-up Atlatec. For public roads, the maps can be ordered. With only a few corrections, the maps could be used for their HAD functions; the corrections mostly concerned small offsets of curbs. These adjustments are done by driving through the test-site and recording LiDAR and localization data (SLAM or GPS). The data can be used to detect the curbs, which are needed to adjust the Lanelets.

For non-public roads, the workflow of creating HD maps at the FZI is as follows:

1. If no LiDAR/GPS-Data is available, satellite images are used to create a rough prototype of the Lanelet-map.

2. At the test-site the FZI records data of the site, for example dGPS-Data from driving close the curb or at best record LiDAR-Data.
3. These LiDAR-Scans are accumulated, so the Lanelets can be modelled precisely to the curbs. The *static information* layer as defined in this deliverable would be satisfied after these two steps.
4. After modelling the geometric layout of the map, the semantic information like right of way, traffic-lights etc. is annotated. This would be represented in the in this deliverable defined layer *Traffic regulations.*

If inaccuracy occurs, e.g. caused by wrong LiDAR-Calibration or GPS-Drift, the steps 2-4 are repeated. This process is the most time consuming. The most problems occur when they are testing the HAD functions and it turns out they have to tune the maps. The *quality information* and *dynamic real-time information* layer as defined in this deliverable are not used/implemented in the current workflow of the FZI.

Updating HD maps

Map updates are considered important, as deviations between the physical environment and the map can cause problems for autonomous driving, like the planning system making an incorrect decision on the behaviour and trajectory due to relying on out-dated maps [143, p. 2].

The reasons for changes can be classified into the following categories [161, p. 11; 30]:

- Changes due to constructions sites,
- Changes without a construction site and
- Mapping errors (caused by data errors or update errors).

Changes due to construction sites are considered easy to detect, because signs, beacons or changes in the lane marking colour indicate construction sites, whereas for the latter two there are no such indicators. Also, road authorities know when road works occur.

The 5G-MOBIX project [162, pp. 38–39] tests generating updates at construction sites. First the vehicle gets the notification from an ITS-Centre about the work zone. If there is no updated map yet available, the driver will take over control and from the perceived sensor data, which is sent to the ITS centre where the changes are saved within the map and sent out to the other vehicles.

For the other two types of changes, Pannen et al. [163] proposed an approach based on floating car data.

Map changes can also be classified into two types [143, p. 4]:

- Physical feature is new, and
- physical feature is deleted.

If a physical feature is moved, it is new in one place and deleted in another. Jo et al. [143] describe two approaches for keeping maps up to date: Firstly, using mapping vehicles, which is considered too expensive and not agile, because the frequency and range of operation is limited for these vehicles, and secondly using perception and localization of individual vehicles. Pannen et al. [163, p. 2288] also state, that the frequency of measurement drives provided by special vehicles is not enough for map updating, as for example HERE had 200 cars worldwide at the end of 2015. Jo et al. [143] proposed a simultaneous localization and map change update algorithm that detected 100% of missing and 92% of the new features, features representing traffic signs in the experiment.

However, there are not only map updates for physical changes. As some file formats are huge in file size, the map can be split into tiles and provided as needed via updates [183]. This is currently investigated in the 5G-CroCro project [184].

Summary

As reported by the literature, a data ecosystem for digital dynamic maps for automated driving will consist of the following parts:

- Static map layers (road model, lane model, including traffic regulations: semantics/traffic rules)
- Quality layer (initial road quality, being updated with vehicle information; map priors, being derived from real-time data)
- Dynamic real-time layer (updating dynamic attributes).

Most probably, the static HD map will be generated by measurement vehicles, as the data accuracy has to be very high. But there might be approaches on the way using orthophotos or unmanned aerial vehicles to provide data for the static layer. Traffic rules are now presented with physical infrastructure but could also be mapped with information provided by the authorities. The map will be hosted on the backend (either by private map providers or public road authorities).

Although named static, the static layer will be only pseudo-static since the world is constantly changing and the HD map has to be regularly updated. This will be done by getting map updates or information on changes from road authorities (since they typically know first that something will change), and by interpreting sensor data from vehicles.

Additionally, the HD map will be enhanced with quality information and map priors. The quality information builds upon road quality with information on e.g. skid resistance or road grip, or verification of traffic signs (occurrence and visibility). The map priors will be derived from vehicles' sensor data, being transferred as pre-processed data stream from vehicles to the backend (e.g. via the SENSORIS interface).

There will be at least one but probably several data channels for transferring relevant parts of the static HD map to the automated vehicle (e.g. HD map delivery for a planned route or for a certain operation area). The same will be true for data channels delivering real-time or live data (which has to be referenced to the HD map). These channels could be long range (e.g. cellular) or short range (e.g. V2X) channels. All data streams have to be merged in the vehicle to a local dynamic HD map which holds all the relevant data for the automated vehicle needed for planning and executing driving manoeuvres. A difficult challenge in this context is to guarantee data integrity and data quality.

7.1.2 Implementation of digital dynamic maps within the SHOW project

The status on digital dynamic maps in the SHOW project was investigated via interviews and questionnaires conducted with the SHOW test sites. 11 Mega and Satellite sites gave information, whereas of these, three sites stated that either they do not use digital dynamic maps (Turin), it is too early to give any information (Copenhagen) or no detailed information (the filled-out questionnaire) could be provided (Trikala). The other 8 mega and satellite sites (Graz, Salzburg, Karlsruhe, Aachen, Rouen, Madrid, Brno, Tampere) were able to provide information on the maps used at their sites. For the methodology of deriving the following insights including a description of the questionnaire, please see Chapter 2.2.2.

Some test sites have provided more than one answer, as they have different maps. The Aachen test site has one map for operation, provided by the operator, which will be referred to as Aachen_O and one map for research purposes (Aachen_R). From the Tampere site, there were questions answered by sensible4 regarding their maps used (Tampere_s4) and by SITOWISE referring to their digital twin (Tampere_DT). At the Trikala site, they have a map which will be created using the robot-buses, and additionally AutoCad-files (no other information given). The Salzburg site provided answers for their self-created HD map, but also gave insights on how EasyMile creates their maps, which are not fully considered as maps here as it is basically a trajectory with driving instructions.

Most of the used HD maps at the pilot sites are generated during measuring the route on a test drive. Mostly LiDAR sensors were mentioned to being used. The test drives are done with the used AV at the majority of the test sites (Graz, Aachen_O, Rouen, Tampere_s4, Trikala), some use extra measurement vehicles (Salzburg) and some did not specify (Aachen_R, Brno). Brno could not specify whether the point cloud data will be used to get maps from the provider Apollo or will be used to create the map themselves.

The pilot sites, which do not use test drives (with LiDAR) are Madrid, where they built their map from orthophotos provided by the Spanish national institution for geography, and Karlsruhe, who derived their maps from Atlatech, which build upon OSM and were then adjusted by the FZI for their needs. For the digital twin in Tampere, they combined aerial photogrammetry (provided by the City of Tampere and Tampereen infra Oy) and a tramline simulation model (from City of Tampere and 3D Talo).

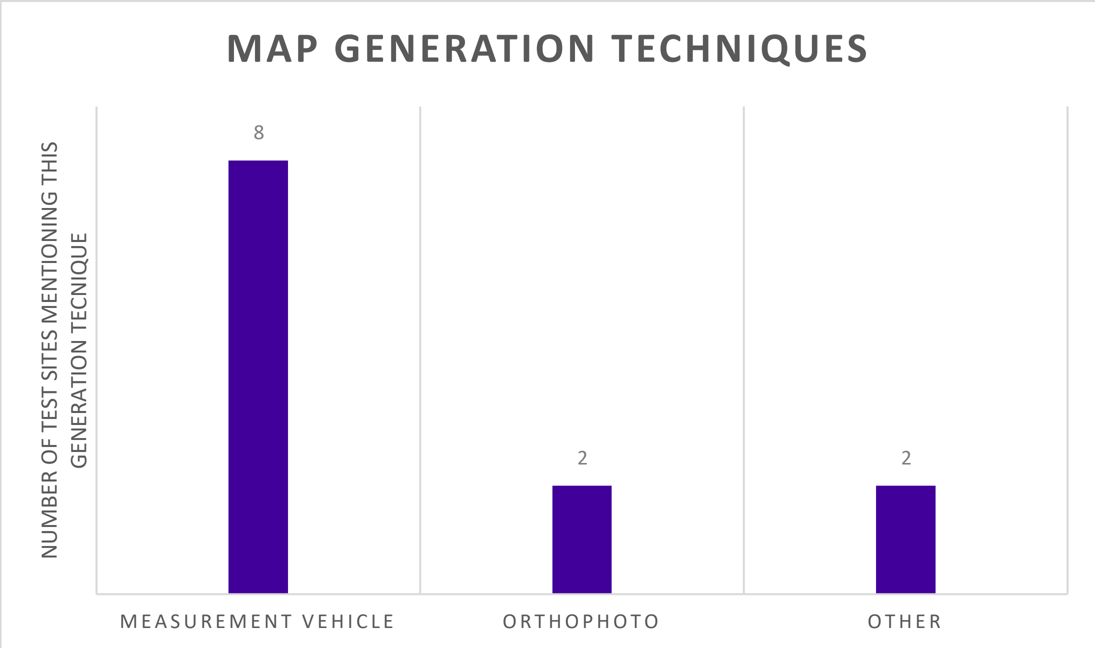


Figure 55: Map generation techniques used at the interviewed test sites.

The formats used are Lanelet or Lanelet-inspired formats, as well as proprietary formats as defined by the vehicle operators, QGIS or ArcMap approaches, OpenDRIVE, NDS or Fbx. The Brno test site had, at the time of the interview, not decided if they would use NDS, OpenDRIVE or a GIS approach for their maps, this is why there are more formats listed. Also, Salzburg has their map available in OpenDRIVE for simulations and in Lanelet2. The map for research purposes in Aachen can also be exported from their QGIS vertices and edges into GeoJson or Lanelet – but this was not considered as a used map format. The Madrid test site responsible reported discussions on using standard formats such as OpenDRIVE or Lanelet2 (currently using a self-made Lanelet-inspired format) in the future.

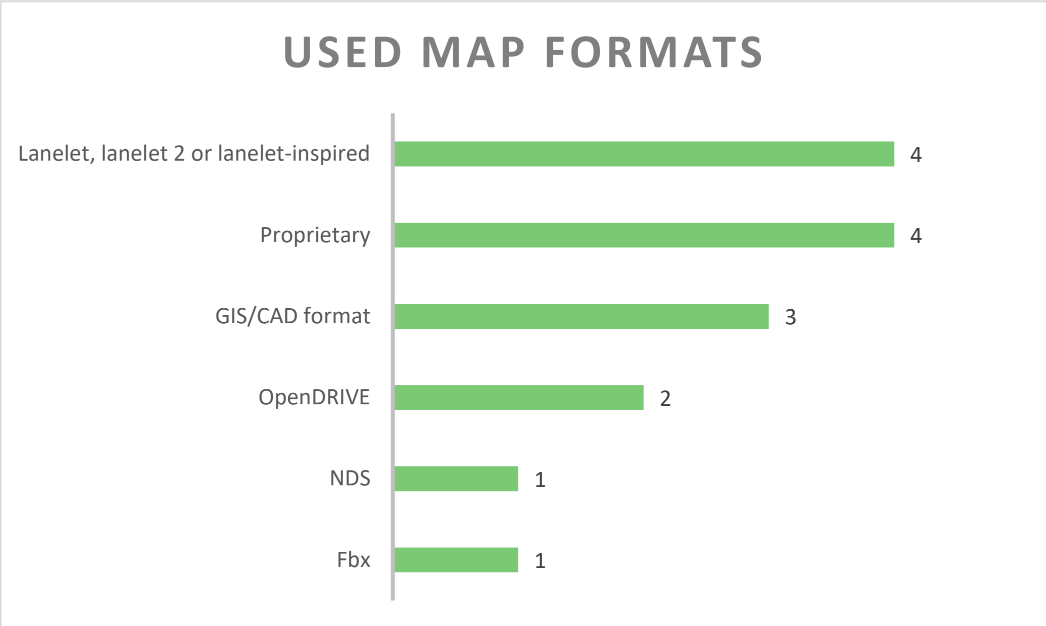


Figure 56: Map formats used at the interviewed pilot sites.

It is known that the sensible4 maps used in Tampere_s4 are maps containing probabilistic distributions and are therefore not considered HD maps, per our definition. But, as other approaches should be discussed here too, we will keep Tampere_s4 in our analysis, to identify potential differences. Also, the operator's map at Aachen_O is considered to be more of a density map than a planar HD map.

For managing the maps, JOSM was mentioned, which is a free OpenStreetMap editor for Lanelet(2), as well as QGIS (by Aachen_R) and Graphium (by the Salzburg test site, for managing map-matching). Tampere_DT listed Autodesk products or Unity, or any other software that can process 3d textured Fbx. A lot of test sites also stated that the tools are proprietary, e.g. at the Rouen test site, they work with different vehicle providers and therefore have four different technologies. Currently, they are figuring out which functionalities are the same. Overall, it can be concluded that the management tools depend on the format used and vice versa.

The HD maps are used at the test sites for the following purposes:

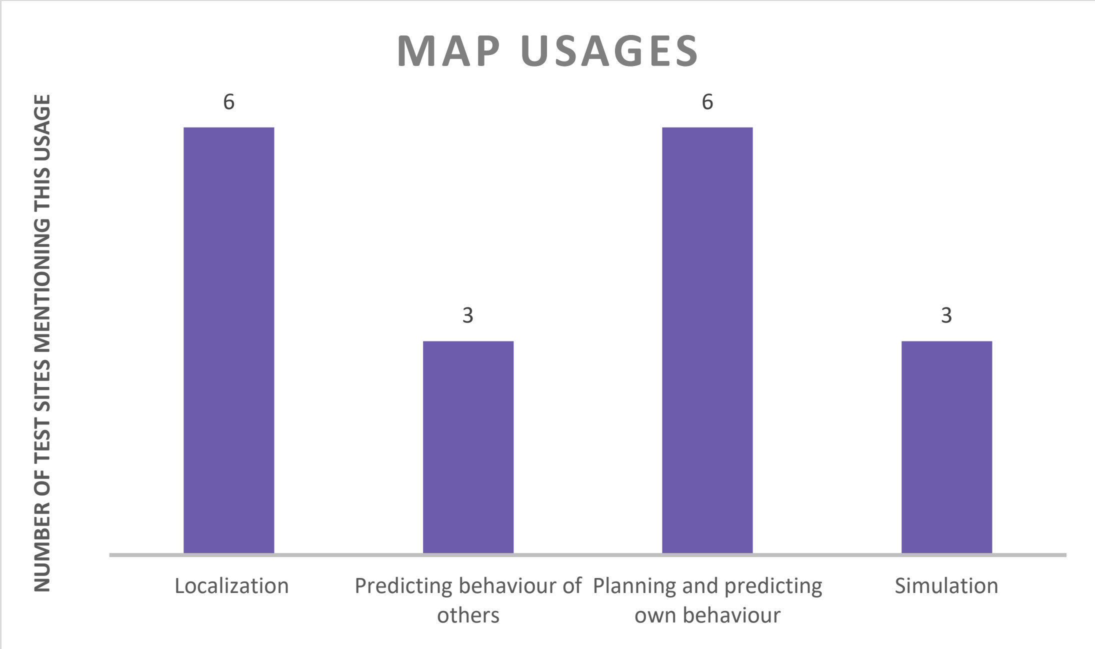


Figure 57: Map usages at the interviewed pilot sites (naming more than one possible).

For localization, some test sites (Karlsruhe, Aachen_O, Tampere_s4) mentioned that this will be done with a LiDAR (density) map, which is a different approach for localization than those proposed in Chapter 7.1.1. Other test sites mentioning the map to be used for localization were Salzburg, Aachen_R, Rouen and Madrid. Predicting other road users' and objects' behaviour is a usage for the test sites in Aachen_O, Karlsruhe, Madrid. The category "Planning and predicting own behaviour" covers driving path generation and adaptation during driving as well as decision making, which is performed by using the map in Aachen_O, Aachen_R, Rouen, Madrid, Karlsruhe, Brno. The map is utilised for simulation at the Salzburg, Madrid and Tampere_DT test sites.

The contents of the HD maps vary at the pilot sites, but still an attempt to categorize them into the four layers of a digital dynamic map as specified in this deliverable was made. A category called "Virtual track" was added, as some test sites mentioned this specifically. The results of the categorization are shown in Table 40. It can be summarized that all interviewed pilot sites have a static layer and most of them have traffic regulations displayed (at the Tampere_DT test site the semantics are not included, which is denoted with *(x)*). Quality information – as defined here as either information on the road condition or the condition of traffic signs, as well as map priors – is not used in any maps at the interviewed SHOW pilot sites. Dynamic real-time information is used at some pilot sites, but mostly not integrated in the map (denoted with *(x)*).

Table 40: Contents of the HD maps at the interviewed SHOW pilot sites categorized into the four map layers.

Test site	Virtual track	Static layer	Traffic regulations	Quality information	Dynamic real-time information
Graz	x	x	Not sure at the time of the interview		

Test site	Virtual track	Static layer	Traffic regulations	Quality information	Dynamic real-time information
Salzburg	x	x	x		(x)
Aachen_O	x	x	x		
Aachen_R	x	x	x		
Karlsruhe		x	x		(x)
Rouen		x	x		(x)
Madrid		x	x		(x)
Brno		x	x		
Tampere_s4		x	x		(x)
Tampere_DT		x	(x)		x

The different contents per layer are analysed separately in more detail for the test sites in Table 41 to Table 44.

Table 41 and Table 42 show the additional category virtual track and the category static information. These categories overlap somehow, as the virtual track is not part of the layer concept, but somehow represents static information. Also, traffic regulations (Table 43) can be presented within the virtual track. The test sites which mentioned having a virtual track were Graz, Aachen_O and Aachen_R. At the Salzburg test site, they can generate the driving lines (in the centre of the lanes) out of the HD map. At the test site Aachen_O a reference trajectory exists, containing the position and velocity. The map used in Aachen_R contains a driving path, which is described by its left and right boundaries – this could be categorized as a virtual track or static information, as the boundaries form street geometry. The existing reference velocity profile for the path can be seen as part of the virtual track or the traffic regulations layer. At the Graz test site, they have a virtual track and a simple representation of the street geometry. Street geometry is considered as static information, which is also represented at the test sites in Salzburg, Karlsruhe, Madrid, Rouen, Brno and Tampere_DT (Table 41). The Rouen test site also mentioned landmarks and 3D points being included in the map, whereas in Brno trees and buildings will be added to the map, if necessary. Buildings and textures are represented in the map of Tampere_DT. The maps of Aachen_O and Tampere_s4 both represent static information differently, as it is either a density map including semantic areas of interest (like crosswalks or intersections), or a 3D map with probabilistic distributions, not physical features.

Table 41: Digital dynamic map contents at the interviewed SHOW pilot sites: Virtual track.

Representing a virtual track (4 of the interviewed test sites)	
Graz	Virtual track, plus simple representation of the street geometry (static information)
Salzburg	The centrelines for driving can be generated from the map.
Aachen_O	Reference trajectory (position and velocity)
Aachen_R	Driving paths (right and left boundary for all directions and roads) + reference velocity profile for ego path

Table 42: Digital dynamic map contents at the interviewed SHOW pilot sites: Static information.

Representing static information (all interviewed test sites)	
Graz	Street geometry
Salzburg	Street geometry
Aachen_O	Density map storing static environment, semantic areas of interest (crosswalks, intersections)
Aachen_R	Driving paths with right and left boundary for all directions and roads
Karlsruhe	Street geometry
Rouen	Street geometry (including 3D points), landmarks
Madrid	Street geometry
Brno	Street geometry (+ trees and buildings if necessary)
Tampere_s4	3D map containing not directly physical features but probabilistic distributions
Tampere_DT	Street geometry, buildings, textures

Table 43 shows the traffic regulations layer. This layer is represented at almost all test sites. The test site in Graz could not give information on that at the time of the interview. Within the Tampere_DT map traffic signs are included, but not their meanings. This is because the map is used for simulation only, and depending on the simulation purpose, the restrictions can be applied independently. The majority of the test sites (Salzburg, Karlsruhe, Rouen, Brno and Madrid) stated, that they (will) include traffic regulations in their maps and did not mention any special representation. Both test sites in Aachen include the traffic regulations to some extent within the reference trajectory or ego path, but in Aachen_R traffic signs are also included in the map, whereas in Aachen_O areas of interest are used for representing right of way. The Tampere_s4 map also includes traffic regulations within points of interest (like crosswalks or intersections).

Table 43: Digital dynamic map contents at the interviewed SHOW pilot sites: Traffic regulations.

Representing traffic regulations (almost all interviewed test sites)	
Graz	Not sure at the time of the interview
Salzburg	x
Aachen_O	Right of way with defined areas of interest, speed limits in reference trajectory
Aachen_R	Traffic signs, velocity profile on ego path
Karlsruhe	x
Rouen	x
Madrid	planned
Brno	x
Tampere_s4	Included in points of interest (e.g. crosswalks, intersections)
Tampere_DT	Road markings and traffic signs are displayed, but no meanings of traffic regulations

Table 44 shows the non-representation of quality information at the interviewed SHOW test sites, as none of the interviewed stated, that they included quality information like road surface quality, skid resistance or detectability of traffic signs within the map. Map priors were not asked, as these came up after setting the questionnaire on digital dynamic maps. But it is assumed that they are not represented at the test sites as nobody mentioned them at any other point.

Table 44: Digital dynamic map contents at the interviewed SHOW pilot sites: Quality information.

Representing quality information (0 of the interviewed test sites)
No interviewed test site stated to use quality information.

In Table 45 the use of dynamic real-time information at the interviewed test sites can be seen. Three test sites mention the traffic lights' status, but it is communicated via V2X or V2I not within the map. The Rouen test site also mentioned that dynamic data is being used, but not funnelled within the map – as the added value is questioned. At the Salzburg test site RSUs are used to help with perception, but this does not seem integrated within the map. The only test site using dynamic real-time information is Tampere_DT, which uses local time and weather data within their simulations. The other interviewed test sites stated that they did not use dynamic real-time information at the time of the interview.

Table 45: Digital dynamic map contents at the interviewed SHOW pilot sites: Dynamic real-time information.

Representing dynamic real-time information (6 of the interviewed test sites)	
Salzburg	ITS-G5 via RSU, helping with perception
Karlsruhe	Traffic lights (connected via V2X) are mapped with their IDs, communication unknown by time of the interview
Rouen	Dynamic data is available but not funnelled in the map
Madrid	Traffic lights' position is read from the map, traffic lights' signal is communicated via V2X
Tampere_s4	V2I at traffic lights
Tampere_DT	Local time and weather data (Separate from the geometry, only included in a local executable)

To ensure data quality, test sites often rely on testing (which results in manual adaptations in case of problems) or manual verification. Crosschecking the map with sensor information was mentioned by the Madrid test site, while Tampere_DT used two sources for generating the map (aerial imagery and GIS data provided by the City of Tampere) for data quality. The quality should be improved by using mobile scan data in the future. At the Salzburg test site, the sensor data from data acquisition was compared to over 400 manually measured reference points. Having good GNSS while collecting data was considered a top priority for data quality by the Rouen test site. The Karlsruhe site relied on high quality data from their map provider (Atlatech).

Updates are not tackled directly in a frequent manner at the test sites, but this can also be due to the fact that mostly static information is represented, which is not found to be changing regularly. If changes occur, they will be recognized by the vehicle and the map will be adapted manually. The Salzburg site responsible noted that the changes noticed due to map-matching can also occur because of bad location quality. The Brno test site reported that the routes will be quite small, so they will notice changes quickly, and as they consider an updated map necessary, they are even planning on having an extra toolset for updating the map (besides the tools for mapping). For the Tampere_DT map, updates are not planned as the map is just used for simulation. The Madrid test site stated that there will not be any significant changes in the test location, but permanent small traffic intrusions like road work signs and space blockages can be modelled as obstacles into the map. Tampere_s4 and Rouen sites mentioned that there is also the possibility of generating a new map when needed. For the future, the Salzburg site discussed generating two maps for different seasons, because the trees can be very different and lead to errors in map-matching.

Besides the digital dynamic map, the pilot sites were also asked about their future plans or goals for the maps or current challenges, which are listed as follows:

- Automating the process for feature extraction from point cloud (currently semi-automatic)
- Getting HD maps as point cloud data
- Adding mobile scan data to the map
- Using public HD maps
- Goal: Map should represent the environment, not more – the vehicle does everything else
- Goal: Mapping all possible routes and use the map to program the shuttles, so changing routes is possible.

- Adjusting the maps to own needs is more important than generating the map (for PTOs)
- Going from driving on virtual track (fixed line) to virtual lane (drive within lane boundaries) technology
- Unknown questions about what software will be standard, or what maps will be used for and if, how acquisition can be automated.

It can be summed up that digital dynamic maps are utilised in the majority of the SHOW test sites. Some are using them for localization, while others rely on LiDAR for this purpose. They make use of the map for simulation or predicting other road users' behaviour or generating and/or adapting driving lines instead. For these purposes, the maps consist of a static layer with traffic regulations – more or less for the whole route or only the driving path. Quality information is not yet being used at all, while dynamic real-time information is not used within the map. In Chapter 7.2 we will describe the benefits of using this data and propose a workflow on how to include it in the digital dynamic map.

7.2 Semi-automated workflow for setting up a DDM

This chapter used the information gathered in Chapter 7.1 to devise a workflow (expressed as a series of steps) that will allow for the setting up of a digital dynamic map (DDM or DD-map), including dynamical information, to be used by (connected) autonomous vehicles or (C)AVs (see for instance [165], [166] for discussions). The workflow is "semi-automated" in the sense that the acquisition and management of the different data sources of a DDM can be handled by specified measurement procedures and added to the DD-map automatically (which is of particular importance for the dynamic data aspects) or manually (for the basic set-up of the map).

In the following, we will assume that geolocalisation (via Global Positioning System (GPS) or Simultaneous Localization and Mapping (SLAM)) of at least the measurement-vehicles/test-driving vehicles can be achieved with sufficient precision for creating a map that a (C)AV can subsequently operate on (see [167], [168] and [169], for a discussion of some of the challenges and opportunities in localisation of CAVs).

The map data structure had been initially specified to consist of 4 layers: static information (the basic structure of roads and lanes/the road geometry), traffic regulations/rules (road signs, right of way, speed limits), quality information (skid resistance, driving comfort) and dynamic real-time information (current traffic, weather, current road blocks). Alternative structures of map layers have been proposed, for instance in the form of the 5 layered Lyft-pyramid (see Chapter 7.1.1). Within this chapter we will stay within the originally proposed layer structure (see Figure 58: below).

Layer Structure

- 4 Layers were specified in the initial phase of the project preparation:

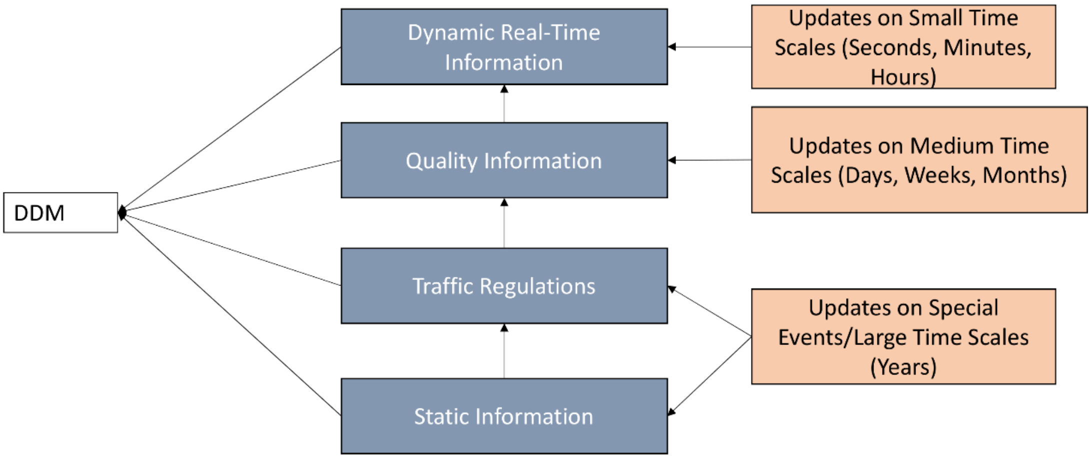


Figure 58: The structure of map layers as envisioned in the proposal with added assumed update frequencies.

A distinction between types of map information within those layers can be made, depending on the time scales they need to be updated. Categories could be "slow changing/static" (changes on the scale of years or only following special events, like the road/lane structure itself, or the meaning of road signs), "medium term changing" (changes on the scale of weeks or months, such as road quality or the presence of road signs/traffic signals) and "fast-changing/dynamical" (such as current weather, traffic information, operation infrastructure availability and road blocks). These correspond roughly to the static layer (static information), traffic regulations/rules layer (static information), quality information layer (medium term information) and dynamic real-time layer (fast changing information), though the feedback between different types of information can make strict separations difficult or impossible.

The fundamental models in the context of static information and thus in a sense the foundation of the DDM are the road model and the lane model. The lane model is assumed to consist of information that is to be represented on a lane (segment) scale: Lane widths (with high precision e.g. <10 cm) and connections between lanes/lane segments (which are of particular importance at intersections). It provides the basis for matching several types of information to a digital model of the physical lane (speed limits or other regulations, road condition information). The road model is assumed to be a coarser representation e.g. a road graph, providing larger scale connections and distances to be used in routing. It provides the basis to align with traffic information or weather warnings, for instance. Examples from the literature can be found in the works discussed in Chapter 7.1.

Two partner test sites (Salzburg, Karlsruhe) provided us with detailed descriptions on their map set-up, which both required high-precision lane models of the area of interest. The same partners also provided us with information on the used data formats, which can be found in Chapter 7.1. For the workflow consideration, we will only rarely reference any given format, except for a few times when we explicitly speak of the lane model of the DDM.

The core challenge of a digital dynamic map is to keep the changing information up to date (see [170] and [171] for an illustration of the challenges of updating, with [171] covering the general aspects of DDMs as well). To manage this, we propose automatable procedures to include current information in the map structure (update loops, which should become increasingly automated).

Current implementations of the maps appear to be focused on the static layer and the traffic rules, by the definitions of the initial proposal. Therefore, we could not yet draw from practical experience in the management of the dynamical layers. Thus, the shown workflow must remain conceptual in its nature and only point to automatable steps in the procedure but cannot provide an example tool or tool chain for dynamic map creation.

7.2.1 Workflow Structure and Map Set-Up:

We assume an initial block of setting up the map (creating the static layer and the traffic rules), followed by a structure of (automatable) updating procedures, to keep the different layers up to date. This core structure can be seen in Figure 59.

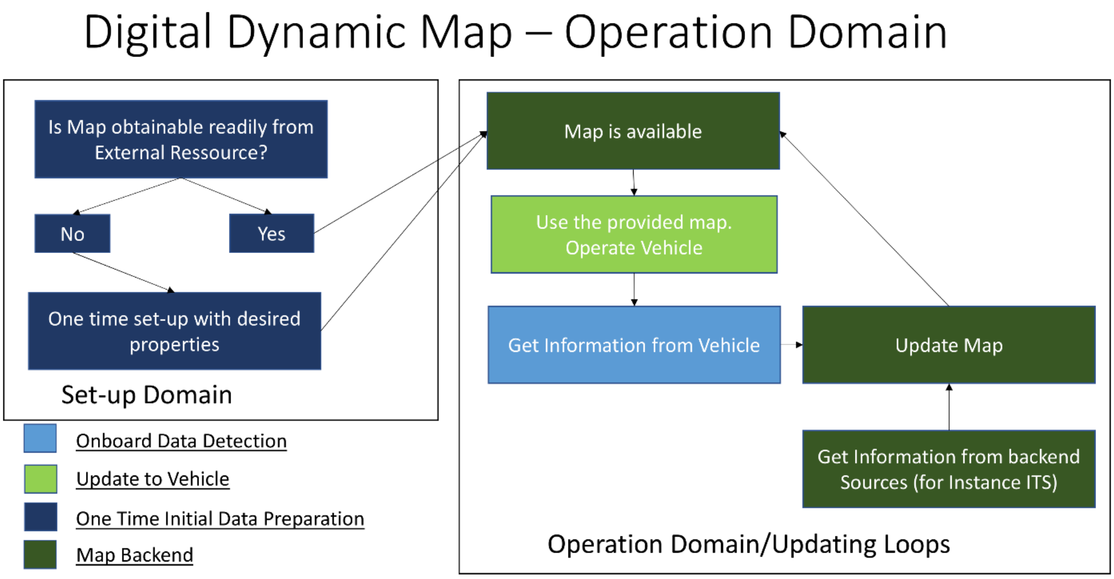


Figure 59: After being set up initially, the digital dynamic map is in a constant loop of updating information, based on diverse sources (vehicle information in light blue, backend information in green). Existing intelligent transportation systems (ITS) would be very valuable to contribute to the flow of real-time information.

Relevant information may be computed/obtained at a map-management-backend or within the vehicle, the preferred variant of which is primarily a matter of how powerful on-board systems can feasibly be and how much more efficient a shift of some planning (routing, traffic information) to a map backend is found to be. We aim to identify components of the map that might be feasibly managed in the map backend and provided to the active vehicles periodically or upon request.

Assuming a Digital Dynamic Map is not already available from a map storage, one might proceed by extracting a road graph from an existing resource like Open Street Maps (OSM) or an orthophoto (see [172] for a discussion). If the orthophoto is of very high quality, it may even be possible to derive a sufficiently good lane model from the photo alone, if the CAV sensors can deal with the resultant imprecisions. Depending on the level of detail required (for instance of errors below 10 cm in the lane description), it may be necessary to acquire the lane model through test drives with specially equipped vehicles, following steps as in Figure 60.

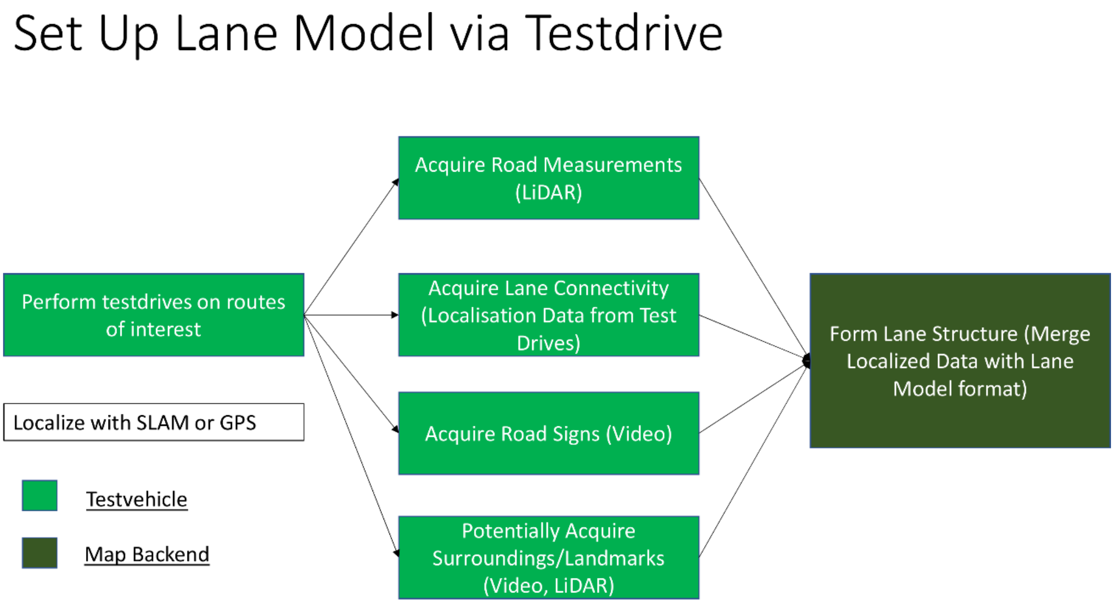


Figure 60: Lane model information a test vehicle (bright green) may acquire during test drives in the area of interest. Road Measurements might require LiDAR, careful localisation needs to be ensured and video may provide elements like road signs or landmarks.

For a map set up, if the area of interest is included in an existing road-model-scale map (see Figure 61), such as OSM, then after obtaining precise lane measurement, the tool Graphium can be used to combine the lane level information (in the "Lanelet2" format for instance) with the information included in OSM or products based on OSM or other existing maps. This procedure has been successfully demonstrated in the Project "Digibus" and has also been described in Chapter 7.1 (see contribution by Salzburg Research on their map set-up therein).

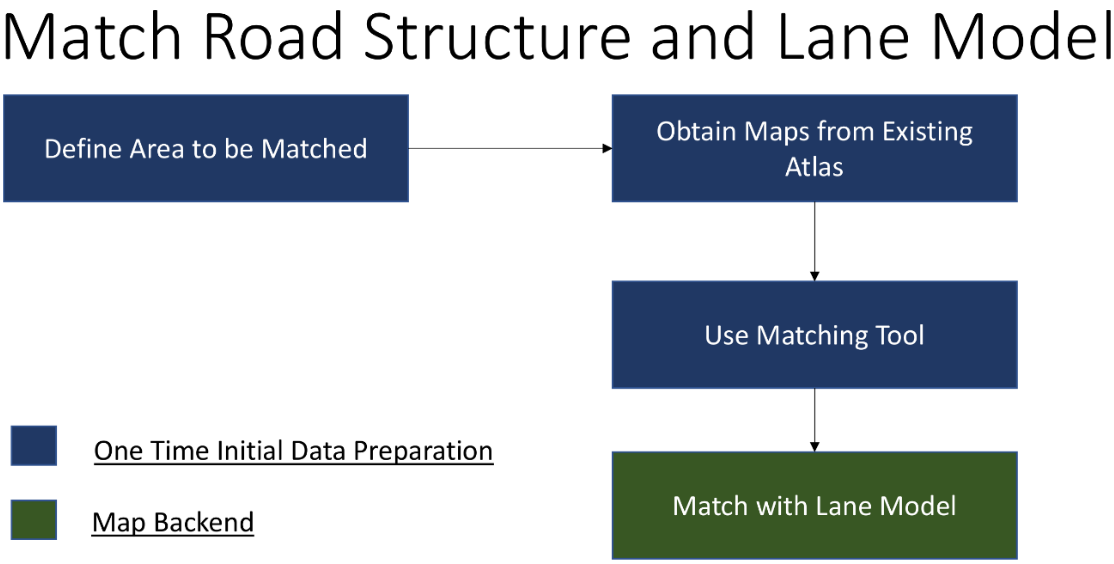


Figure 61: Given the features contained in already existing maps, it can be beneficial to match a detailed lane model with a higher level map structure.

Besides this, a list of requirements based on the properties of the vehicles of interest should be made. The following discussion aims to cover the most important types of information, which may be of relevance to CAVs in general. The identified categories are listed in Table 46 before discussing them in detail.

Table 46: Types of map information to be included.

Data	Model	Scale	Layer	Updating	Measurement
Road Connections	Road Model	Topological (Graph), Distances	Static	Test Drives, manually	Map Data, Test Drives
Lane Dimensions	Lane Model	Several cm	Static	Via Metrics Validations	LiDAR
Lane Connections	Lane Model	Topological (Graph)	Static	Test Drives, manually	Test Drives, manually
Skid Resistance	Lane Model	Meter or cm	Static/Quality	Special Measurements, Vehicle Dynamics	Laser Scan, Mechanical Measurement
Road Signs	Road Model, Location-Type	Local area, Position, Image	Static	Manually, ITS, Object updating	Video, ITS
Road Texture	Lane Model	Meter or cm	Static/Quality	Special Measurements	Laser Scan, Mechanical Measurement
Traffic Rules	Lane Model, Road Model	Local Area, State Traffic Rules	Traffic Rules	Manually, ITS, Object updating	Public Systems, Video, Test Drives
Metrics Validations	Lane Model	Several cm	Quality	CAV Systems, Probe Vehicle	Video, LiDAR, Trajectories
Vehicle Dynamics	Lane Model	Several cm	Quality	CAV Systems	CAN-Bus or similar
Object (Position) Updating	Location-Type	Local area, Position, Image	Quality	CAV Systems	Video, possibly other
Traffic Data	Road Model	Roads, Flow on Graph	Dynamic	(C)ITS, Vehicle Counts, GPS	Vehicle Counts, Traffic Model
Debris/Road Block/Wet Road	Lane or Road Model + Location	Affected Lanes/Roads (Segments)	Dynamic	CAV Systems	Video, Vehicle Dynamics
Communications	Local Area + Road Model	Local Area, Segments in Area	Static/Dynamic	ITS, CAV Systems	External, CAV Systems

Data	Model	Scale	Layer	Updating	Measurement
Weather	Local Area + Road Model	Local Area, Segments in Area	Dynamic	ITS/Weather Data Provider	External

7.2.2 Map Layers

Static Information

The static information layer is supposed to consist of unchanging or only very rarely changing elements. As such, it is apparent that the road map (which roads are connected) should be included in this layer. Considering the necessary level of detail of maps underlying the DDMs, currently lane models, which contain the information of how different lanes connect to one another and how wide those lanes are, are recommended. This could be eased, if lane marking allowed for an easy acquisition of the lane dimensions, either during the process of creating the map or even "on the fly" while driving.

What may also be included in the static information is the position of road signs, landmarks (for positioning and to be validated by the vehicles within the quality information layer) and vehicle operating infrastructure (charging, parking). An overview can be found in Figure 62.

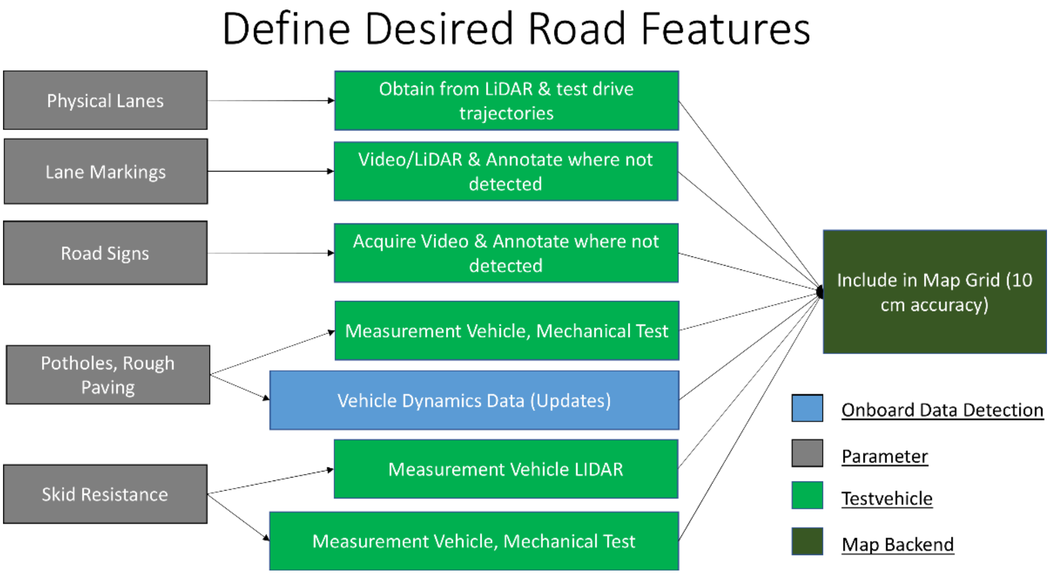


Figure 62: A list of example static layer features and how they can be obtained during test drives on the area of interest. The detection of potholes/driving comfort already points to the quality information layer. The 10 cm accuracy was suggested from desk research and in consultations with partner test sites.

Traffic Regulations/Rules

If the (localized) information on traffic regulations cannot be obtained from ITS or government authorities, this information has to be added manually or possibly through "reference test drives" providing the speed information and allowed maneuvers (similar to training data in a supervised learning approach). Lane model formats allow for this information to be encoded on the lane model scale (such as Lanelet2, see [173]). Infrastructure assistance such as easily readable signals/road signs might ease the creation of such a map or the flexible use of CAVs, if for instance those signs give information not accounted for in the map used by the CAV. See an illustration in Figure 63.

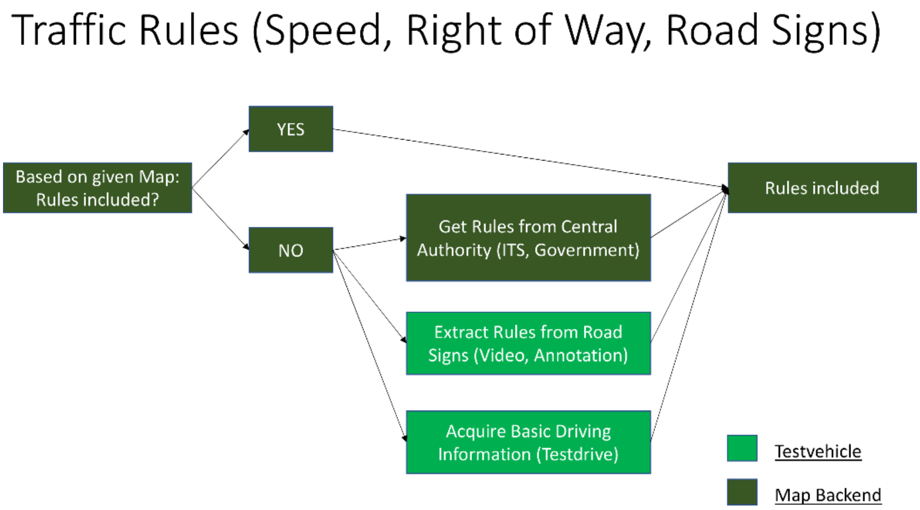


Figure 63: Procedures for adding traffic rules. Unless a central authority provides the rules in CAV compatible form (government, public standard, ITS), it will be necessary to perform test drives in the area and confirm the valid rules.

Quality Information

Road quality will contain mid-term changing information such as skid resistance or road grip, which can provide valuable information for driving safely. The relevant measurements currently need to be carried out by specially equipped vehicles, to obtain the texture of the road surface. Other typical types of information in this layer might be driving comfort (see [174] on a discussion of how to define a measure of driving comfort) on the road, which would be affected by potholes or general road condition and could be measured by vehicle dynamics (and/or user feedback during or after travelling). This information (Vehicle Accelerations, Rotational Dynamics e.g. Yaw-Rate, Roll-Rate, Pitch-Rate, aggregated on a lane model scale) would be gathered in the vehicle, through interfaces such as the CAN-Bus or similar systems, and provided to a map backend. If provided to a central backend, several measurements could be gathered into a summary update of the map information on road quality.

Included in the concept of quality information could be the “validation” of known landmarks (road signs, buildings, elements on the sidewalk) with video or LiDAR (i.e. the vehicle verifying whether it can detect them in the expected place) and the repeated measurements of properties like lane width, either via video, GPS (driving trajectories for the position of the middle lane) or special measurement equipment included in the AVs. This is, again, information that could be gathered in the backend, to notify the map maintainers about noticeable changes and, if appropriate, to adjust the maps (we assume manual control, in plausibility and quality checks for the foreseeable future, although this step would ideally also be automated in the future).

Additionally, behavioural information could be included in the same fashion, i.e. where traffic participants of various types are usually moving, which could be road safety relevant information (see also [175] for a use-case employing behavioural information).

An overview of the relevant updating loops can be seen in Figures 64-66.

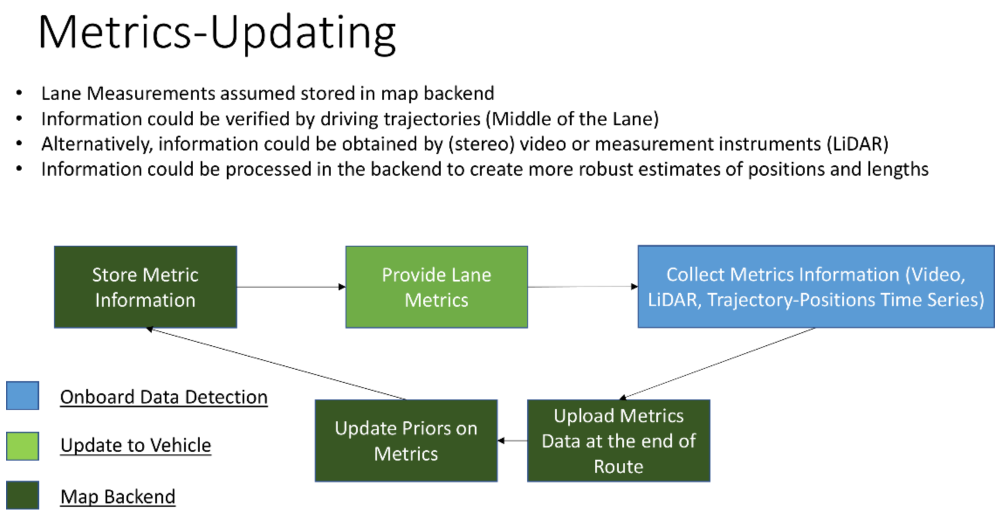


Figure 64: Updating loop for road metrics/measurements

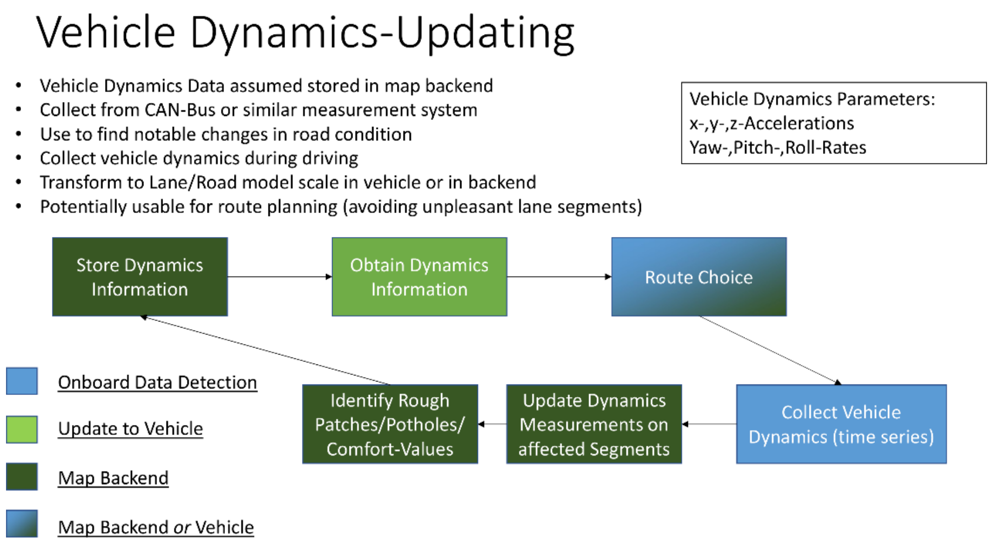


Figure 65: Updating loop for vehicle dynamics

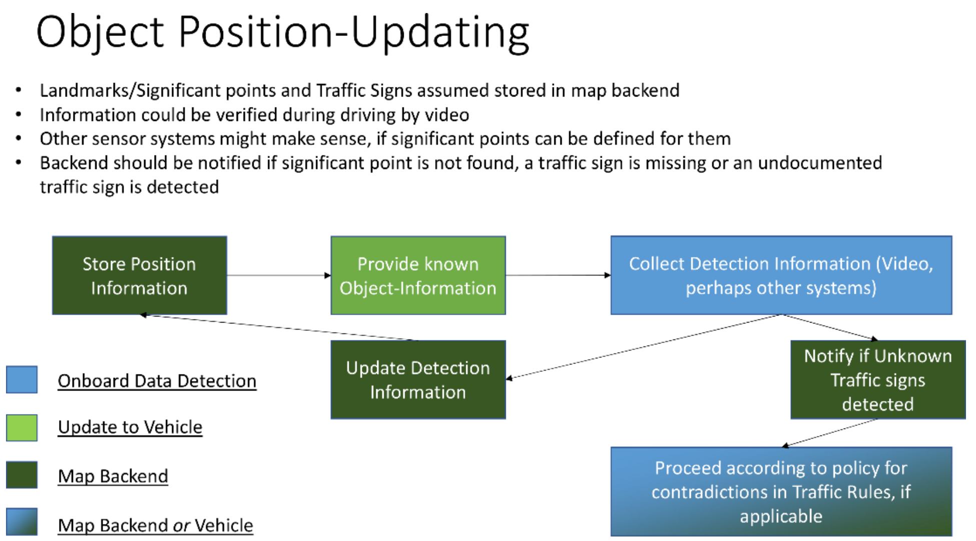


Figure 66: Updating loop for objects/positions

Dynamic Real-Time Information

This layer is quite diverse in the types of information that it holds and is intended to cover driving-relevant content that changes on a fast (minutes or seconds) time scale. First and foremost, information on the flow of traffic is important for route planning. That information could be provided by an intelligent transportation system (ITS, see also EU resources on ITS, see [176] and [177]) either directly to the vehicle or to the map-backend, so that efficient planning and traffic management can take place, based on traffic information and travel times. For the purpose of robust operation, the CAV could aim to obtain this information first from the map backend and only once that fails, contact the ITS directly for instance. Additionally, the vehicle might provide information on the level of traffic currently observed (i.e. early stage traffic jams), but that would be up to future capabilities of CAVs and video analysis in traffic. We note that, while this is in general dynamical information as per our understanding of the four layers above, it may be that recurring features, such as domains of repeated traffic jams might be included in the midterm information (quality information) of an advanced map in the future.

See an example of a traffic planning that could be either backend managed or in-vehicle planning in Figure 67.

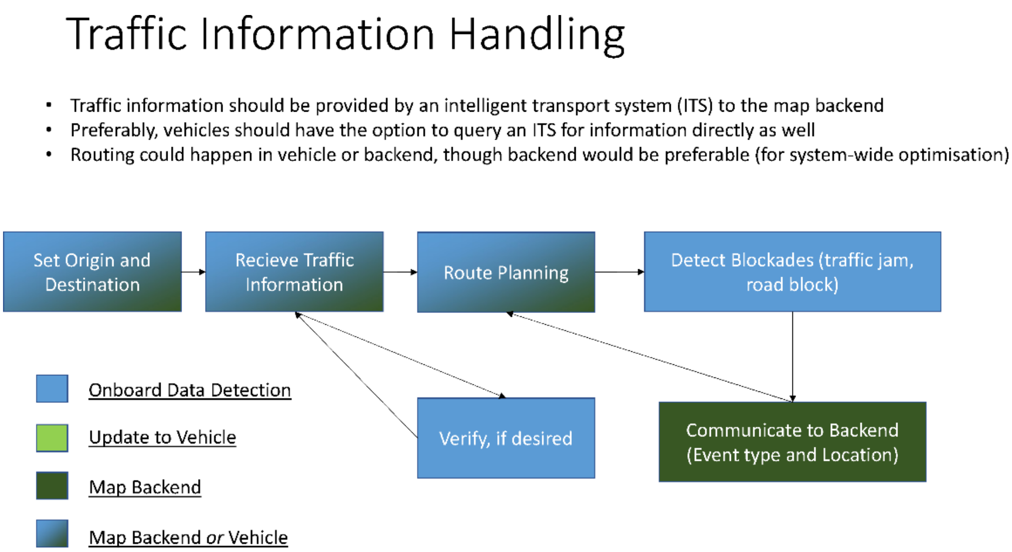


Figure 67: Flow of Information for route planning

Similarly, information on road blockages should be provided by an ITS or reports from vehicle sensors (consistent changes in driven trajectories, video detection). Local planning capabilities should be available within the vehicle, in case of a loss of connection to the external data sources. The vehicle should have a map for the whole region of interest available until the current destination, or some reasonable stopping point that can be expected to have good communications connectivity, is reached. While this is in general dynamic information as per our understanding above, it may be that domains of repeated loss of connectivity might be included in the midterm information (quality information) of an advanced map. See an illustration in Figure 68.

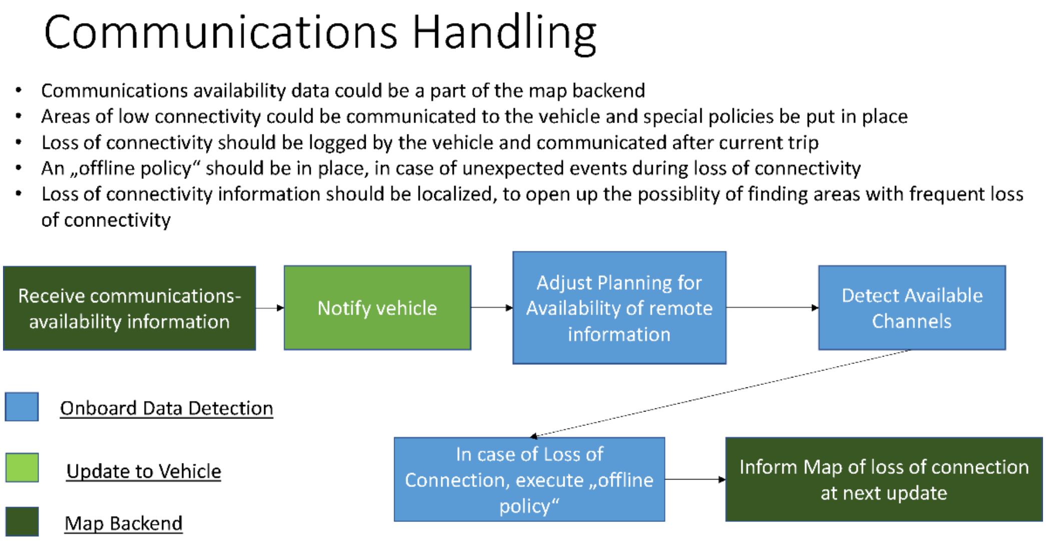


Figure 68: Flow of information in case the backend receives information of an impending limited connectivity or the vehicle notes the lack of communications and sends a notification as soon as possible.

The operation infrastructure (recharging, parking if necessary) of the autonomous vehicle could be handled in a similar manner. The dynamical aspect of this operation infrastructure is the availability for use by the CAV (how many parking spots are free? Will a charging spot be available later?), which would ideally be conferred by an ITS through the map-backend, although the possibility of the vehicle querying the respective data source directly would again be a useful backup channel. This information would not be part of the map itself, but would improve the quality of planning, if it could be queried upon demand by the vehicle or the map-backend.

Finally, weather information should probably only be conveyed to the vehicle in case relevant weather conditions might impact the planned route i.e. weather warnings or potential weather warnings would be given to the CAV in case adverse weather conditions seem likely during operation. The weather information itself does not have to be stored in the map backend or the vehicle map itself, only the relevant information should be passed (see Figure 69).

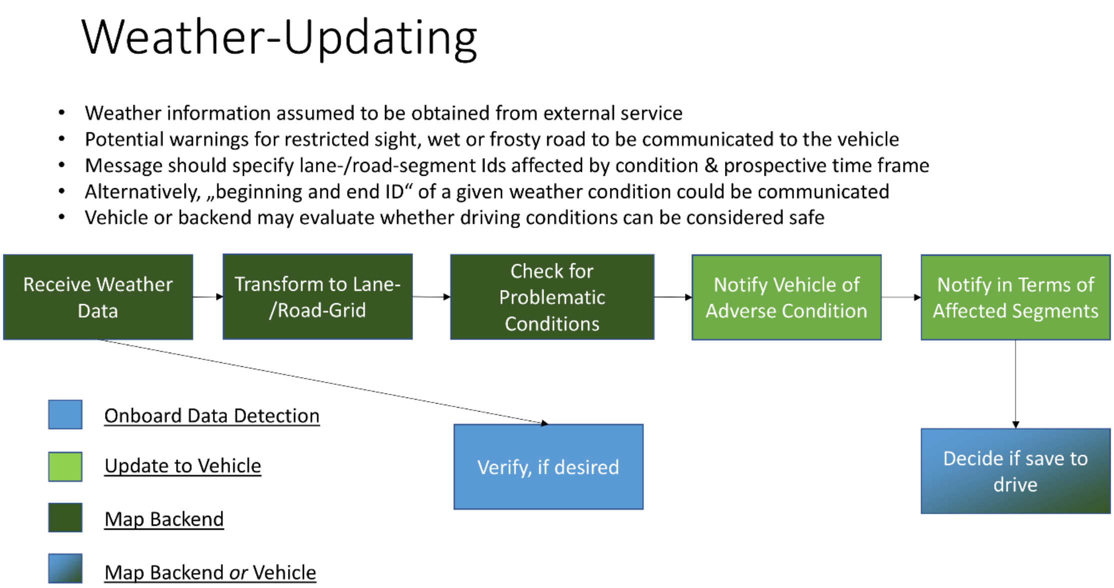


Figure 69: Possible processing of weather information.

7.2.3 Data Sources and Workflow:

Based on the discussions above, we have the following ***resources*** and steps for setting up layer information in a DDM (assuming no ITS to be in place to provide this data):

- A static layer is assumed to require a lane model. This necessitates a ***localized (via SLAM and/or GNSS) test drive*** on the tracks of interest to obtain the existing lanes and their interconnection.
- If high precision data is required by the AV systems, ***LiDAR measurements*** may be necessary.
- Once the necessary data for the Lane model is obtained, the Lane model itself is matched with a larger scale road model. A possible procedure for this is the ***combination with existing map structures***, such as OSM via tools like Graphium.
- To validate the traffic regulations or to obtain them in case the local authorities could not provide them, ***test drives*** can be necessary and should be accompanied by ***video acquisition*** and ***(human) annotation***.
- The source for quality information is ***test drives*** and the ***vehicle sensors*** of actual AVs and/or test vehicles, i.e. systems that acquire ***vehicle dynamics*** (such as the ***CAN-bus***), localize ***objects*** (***video with object recognition***), find ***driving trajectories*** (***GNSS, SLAM***) and/or measure distances more specifically (***LiDAR***).
- The sources for dynamic real time information are quite diverse: Traffic Information could be obtained from ***traffic counts*** and a ***traffic model*** to interpolate between the actual measured locations. Weather data will likely have to be produced from ***specialized measurement systems*** and ***forecast services***. Road blockages require a ***real time notification system*** for road (and lane) blockages. Communication availability needs to be updated based on ***vehicle data*** sent back ***from the respective locations*** and/or ***provider information*** on actual connectivity.
- In case of restricted connectivity, an "***offline policy***" for the AVs behaviour needs to be in place.

Summary and Workflow:

Setting up the underlying map requires a considerable amount of effort, if it is to be created from scratch. We have presented a workflow including potential data sources and structures for providing a digital dynamic map with relevant information. Said information was separated into 4 layers (static information, traffic regulations, quality information, dynamic real time information) and the respective properties of these layers were discussed separately. Finally, the steps for setting up the DDM were summarized in 4 compact lists augmented by several tables (Table 47-52).

Workflow Static Information:

1. Determine area of interest
2. Drive on each lane to obtain lane model information. Use video, driving trajectories, LiDAR to obtain high precision data
3. Associate data to lane segments -> Lane Model
4. Note connection to other lane IDs

5. Build (or match with) connection graph on top (for routing) -> Road Model (Connected to Lane)
6. Potentially match model with existing map resources

Table 47: Basic Lane Model Structure

Segments	Metric	Connects to	Position	Properties
Lane (Segment) ID	Segment width and length	Neighbouring Lane Segment IDs	Coordinates within map/GPS bounds	Lane markings, other Infrastructure

Table 48: Basic Road Model Structure

Road Connections	Lengths	Connects to	Position	Includes
Roads Segment ID	Segment Length	Neighbouring Road Segments	Coordinates within map/GPS bounds	Lane IDs

Table 49: Basic Object Position Structure

Objects	Verification Data	Position
Landmarks, Road Signs	Video or similar Data	Coordinates within map/GPS bounds

Workflow Traffic Regulations:

1. Obtain information on speed limits and traffic rules from road authority
2. Determine relevant scale (Road or Lane level)
3. Store interpretation of road signs.

Table 50: Basic Lane Model Regulations Structure. Road Model Regulations analogous to Lane model Regulations, with the added requirement of the CAV's algorithms to interpret the Road Level Rules on the lane level.

Segments	Speed Limit	Special Provisions	Right of Way
Lane Segment ID	Limit on the respective Segment	If applicable to segment and relevant to CAV	Priority rules when crossing to another segment, Priority of other traffic users

Workflow Quality Information:

1. Determine Quality Information to be collected by CAVs or Probe Vehicles
2. Associate sensor-type (GPS, Video, LiDAR, CAN-Bus)
3. Collect frequently or continuously
4. Determine Update Criteria (significant change of condition or continuous updating)

Table 51: Quality Information Structure.

Scale	Quality Information	Usage	Measurement
Lane Segment ID	Driving Trajectory	Validate/Refine Lane position	Positioning/GPS
Lane Segment ID	Road Texture	Find skid resistance/Potholes	Probe Vehicle/LiDAR
Lane Segment ID	Vehicle Dynamics	Find issues in road condition/comfort	CAN-Bus or similar
Object Position	Behaviour	Information on local interactions „hot spots“ with other road users	Video, Accident reports, official road crossings
Object Position	Position Validation	Confirm reference objects in specified location	Video

Workflow Dynamic Real Time Information:

1. Determine Dynamic Real Time Information to be communicated between CAVs, map backend and ITS
2. Set up connection to data providers (Traffic Data, Operation Infrastructure, Weather, Communications)
3. Determine procedures to obtain & process at backend and at vehicle

Table 52: Dynamic Real Time Information Structure.

Scale	Information	Usage	Source
Lane Segment ID	Status: Blocked	If negative, path is free	Traffic Reports, Video
Whole Route (Road Model)	(Expected) Travel Time	Plan the best route	ITS, Traffic Model at map backend or vehicle
Lane Segment ID	Communications availability	Find issues in connection to map backend	Connection attempts by CAV, Provider Information
Lane Segment ID	Weather Status/Warning	If no warning, path is free. Dynamics might be adjusted for slippery road	ITS, vehicle reports, data provider
Lane Segment ID	Debris on Road, Slippery Road	Give warning to other vehicles, Evade or adjust dynamics	Video, vehicle reports, ITS
Object Position	Parking or Charging Infrastructure	Plan for parking or charging	ITS, data provider, vehicle reports

7.2.4 Conclusions

If DDMs are to be widely available, a joint effort in the industry or by the official state agencies may be helpful to create an up-to-date repository of fundamental data for maps (traffic regulations on a road model, perhaps a lane model, perhaps real-time data on traffic, weather & communications). Similarly, ITS availability would be important for forming DDMs [178], as many of their most important functions (route planning, operation infrastructure, potentially traffic rules) could be readily provided to either the map backend or the vehicle directly this way. European efforts in this direction are progressing (see ITS Actions plans [179] and [176]).

As an example, in the local context of Austria, current ITS systems such as the graph integration platform (GIP) and the real time traffic information system (EVIS) are being implemented, which, once sufficiently detailed, would allow to provide Information directly to map operators, where this information could be used to either create maps (by combining localized Traffic Regulations with a predetermined road/lane model) or to update operational maps.

Ultimately, the exact requirements do depend on the vehicle and its flexibility of use. The factors discussed here should be of potential relevance to most, if not all CAVs.

8 Summary and Conclusions

The objectives of A8.1 were to investigate and specify efficient road infrastructure adaptations and measures for automated urban mobility and to develop a semi-automated workflow to acquire and manage various data sources for the four layers of a digital dynamic street map.

The deliverable provides a detailed description and analysis of physical road infrastructure adaptations relevant for automated mobility by providing results from literature reviews, stakeholder surveys and interviews and consultations with the SHOW pilot sites. Moreover, a segmentation tool for the classification and assessment of road infrastructure elements for AD, to be used by pilot site managers, was developed in this task by AIT and a manual is provided in Appendix III. Finally, a workflow for setting up a digital dynamic map including information on many driving relevant aspects (routing, weather and road conditions) is presented.

Physical road infrastructure currently plays only a minor role in urban automated mobility and is not considered a number one priority when preparing pilot test routes for testing automated vehicles in an urban environment. Automated shuttle solutions should be deployable anywhere without critical infrastructural adaptations or major investments. The following remarks can be considered:

- The choice of pilot test routes focuses on using the physical infrastructure as it is and therefore challenging conditions are avoided from inception (e.g. higher slopes that would impede optimum vehicle operation; uncontrolled parking along the route; roadside vegetation that would obstruct the vehicle's sensors; temporary roadworks, rough pavement etc.).
- In urban environments, automated shuttles still drive at low speeds (approx. 30 km/h), significantly reducing the safety risk.
- Some pilot test sites aim to develop their technologies to fit any physical infrastructure.
- Most pilot sites include most infrastructural elements in a pre-programmed digital dynamic map (e.g. traffic signs, lane markings, lane width, traffic lights, pedestrian crossing, road geometry etc.).
- Physical infrastructure structures are rather used to improve localization, serving as reference points to the automated vehicles on their routes.

Nevertheless, a number of infrastructure measures and adaptations are necessary to ensure optimum operation at urban pilot sites. This includes optimisation of the road surface, ensuring safe and efficient access to terminals/stations, improving lane marking quality, regular maintenance of roadside vegetation, installation of additional landmarks/signs for the improvement of the vehicle's navigation and regular road and traffic sign maintenance. Infrastructure adaptations and measures also serve information purposes for other road users to make them aware of automated driving pilots in the area e.g. new traffic signs (sometimes also denoted as warning (!) signs).

Urban automated vehicles should also be assimilated into daily traffic, including PT hubs. The following elements are necessary to achieve a seamless integration:

- supporting facilities with service and charging of AVs;
- staging areas for storing unused vehicles;
- curb modifications when reconsidering parking permits and inner-city parking solutions;
- mobility hubs as access point with improved accessibility to available transportation modes.

Regarding safety, these elements are facing new challenges to create an environment where pedestrians are able to board and alight in the safest way possible. Also, the access to the hubs itself should be taken into consideration as traffic changes. To create a cost-sensitive testbed for research on safety, placement of public transport hub elements and changes in traffic flow induced by AVs, simulation scenarios will be created in WP10 of this project.

Overall, as real-world traffic is highly complex and automated mobility technology will continue to evolve, automated vehicles will still have to cope with the following considerations:

- Traffic events such as temporary road works, illegal parking, accidents or other spontaneous and unpredictable occurrences remain critical challenges for AD.
- Vulnerable road users are currently not connected and require special attention and protection that cannot end in banning them from the roads.
- Over time, road damages will occur, and thus road monitoring and damage maintenance will be important services and investments for infrastructure operators.
- Higher speeds will bring forward new challenges in terms of localization, detection and safety.

Whether physical road infrastructure needs to be adapted in real world traffic has to be further investigated in large-scale demonstrations for AD in the future.

Pilot managers are provided with a quick and efficient tool to assess the readiness of a pilot site for urban automated mobility (see Appendix III for the SHOW segmentation tool manual). The SHOW segmentation tool is able to classify different road elements with specific SHOW pilot site characteristics and provide pilot site representatives with a methodology for a quick-scan road safety assessment concerning the infrastructure elements lane markings, traffic signs and sight distances.

The software tool works similar to modern routing mapping systems, i.e. the user scrolls through a digital map to move the display window to the area of interest. Several checklists were developed for the evaluation of physical infrastructure requirements. Those checklists allocate individual grades (1-5) according to the personal assessment of the site manager during the test site inspection. After completing the checklists for a specific road segment, a summary of the allocated risk levels is given. The output shows both the individual risk per category (roadside equipment, traffic information and rules etc.) and the highest risk value in general. The final outcome of the evaluation process is a graphical representation of all road segments investigated including the road element annotation plus the respective hazard/risk level.

With regard to digital dynamic maps, it can be concluded that a DDM will consist of the following: a static map layer (combining the static information and traffic regulations layer), a quality layer and a dynamic real-time layer. The static HD map layer will most probably be generated by measurement vehicles in order to reach the needed accuracy and will be provided either by private map providers or public road authorities. But, as this static layer will only be pseudo-static because the environment is constantly changing, updates will be needed, either pushed by vehicle dynamics or information from road authorities. There will probably be several data channels for transferring the relevant data for the digital dynamic map, being either short range (e.g. V2X) or long range (cellular) channels. All data streams have to be merged in the vehicle to a local dynamic HD map, which holds all the relevant data for the automated vehicle needed for planning and executing driving manoeuvres. A difficult challenge in this context is to guarantee data integrity and data quality.

The developed semi-automated workflow (series of steps) presents, on an abstract level, the requirements for setting up a digital dynamic map including information on many driving relevant aspects (routing, weather and road conditions) as well as updating procedures. The purpose of the abstract workflow is to provide a kind of check-list and overview on what aspects might be included in a digital dynamic map that is being newly set-up, and hence make it easier to create a solution tailor-made for the needs of a particular CAV type. Requirements of different vehicles and data formats used could vary substantially, currently forestalling the possibility to implement a single explicit workflow (from measurement data to a fully functional digital dynamic map containing real time information) for all developers of autonomous vehicles within the EU.

It was determined that in order to set up a high quality digital dynamic map, static information (road geometry and lane connections) will, for the foreseeable future, still require test drives with high precision measurement equipment (in particular LiDAR). Similarly, traffic rules (speed limits, right of way) will typically have to be obtained manually (acquired from local government or test drives), while quality information (objects, changing road condition) could be obtained through occasional test drives. Intelligent transportation systems (ITS) could provide much of the required real-time information (traffic, route planning, parking possibilities, weather warning, road blockages warnings) and therefore EU wide efforts in setting up and improving ITS capabilities should prove helpful to mapmakers and operators of autonomous vehicles.

8.1 Criteria catalogue for PI for automated driving

The criteria catalogue for PI for automated driving constitutes the summary of all relevant findings on PI in relation to AD of this deliverable in a structured manner. More detailed information can be found in the related chapters linked within this table.

Table 53: Criteria catalogue for PI for automated driving.

Criteria catalogue for PI for automated driving						
PI elements	**Purpose relevant for AD**	**SoA**	**Methodology**	**Standards**	**Check Lists**	**Chapter of D8.1**
Lane markings	Some AV technologies (e.g. LKA, LDW) need lane markings to: • delineate roads • separate opposing traffic streams • divide the total road area into sub-areas for different road users	• Visibility of lane markings (size, colour, age, retroreflectivity etc.) plays a major role for AD capability • Lane markings range from low to good quality and 0 to 100% availability at the pilot sites	• Pilot site questionnaire • Literature research	• No standard available or derivable from the pilot sites • Chapter 3.2.1 investigates international standards concerning the visibility and detectability of lane markings	Chapter 3.3.1 concerning the definition of thresholds in an urban road environment based on the results of a literature review and stakeholder interviews	Chapters 3.3.1, 3.2.1, 3.3.1 and Chapter 4.1.2 for the pilot sites
Traffic signs	Vertical traffic signs are signs placed along the roads that inform drivers of road conditions and restrictions or the	• In Europe, traffic signs are standardized by means of the “Vienna Convention on	• Pilot site questionnaire • Literature research	Chapter 3.2.2 gives an overview on relevant international standards for traffic signs	To provide adequate infrastructure for automated driving with a variety of technologies, the traffic signs at the test sites should allow	Chapters 3.1.2, 3.2.2, 3.3.2, and Chapter 4.1.2 for the pilot sites

Criteria catalogue for PI for automated driving						
PI elements	**Purpose relevant for AD**	**SoA**	**Methodology**	**Standards**	**Check Lists**	**Chapter of D8.1**
	possible direction of travel. Some AV technologies use traffic sign recognition to interprete traffic rules and deduct possible driving manoeuvres.	Traffic Signs and Signals” • Traffic signs are present at almost all SHOW pilot sites, although no test site stated clearly that they do traffic sign recognition.			automatic detection (reflections would have to be checked in detail). A checklist for traffic signs for AVs in an urban environment is given in chapter 3.3.2	
Sight distances	• Concerning AD, sight distances are highly relevant due to the fact that the sensors' view is more limited than the human eye • Road barriers, trees or bushes can limit sight distances, which are especially needed at	• A human operator always has to confirm it is safe for an AV to enter a junction • The low operating speed of current automated shuttle buses diminish the influence of adequate sight distances at	Literature research	Relevant international standards for sight distances and visibility at junctions can be found in chapter 3.2.3	Chapter 3.3.3 provides a checklist for sight distances and visibilities at junctions	Chapters 3.1.3, 3.2.3, 3.3.3

Criteria catalogue for PI for automated driving						
PI elements	**Purpose relevant for AD**	**SoA**	**Methodology**	**Standards**	**Check Lists**	**Chapter of D8.1**
	intersections or crossings	critical local road elements				
Intersections	Intersections affect the complexity of driving	Both signalized and unsignalized intersections occur at the pilot sites.	Pilot site questionnaire	No standard but the consent that signalized intersections are easier to handle than unsignalized intersections.	None	Chapter 4.1.2
Road surface material and quality	Road safety and lane marking detectability	The road surface material at the SHOW pilot sites is mostly asphalt, at some sites potholes occur.	Pilot site questionnaire	Standards from lane markings	Recommendations: • Fix potholes, also for general road safety concerns • If the surface material is other than asphalt, make sure the lane markings are still detectible (see	Chapter 4.1.2

Criteria catalogue for PI for automated driving						
PI elements	**Purpose relevant for AD**	**SoA**	**Methodology**	**Standards**	**Check Lists**	**Chapter of D8.1**
					criteria catalogue on lane markings)	
Vegetation along the route	Vegetation might confuse LiDAR-systems.	Almost all test sites have trees and bushes along the route.	Pilot site questionnaire	Trim trees and bushes.	Recommendation: Trim trees and bushes regularly.	Chapter 4.1.2
On-street Parking	On-street parking might cause difficulties for AVs (opening doors, vehicles leaving the parking spot, vehicles backing into a parking space)	Occurs at many pilot sites, but for the majority it is not an issue. Illegal parking is an issue.	Pilot site questionnaire	None.	Recommendation: SHOW demonstrations will show whether parking is an issue or not.	Chapter 4.1.2
PT Hubs	design of access and safety for both users and AD vehicles important for future usage and success, discussing	standardization of existing components and future elements	• Literature research	National guidelines for station design in form of a handbook, national standards	Chapter 3.3.4	Chapter 3, 3.2.4 (Accessibility) and 3.2.5 (Safety)

Criteria catalogue for PI for automated driving						
PI elements	**Purpose relevant for AD**	**SoA**	**Methodology**	**Standards**	**Check Lists**	**Chapter of D8.1**
	future components necessary to solve last-mile problem			for single components of PT Hubs		
Bus stops	AV driving tasks differ depending on the bus stop type (bus bay, stop on lane, stop at a PT hub, other)	Bus bays, stops on lane, stops on dedicated bus lanes and some other types occur at the pilot sites.	Pilot site questionnaire	No standard available. Some test sites preferred stop on lane while others used what was already existing.	Recommendation: Investigate the different types of bus stops and their advantages and challenges for automated driving within the SHOW demonstrations as there is no standard available.	Chapter 4.1.2
Segmen-tation tool	Classification of different road elements due to specific site characteristics and provide a quick-scan road safety assessment concerning lane markings, traffic signs and sight distances	Proprietary software development	• Stakeholder interviews Literature research	National guidelines for road safety inspection (Reference No. [181] and road safety auditing (References No. [182])	• Allocation of individual grades (1-5) according to the personal assessment of the site manager during test site inspection. • After completing the checklists for a specific road segment, a summary	Chapter 5, Appendix III

Criteria catalogue for PI for automated driving						
PI elements	**Purpose relevant for AD**	**SoA**	**Methodology**	**Standards**	**Check Lists**	**Chapter of D8.1**
					of the allocated risk levels is given	
HD-Maps	• Improve navigation, route planning, localization • Include dynamic data sources • Ensure safe operation conditions	mostly static information HD maps, no standardized data or map interfaces, very different requirements for different AV approaches	• Stakeholder interviews • Literature research	at time of writing no established ones	Chapter 7.1.2 on actual implemented map features at partner sites (several tables)	Chapter 7, 7.1
Workflow for map creation and operation	Setting up a digital dynamic map, with a number of standard components and discussing the necessary updating procedures	no standardized approach for setting up a digital dynamic map has surfaced, different requirements for different AVs lead to different maps	• Stakeholder interviews • Literature research	at time of writing no established ones	Chapter 7.2.1 and following. Several lists on aspects to be considered when setting up a map (all the figures, tables and lists in the chapter)	Chapter 7, 7.2

8.2 Site specific implementation of PI recommendations

This chapter constitutes the outcomes of D8.1 and how test sites will be able to make use of the results of this deliverable. For this purpose, in A8.1 two spreadsheets were developed:

1. Recommendations table for PI adaptations at test sites
2. Recommendations table to improve HD-Maps

Both tables build on the findings gained through the work in A8.1/D8.1, mainly written down in chapters 4, 7 and 8.1 and provide PI and HD maps recommendations customized for each individual SHOW test site. To verify if our recommendations were followed, we asked all the test sites for an update of those tables.

While the "*Recommendations table to improve HD-Maps*" is a more static document as properties of HD-Maps are mainly fixed in the beginning we regard the "*Recommendations table for PI adaptations at test sites*" as a living document that was handed over to all SHOW test sites and should be revised regularly – in any case after the Pre-Demo-Phase and Demo-Phase – by test site managers. Thus, all adaptations caused by automated driving before and during operation of test sites can be documented in a structured way and constitute new comparable knowledge on the role of PI for AD beyond the current state of the art. In further consequence, this new knowledge can be the basis for future initiatives implementing automated driving.

8.2.1 Recommendations for PI adaptations at test sites

This table (see table 54 next page) was developed following the "Criteria Catalogue for PI for AD" presented in chapter 8.1 and is based on the answers concerning the current state of PI and planned adaptations/measures given by the test sites and summarised in chapter 4. The table provides structured information on specific recommendations (drop-down menus) customized to each single SHOW test site and also indicates reasons (drop-down menus) why single recommendations have not been followed.

It was handed over as living document to test sites including three identical table sheets – the first for the current status at test sites, the second and third to be used for an update after the Pre-Demo-Phase and Demo-Phase. Entries in the latter two sheets should document how further adaptations/measures for PI at test sites were needed during operation in real world conditions. The findings from comparing these three sheets in different phases of test site operation could be used as valuable lessons learned and the gathered real-world experience is relevant for future initiatives when preparing the ground for automated driving. This is a step forward to clarify the role of PI for automation in transport.

The following subchapters provide examples of how the SHOW A8.1 recommendations for PI for AD have been implemented at five test sites.

Table 54: Template Recommendations table for PI adaptations at test sites (with example entries).

Country	Test site	Vehicle type	Indicated adaptions and measures of PI (yes/no)		If YES, what adaptation	If No, please give a reason (choose from the drop-down list)	Recommendations WP8 for PI adaptations	Recommen-dations implemented	Only if recommendation was NOT implemenetd please provide reasoning (choose from the drop-down list)	Comments
			please check if you agree with this reason, or choose another			In this column, please check if you agree with this reason, or choose another		In these columns, please check if you agree with this reason, or choose another		
			Lane markings (LM)	No	N/A	LM: Adverse weather conditions (snow, rain, fog etc.)	LM: Clear continuity lines on both lane sides and consistent lane width			
							LM: Halt the practice of mixing yellow and white pavement markings on construction sites			
							LM: Remove redundant markings and phantom markings			
							LM: Minimum luminance coefficient (dry road surface) at hotspots: 130 mcd/lx/m2			
							LM: Minimum luminance coefficient (daytime) for all other road elements: 100 mcd/lx/m2			
							LM: Minimum retroreflectivity (dry road surface) at hotspots: 150 mcd/lx/m2			
							LM: Minimum retroreflectivity (dry road surface) for all other road elements: 100 mcd/lx/m2			
							LM: Minimum 3:1 contrast ratio between longitudinal pavement markings and surrounding substrate			
			Traffic signs (TS)	Yes	N/A		TS: Traffic sign condition without wear			
							TS: Correct sign positioning without tilting			
							TS: Machine-readability			
							TS: Sign visibility without obstruction			
							TS: Placement of traffic signs in logical sequence without contradicting each other			
			Sight distances (SD)	No	N/A	SD: Human intervention	SD: Elimination of visual obstructions at crossroads/intersections			
							SD: Prevention of phantom detections due to reflective surfaces			
			PT Hubs & stations (PTHS)	Yes	N/A		PTSH: Provide adequate space for maintenance, storage and charging facilities			
							PTSH: Ensure barrier free accessibility to PT hubs and stations			
							PTSH: Provide adequate space for waiting areas in PT hubs and stations			
			Others	Yes	road side vegetation		OTH: Evaluate safety level at unsignalized intersection	No	TS: No traffic signs along AV route	
							OTH: Fix pothols and cracks in road surface	No	OTH: Road surface in adequate condition	
							OTH: Trim trees and bushes along the AV route	Yes		

Please fill in the yellow cells.

You do not have to fill in white cells

Abbreviations	
LM	Lane markings
TS	Traffic Signs
SD	Sight distances
PTHS	PT Hubs & stations
OTH	Others

Current status at test site | 1. Update Predemo-Phase | 2. Update Demo-Phase | Drop Down List

8.2.1.1 *Agreed recommendations for PI at specific test sites*

8.2.1.1.1 Brno

The Brno test site implemented only a few adaptations concerning the physical infrastructure due to the fact that the AV used for the SHOW use case already employs technology which is not dependent on state-of-the-art lane marking quality for vehicle navigation. Traffic signs were inspected and amended in order to be both correctly positioned and of adequate condition. The logical sequence of the traffic signs was also considered up front. Furthermore, all traffic sign rules along the route were incorporated in a HD map for AV support. Inadequate sight distances are not relevant due to the reduced operating speed of the test vehicle. Limited financial resources prohibited the Brno site management to improve the PT hubs and stations.

Table 55: Recommendations followed by test site in Brno.

State	Test site	Vehicle type	Adaptation and PI measures		Type of adaptation	If NO, please provide a reason	WP8 recommendations for PI adaptation	Recommend-ations implemented	Comments
CZ	Brno	EasyMile EZ10, Hyunday i40, TPCI shuttle	Lane markings	No		Vehicle technology not dependent on lane markings			
			Traffic signs	Yes	Incorporation of traffic rules in HD map		Traffic sign condition without wear	Yes	
							Correct sign positioning without tilting	Yes	
							Machine-readability	No	Incorporation of traffic sign rules in HD map
							Sign visibility without obstruction	Yes	
							Placement of traffic signs in logical sequence without contradiction	Yes	
			Sight distances	No		Reduced operating speed of AV			
			PT Hubs and stations (PTHS)	No		Limited financial resources			
			Others	No		Unsignalized intersections not critical due to low AADT, speed etc.			

8.2.1.1.2 Karlsruhe

Similar to the Brno test site, Karlsruhe strongly relies on latest vehicle technology and area-wide HD maps to handle missing/inadequate lane markings and contradicting/incorrect positioned traffic signs. Furthermore, traffic sign rules are also incorporated in the digital map. Inadequate sight distances at intersections and critical locations along the route are counteracted by reducing the operating speed of the AV. PT hubs and stations were the focus of various adaptation measures: Shuttle depots were planed/adapted to provide adequate space for maintenance work, storage and charging facilities and barrier-free accessibility to the PTHS was also ensured via ramps. In order to enhance the safety level at unsignalized intersections, human intervention is an integral part of the vehicle avigation. The road surface is also of adequate condition to ensure a safe test run.

Table 56: Recommendations followed by test site in Karlsruhe.

State	Test site	Vehicle type	Adaptation and PI measures		Type of adaptation	If NO, please provide a reason	WP8 recommendations for PI adaptation	Recommend-ations implemented	Comments
GER	Karls-ruhe	Adapted Easymile EZ10 Gen2	Lane markings	No		Vehicle technology not dependent on lane markings			
			Traffic signs	No		Incorporation of traffic sign rules in HD map			
			Sight distances	No		Reduced operating speed of AV			
			PT Hubs and stations (PTHS)	Yes	Mobile accomodation		Provide adequate space for maintenance, storage and charging facilities	Yes	For shuttle depots
							Ensure barrier free accessibility to PTHS	Yes	Via ramp by EasyMile-Shuttles
							Provide adequate space for waiting areas in PTHS	No	On demand service and virtual stations hand selected
			Others	No		Human intervention	Evaluate safety level at unsignalized intersections	No	Human intervention
							Fix potholes and cracks in road surface	No	Road surface in adequate condition
							Trim trees and bushes along the AV route	Yes	Safety area has to be respected

8.2.1.1.3 Tampere

PI adaptations at the Tampere test site focuses on both correctly positioned traffic signs and adequate conditions. The machine-readability is also considered of major importance to guarantee a safe and continuous AV service at the test site. Due to adverse weather conditions (rain, fog, snow etc.) during most of the year, lane marking quality is not deemed relevant for applying automated vehicle services. Shuttle depots are planed/adapted to provide adequate space for maintenance work, storage and charging facilities and barrier-free accessibility to the PTHS is also of considered. Additional measures considering road condition maintenance (not only along the route but also at temporary work zones) amount to fixing potholes and cracks in the road surface and regularly trim trees and bushes along the AV route.

Table 57: Recommendations followed by test site in Tampere.

State	Test site	Vehicle type	Adaptation and PI measures		Type of adaptation	If NO, please provide a reason	WP8 recommendations for PI adaptation	Recommend-ations implemented	Comments
FI	Tampere	Toyota, ProAce, Auvetech	Lane markings	No		Adverse weather conditions			
			Traffic signs	Yes	Signs have been checked		Traffic sign condition without wear	No	No need for measure
							Correct sign positioning without tilting	No	No need for measure
							Machine-readability	Yes	
							Sign visibility without obstruction	No	No need for measure
							Placement of traffic signs in logical sequence without contradiction	Yes	
			Sight distances	No		Reduced operating speed of AV			
			PT Hubs and stations (PTHS)	Yes	PTHS have been identified		Provide adequate space for maintenance, storage and charging facilities	Yes	For shuttle depots
							Ensure barrier free accessibility to PTHS	Yes	Hubs, stations and stops are barrier free
							Provide adequate space for waiting areas in PTHS	Yes	Adequate space in PTHS available
			Others	Yes	Road condition maintenance		Evaluate safety level at unsignalized intersections	Yes	Also at temporary working zones
							Fix potholes and cracks in road surface	Yes	
							Trim trees and bushes along the AV route	Yes	

8.2.1.1.4 Brainport

The Dutch test site in Brainport implemented a different safety strategy than any other test site investigated. According to the site management, there are no traffic signs situated along the AV route which reduces the complexity level for automated vehicles to cope with. Inadequate sight distances at intersections and critical locations are tackled by installing additional V2X communication modules. Lane markings are deemed in good conditions and therefore don't need further adaptation measures. All the recommendations concerning traffic lights, pedestrian and bicycle crossings were also implemented.

Table 58: Recommendations followed by test site in Brainport.

State	Test site	Vehicle type	Adaptation and PI measures		Type of adaptation	If NO, please provide a reason	WP8 recommendations for PI adaptation	Recommend-ations implemented	Comments
NL	Brainport	Renault Sceneic	Lane markings	No		Lane markings in good condition			
			Traffic signs	No		No traffic signs along the AV route			
			Sight distances	Yes		V2X communication	Elimination of visual obstructions at crossroads/intersections	Yes	
							Prevention of phantom detections due to reflective surfaces	Yes	
			PT Hubs and stations (PTHS)	No		PTHS are not considered at the test site			
			Others	Yes	Traffic lights, pedestrian and bicycle crossings		Evaluate safety level at unsignalized intersection	Yes	
							Fix potholes and cracks in road surface	Yes	
							Trim trees and bushes along the AV route	Yes	

8.2.1.1.5 Salzburg

The Salzburg test site in the village of Koppl relies on a recently developed HD map to incorporate traffic sign rules in a digital format. Concerning lane markings, the test vehicle provided by EasyMile is equipped with stat-of-the-art technology which is able to recognize and interpret markings automatically on the fly. Due to specific safety regulations in the federal state of Salzburg, lane markings are not applied on the road surface in the village centre of Koppl. The recommendations provided by deliverable D8.1 for PT hubs and stations could only partly be implemented due to both limited space and financial resources. In order to enhance the overall safety level at unsignalized intersections and other hotspots during the test trials, human intervention is an integral part of the AV test setting.

Table 59: Recommendations followed by test site in Salzburg.

State	Test site	Vehicle type	Adaptation and PI measures		Type of adaptation	If NO, please provide a reason	WP8 recommendations for PI adaptation	Recommend-ations implemented	Comments
AT	Salzburg	Easymile	Lane markings	No		Vehicle technology not dependent on lane markings			Due to safety reasons, no lane markings are used within village roads in the Federal State of Salzburg
			Traffic signs	No		Incorporation of traffic signs rules in HD map			
			Sight distances	No		Human intervention			
			PT Hubs and stations (PTHS)	Yes			Provide adequate space for maintenance, storage and charging facilities	Partial	Limited space
							Ensure barrier free accessibility to PTHS	Partial	Limited financial resources
							Provide adequate space for waiting areas in PTHS	Partial	Limited space
			Others	Yes	Road side vegetation		Evaluate safety level at unsignalized intersections	No	Human intervention
							Fix potholes and cracks in road surface	No	Road surface in adequate condition
							Trim trees and bushes along the AV route	Yes	

8.2.1.1.6 Graz

The test site in the city of Graz (Austria) uses a purpose-built vehicle for their predefined SHOW use case(s). The vehicle technology does not depend on a specific quality level for lane markings and traffic sign information is provided via digital infrastructure. Hence, no additional adaptation measures are needed for those PI components. The issue of minimum sight distances at critical sites along the route is solved by providing human intervention at specific hotspots (e.g. unsignalized intersections). At railway crossings and in sections with tram tracks, safety levels were evaluated to assess if additional adaptation measures are necessary. The road surface conditions are adequate shape and vegetation is of no concern for safety.

Table 60: Recommendations followed by test site in Graz.

State	Test site	Vehicle type	Adaptation and PI measures		Type of adaptation	If NO, please provide a reason	WP8 recommendations for PI adaptation	Recommend-ations implemented	Comments
AT	Graz	Purpose-built vehicle	Lane markings	No		Vehicle technology not dependent on lane markings			
			Traffic signs	No		Traffic signs provided by digital infrastructure			
			Sight distances	No		Human intervention			
			PT Hubs and stations (PTHS)	No		Limited space			
			Others	Yes	Regulation at tram track and/or railway crossing		Evaluate safety level at unsignalized intersection	Yes	
							Fix potholes and cracks in road surface	No	Road surface in adequate condition
							Trim trees and bushes along the AV route	No	No vegetation along AV route

8.2.1.1.7 Geneva

The Geneva test site uses autonomous vehicles provided by NAVYA. Concerning additional investments in the physical infrastructure, additional space for maintenance, storage and charging facilities is provided in the shuttle depots. Due to the fact that the test site is on private property, no measures are implemented to ensure barrier free accessibility. According to the test site manager, once in the test site, there are no barriers for people with special needs. The Geneva test site is situated in an environment with low AADT and speed limit. Hence, no additional adaptation measures are deemed necessary.

Table 61: Recommendations followed by test site in Geneva.

State	Test site	Vehicle type	Adaptation and PI measures		Type of adaptation	If NO, please provide a reason	WP8 recommendations for PI adaptation	Recommend-ations implemented	Comments
CH	Geneva	NAVYA	Lane markings	No					
			Traffic signs	No					
			Sight distances	No					
			PT Hubs and stations (PTHS)	Yes			Provide adequate space for maintenance, storage and charging facilities	Yes	Concerns shuttle depots
							Ensure barrier free accessibility to PT hubs and stations	No	Private site. However, once in the site there are no barriers to access PT hubs
							Provide adequate space for waiting areas in PT hubs and stations	No	Not required in the current deployment
			Others	Yes	Road condition maintenance		Evaluate safety level at unsignalized intersections	No	Unsignalized intersections not critical due to low AAST, speed etc.
							Fix potholes and cracks in road surface	No	Road surface in adequate condition
							Trim trees and bushes along the AV route	Yes	

8.2.1.2 *Proposed recommendations for PI at specific test sites*

This section focuses on the proposed recommendations for the rest of the sites, that however, have not been yet confirmed. Upon confirmation, that is going to take place in the coming period, the respective content will be reflected in the previous table of section 8.2.1.1.

Table 62: Proposed recommendations for the test site in Klagenfurt.

Country	Test site	Indicated adaptions and measures of PI (yes/no)		If YES, what adaptation	If No, please give a reason (choose from the drop-down list)	Recommendations WP8 for PI adaptations	Recommen-dations implemented	Only if recommendation was NOT implemenetd please provide reasoning (choose from the drop-down list)	Comments
AT	Klagenfurt	Lane markings (LM)	No		LM: Lane marking in good condition	LM: Clear continuity lines on both lane sides and consistent lane width			
						LM: Halt the practice of mixing yellow and white pavement markings on construction sites			
						LM: Remove redundant markings and phantom markings			
						LM: Minimum luminance coefficient (dry road surface) at hotspots: 130 mcd/lx/m2			
						LM: Minimum luminance coefficient (daytime) for all other road elements: 100 mcd/lx/m2			
						LM: Minimum retroreflectivity (dry road surface) at hotspots: 150 mcd/lx/m2			
						LM: Minimum retroreflectivity (dry road surface) for all other road elements: 100 mcd/lx/m2			
						LM: Minimum 3:1 contrast ratio between longitudinal pavement markings and surrounding substrate			
		Traffic signs (TS)	Yes	signs will be set up		TS: Traffic sign condition without wear	Yes		
						TS: Correct sign positioning without tilting	Yes		
						TS: Machine-readability			
						TS: Sign visibility without obstruction	Yes		
						TS: Placement of traffic signs in logical sequence without contradicting each other	Yes		information signs, bus signs for stations and waiting areas will be set up
		Sight distances (SD)	No		SD: Human intervention	SD: Elimination of visual obstructions at crossroads/intersections			
						SD: Prevention of phantom detections due to reflective surfaces			
		PT Hubs & stations (PTHS)	Yes	set up in planning		PTSH: Provide adequate space for maintenance, storage and charging facilities	Yes		not yet decided, concerns also shuttle depots, garage needs to be set up
						PTSH: Ensure barrier free accessibility to PT hubs and stations			not yet decided
						PTSH: Provide adequate space for waiting areas in PT hubs and stations			not yet decided
		Others	Yes	control of roadside vegetation		OTH: Evaluate safety level at unsignalized intersection			
						OTH: Fix pothols and cracks in road surface			
						OTH: Trim trees and bushes along the AV route	Yes		otherwise shuttle would detect branches as obstacles

Table 63: Proposed recommendations for the test site in Pörtschach.

Country	Test site	Indicated adaptions and measures of PI (yes/no)		If YES, what adaptation	If No, please give a reason (choose from the drop-down list)	Recommendations WP8 for PI adaptations	Recommen-dations implemented ….	Only if recommendation was NOT implemenetd please provide reasoning (choose from the drop-down list)	Comments
AT	Pörtschach	Lane markings (LM)	Yes			LM: Clear continuity lines on both lane sides and consistent lane width	No	LM: Vehicle technology not dependent on lane markings	
						LM: Halt the practice of mixing yellow and white pavement markings on construction sites	No	LM: Vehicle technology not dependent on lane markings	
						LM: Remove redundant markings and phantom markings	No	LM: Vehicle technology not dependent on lane markings	
						LM: Minimum luminance coefficient (dry road surface) at hotspots: 130 mcd/lx/m2	No	LM: Vehicle technology not dependent on lane markings	
						LM: Minimum luminance coefficient (daytime) for all other road elements: 100 mcd/lx/m2	No	LM: Vehicle technology not dependent on lane markings	
						LM: Minimum retroreflectivity (dry road surface) at hotspots: 150 mcd/lx/m2	Yes		lane markings on some parts of the roads were renewed. This is a nice to have but no must.
						LM: Minimum retroreflectivity (dry road surface) for all other road elements: 100 mcd/lx/m2	No	LM: Vehicle technology not dependent on lane markings	
						LM: Minimum 3:1 contrast ratio between longitudinal pavement markings and surrounding substrate	No	LM: Vehicle technology not dependent on lane markings	
		Traffic signs (TS)	Yes			TS: Traffic sign condition without wear	Yes		
						TS: Correct sign positioning without tilting	Yes		
						TS: Machine-readability			
						TS: Sign visibility without obstruction	Yes		
						TS: Placement of traffic signs in logical sequence without contradicting each other	Yes		information signs (test area for autonomous driving) were installed
		Sight distances (SD)	Yes			SD: Elimination of visual obstructions at crossroads/intersections	Yes		a mirror was installed to increase visibility for the operator at one intersection
						SD: Prevention of phantom detections due to reflective surfaces	Yes		
		PT Hubs & stations (PTHS)	Yes			PTSH: Provide adequate space for maintenance, storage and charging facilities	Yes		shuttle depots: not yet decided. Tent garage was used (not suitable for cold weahter conditions)
						PTSH: Ensure barrier free accessibility to PT hubs and stations	Yes		
						PTSH: Provide adequate space for waiting areas in PT hubs and stations	Yes		stops are clearly visible for passengers (autonomous driving signs)
		Others	Yes	control of roadside vegetation		OTH: Evaluate safety level at unsignalized intersection			
						OTH: Fix pothols and cracks in road surface	No	OTH: Road surface in adequate condition	
						OTH: Trim trees and bushes along the AV route	Yes		

Table 64: Proposed recommendations for the test site in Madrid Carabanchel.

Country	Test site	Indicated adaptions and measures of PI (yes/no)		If YES, what adaptation	If No, please give a reason (choose from the drop-down list)	Recommendations WP8 for PI adaptations	Recommen-dations implemented	Only if recommendation was NOT implemenetd please provide reasoning (choose from the drop-down list)	Comments
ES	Madrid Carabanchel	Lane markings (LM)	Yes	improve lane markings in the working area		LM: Clear continuity lines on both lane sides and consistent lane width			
						LM: Halt the practice of mixing yellow and white pavement markings on construction sites	Yes		Repaint the workplaces for a beter perception
						LM: Remove redundant markings and phantom markings			
						LM: Minimum luminance coefficient (dry road surface) at hotspots: 130 mcd/lx/m2			
						LM: Minimum luminance coefficient (daytime) for all other road elements: 100 mcd/lx/m2			
						LM: Minimum retroreflectivity (dry road surface) at hotspots: 150 mcd/lx/m2			
						LM: Minimum retroreflectivity (dry road surface) for all other road elements: 100 mcd/lx/m2			
						LM: Minimum 3:1 contrast ratio between longitudinal pavement markings and surrounding substrate	Yes		imptrove pedestrians crossing line detection
		Traffic signs (TS)	No		TS: No traffic signs along AV route	TS: Traffic sign condition without wear			
						TS: Correct sign positioning without tilting			
						TS: Machine-readability			
						TS: Sign visibility without obstruction			
						TS: Placement of traffic signs in logical sequence without contradicting each other			
		Sight distances (SD)	Yes	HD maps		SD: Elimination of visual obstructions at crossroads/intersections	Yes		use of HD maps and high perception
						SD: Prevention of phantom detections due to reflective surfaces	Yes		
		PT Hubs & stations (PTHS)	No		PTHS: Limited financial resources	PTSH: Provide adequate space for maintenance, storage and charging facilities			
						PTSH: Ensure barrier free accessibility to PT hubs and stations			
						PTSH: Provide adequate space for waiting areas in PT hubs and stations			
		Others	Yes	increase safety in the working area		OTH: Evaluate safety level at unsignalized intersection	Yes	OTH: other reasons (please specify in the comments field)	temporary road works: situations change daily; adaptations depending on the situations; the whole test site is a workinkg area; need to increase safety for the workers, and comunication when an AV is operating
						OTH: Fix pothols and cracks in road surface	No	OTH: Road surface in adequate condition	
						OTH: Trim trees and bushes along the AV route	No	OTH: Vegetation not relevant for AV	
		Others	Yes	safety at pedestrian corssings		OTH: Evaluate safety level at unsignalized intersection	Yes	OTH: other reasons (please specify in	improve safety
						OTH: Fix pothols and cracks in road surface			
						OTH: Trim trees and bushes along the AV route			
		Others	Yes	street side parking		OTH: Evaluate safety level at unsignalized intersection			improve detection of different vehicles parked like busses, lorries and cars
						OTH: Fix pothols and cracks in road surface			
						OTH: Trim trees and bushes along the AV route			

Table 65: Proposed recommendations for the test site in Madrid Villaverde.

Country	Test site	Indicated adaptions and measures of PI (yes/no)		If YES, what adaptation	If No, please give a reason (choose from the drop-down list)	Recommendations WP8 for PI adaptations	Recommen-dations implemented	Only if recommendation was NOT implemenetd please provide reasoning (choose from the drop-down list)	Comments
ES	Villaverde	Lane markings (LM)	Yes	Repaint the street for a beter perception, markings for curbs		LM: Clear continuity lines on both lane sides and consistent lane width	Yes		
						LM: Halt the practice of mixing yellow and white pavement markings on construction sites	No	LM: other reasons (please specify in the comments field)	curbs: yellow LM to avoid illegal parking in some places
						LM: Remove redundant markings and phantom markings			
						LM: Minimum luminance coefficient (dry road surface) at hotspots: 130 mcd/lx/m2			
						LM: Minimum luminance coefficient (daytime) for all other road elements: 100 mcd/lx/m2			
						LM: Minimum retroreflectivity (dry road surface) at hotspots: 150 mcd/lx/m2			
						LM: Minimum retroreflectivity (dry road surface) for all other road elements: 100 mcd/lx/m2			
						LM: Minimum 3:1 contrast ratio between longitudinal pavement markings and surrounding substrate			
		Traffic signs (TS)	Yes	improve visibility		TS: Traffic sign condition without wear			
						TS: Correct sign positioning without tilting			
						TS: Machine-readability			
						TS: Sign visibility without obstruction	Yes		prune various tree branches that cover some signs
						TS: Placement of traffic signs in logical sequence without contradicting each other			
		Sight distances (SD)	Yes	improving traffic light communication		SD: Elimination of visual obstructions at crossroads/intersections	No	SD: Signalized crossroads	
						SD: Prevention of phantom detections due to reflective surfaces	No	SD: Signalized crossroads	
		PT Hubs & stations (PTHS)	Yes	create areas for for bus stops		PTSH: Provide adequate space for maintenance, storage and charging facilities			
						PTSH: Ensure barrier free accessibility to PT hubs and stations			
						PTSH: Provide adequate space for waiting areas in PT hubs and stations	Yes		
		Others	Yes	road side vegetation, road condition		OTH: Evaluate safety level at unsignalized intersection	Yes		at junctions, road side parking
						OTH: Fix pothols and cracks in road surface	Yes		improve road condition
						OTH: Trim trees and bushes along the AV route	Yes		
		Others	Yes	street side parking		OTH: Evaluate safety level at unsignalized intersection			improve detection of different vehicles parked like busses, lorries and cars, observe and take action at places where vehicles are
						OTH: Fix pothols and cracks in road surface			
						OTH: Trim trees and bushes along the AV route			

Table 66: Proposed recommendations for the test site in Rouen.

Country	Test site	Vehicle type	Indicated adaptions and measures of PI (yes/no)		If YES, what adaptation	If No, please give a reason (choose from the drop-down list)	Recommendations WP8 for PI adaptations	Recommen-dations implemented	Only if recommendation was NOT implemenetd please provide reasoning (choose from the drop-down list)	Comments
FR	Rouen	5 i-Cristall shuttles (up to 16 people), built by Lohr and transdev, technology from Torc. 4 Renault Zoe robotaxis	Lane markings (LM)	No		LM: Lane marking in good condition	LM: Clear continuity lines on both lane sides and consistent lane width			
							LM: Halt the practice of mixing yellow and white pavement markings on construction sites			
							LM: Remove redundant markings and phantom markings			
							LM: Minimum luminance coefficient (dry road surface) at hotspots: 130 mcd/lx/m2			
							LM: Minimum luminance coefficient (daytime) for all other road elements: 100 mcd/lx/m2			
							LM: Minimum retroreflectivity (dry road surface) at hotspots: 150 mcd/lx/m2			
							LM: Minimum retroreflectivity (dry road surface) for all other road elements: 100 mcd/lx/m2			
							LM: Minimum 3:1 contrast ratio between longitudinal pavement markings and surrounding substrate			
			Traffic signs (TS)	No		TS: other reasons (please specify in the comments field)	TS: Traffic sign condition without wear			existing bus stop signs and warning signs of automated vehicles will be used
							TS: Correct sign positioning without tilting			
							TS: Machine-readability			
							TS: Sign visibility without obstruction			
							TS: Placement of traffic signs in logical sequence without contradicting each other			
			Sight distances (SD)	Yes	add traffic lights		SD: Elimination of visual obstructions at crossroads/intersections		SD: Signalized crossroads	Addition of a traffic light to increase safety on a limited visibility crossing
							SD: Prevention of phantom detections due to reflective surfaces		SD: Signalized crossroads	
			PT Hubs & stations (PTHS)	Yes	shuttle depots		PTSH: Provide adequate space for maintenance, storage and charging facilities	Yes		for shuttle depots: using an existing workshop close to the test site, adapting it to our needs
							PTSH: Ensure barrier free accessibility to PT hubs and stations			
							PTSH: Provide adequate space for waiting areas in PT hubs and stations	Yes		set up of a new platform to the Zenith terminal and a bus bay at Cateliers terminal
			Others	Yes	traffic lights		OTH: Evaluate safety level at unsignalized intersection	Yes		installation of traffic lights where needed
							OTH: Fix pothols and cracks in road surface	No	OTH: Road surface in adequate condition	
							OTH: Trim trees and bushes along the AV route	No	OTH: Vegetation not relevant for AV	

Table 67: Proposed recommendations for the test site inTrikala.

Country	Test site	Indicated adaptions and measures of PI (yes/no)		If YES, what adaptation	If No, please give a reason (choose from the drop-down list)	Recommendations WP8 for PI adaptations	Recommen-dations implemented ….	Only if recommendation was NOT implemenetd please provide reasoning (choose from the drop-down list)	Comments
GR	Trikala	Lane markings (LM)	Yes			LM: Clear continuity lines on both lane sides and consistent lane width	Yes		also in terms of road side parking
						LM: Halt the practice of mixing yellow and white pavement markings on construction sites			Lane markings will be enhanced according to the standards and national legislation
						LM: Remove redundant markings and phantom markings			
						LM: Minimum luminance coefficient (dry road surface) at hotspots: 130 mcd/lx/m2			
						LM: Minimum luminance coefficient (daytime) for all other road elements: 100 mcd/lx/m2			
						LM: Minimum retroreflectivity (dry road surface) at hotspots: 150 mcd/lx/m2			
						LM: Minimum retroreflectivity (dry road surface) for all other road elements: 100 mcd/lx/m2			
						LM: Minimum 3:1 contrast ratio between longitudinal pavement markings and surrounding substrate			
		Traffic signs (TS)	Yes			TS: Traffic sign condition without wear			
						TS: Correct sign positioning without tilting			
						TS: Machine-readability			
						TS: Sign visibility without obstruction			
						TS: Placement of traffic signs in logical sequence without contradicting each other			
		Sight distances (SD)	Yes		SD: Signalized crossroads	SD: Elimination of visual obstructions at crossroads/intersections	No	SD: Signalized crossroads	traffic lights will just work when the AV approaches the intersection
						SD: Prevention of phantom detections due to reflective surfaces	No	SD: Signalized crossroads	some pedestrian crossings will be regulated by traffic lights
		PT Hubs & stations (PTHS)	No		PTHS: other reasons (please specify in the comments field)	PTSH: Provide adequate space for maintenance, storage and charging facilities			The design of the terminal and the depot is under investigation. No major adaptations are however expected.
						PTSH: Ensure barrier free accessibility to PT hubs and stations			
						PTSH: Provide adequate space for waiting areas in PT hubs and stations			
		Others	Yes	traffic lights, pedestrian corssings, street side parking regulated by the police		OTH: Evaluate safety level at unsignalized intersection	Yes		installation of traffic lights where needed, road side parking?
						OTH: Fix pothols and cracks in road surface	Yes		road condition maintenace due to weather conditions; road will be checked and roadworks will be performed for all the potholes on the route
						OTH: Trim trees and bushes along the AV route	No	OTH: Vegetation not relevant for AV	

Table 68: Proposed recommendations for the test site in Turin.

Country	Test site	Indicated adaptions and measures of PI (yes/no)		If YES, what adaptation	If No, please give a reason (choose from the drop-down list)	Recommendations WP8 for PI adaptations	Recommen-dations implemented	Only if recommendation was NOT implemenetd please provide reasoning (choose from the drop-down list)	Comments
IT	Torino	Lane markings (LM)	No			LM: Clear continuity lines on both lane sides and consistent lane width			
						LM: Halt the practice of mixing yellow and white pavement markings on construction sites			
						LM: Remove redundant markings and phantom markings			
						LM: Minimum luminance coefficient (dry road surface) at hotspots: 130 mcd/lx/m2			
						LM: Minimum luminance coefficient (daytime) for all other road elements: 100 mcd/lx/m2			
						LM: Minimum retroreflectivity (dry road surface) at hotspots: 150 mcd/lx/m2			
						LM: Minimum retroreflectivity (dry road surface) for all other road elements: 100 mcd/lx/m2			
						LM: Minimum 3:1 contrast ratio between longitudinal pavement markings and surrounding substrate			
		Traffic signs (TS)	Yes			TS: Traffic sign condition without wear			The route will be equipped with traffic signs (warning/informative signs) to warn the public about the presence of an AV. Estimation is
						TS: Correct sign positioning without tilting	Yes		
						TS: Machine-readability			
						TS: Sign visibility without obstruction			
						TS: Placement of traffic signs in logical sequence without contradicting each other			
		Sight distances (SD)	No			SD: Elimination of visual obstructions at crossroads/intersections			
						SD: Prevention of phantom detections due to reflective surfaces			
		PT Hubs & stations (PTHS)	No			PTSH: Provide adequate space for maintenance, storage and charging facilities			
						PTSH: Ensure barrier free accessibility to PT hubs and stations			
						PTSH: Provide adequate space for waiting areas in PT hubs and stations			
		Others	No			OTH: Evaluate safety level at unsignalized intersection			
						OTH: Fix pothols and cracks in road surface			
						OTH: Trim trees and bushes along the AV route			

Table 69: Proposed recommendations for the test site in Gothenburg.

Country	Test site	Indicated adaptions and measures of PI (yes/no)		If YES, what adaptation	If No, please give a reason (choose from the drop-down list)	Recommendations WP8 for PI adaptations	Recommen-dations implemented	Only if recommendation was NOT implemenetd please provide reasoning (choose from the drop-down list)	Comments
SE	Gothenburg	Lane markings (LM)	Yes	will be evaluated		LM: Clear continuity lines on both lane sides and consistent lane width			could be added
						LM: Halt the practice of mixing yellow and white pavement markings on construction sites			
						LM: Remove redundant markings and phantom markings			
						LM: Minimum luminance coefficient (dry road surface) at hotspots: 130 mcd/lx/m2			
						LM: Minimum luminance coefficient (daytime) for all other road elements: 100 mcd/lx/m2			
						LM: Minimum retroreflectivity (dry road surface) at hotspots: 150 mcd/lx/m2			
						LM: Minimum retroreflectivity (dry road surface) for all other road elements: 100 mcd/lx/m2			
						LM: Minimum 3:1 contrast ratio between longitudinal pavement markings and surrounding substrate			
		Traffic signs (TS)	Yes	signs as information for all road users		TS: Traffic sign condition without wear			
						TS: Correct sign positioning without tilting			
						TS: Machine-readability			
						TS: Sign visibility without obstruction			
						TS: Placement of traffic signs in logical sequence without contradicting each other	Yes		Sign Information on poles that an autonomous bus is running in the area
		Sight distances (SD)	No			SD: Elimination of visual obstructions at crossroads/intersections			
						SD: Prevention of phantom detections due to reflective surfaces			
		PT Hubs & stations (PTHS)	Yes	simple bus stops		PTSH: Provide adequate space for maintenance, storage and charging facilities	Yes		also for shuttle depots, using depot or garage very close to the operated route
						PTSH: Ensure barrier free accessibility to PT hubs and stations			simple busstop with poles and signs and possibly bus shelters
						PTSH: Provide adequate space for waiting areas in PT hubs and stations			
		Others	Yes	road side vegetation, road works, sparate lane for AV, narrow lane section, accident hot spots		OTH: Evaluate safety level at unsignalized intersection	Yes		also around road works and accident hot spots, narrow lane section: install digital priority zones, and lower speeds
						OTH: Fix pothols and cracks in road surface			
						OTH: Trim trees and bushes along the AV route	Yes		

Table 70: Proposed recommendations for the test site in Linköping.

Country	Test site	Indicated adaptions and measures of PI (yes/no)		If YES, what adaptation	If No, please give a reason (choose from the drop-down list)	Recommendations WP8 for PI adaptations	Recommen-dations implemented ….	Only if recommendation was NOT implemenetd please provide reasoning (choose from the drop-down list)	Comments
SE	Linköping	Lane markings (LM)	No		LM: Adverse weather conditions (snow, rain, fog etc.)	LM: Clear continuity lines on both lane sides and consistent lane width			
						LM: Halt the practice of mixing yellow and white pavement markings on construction sites			
						LM: Remove redundant markings and phantom markings			
						LM: Minimum luminance coefficient (dry road surface) at hotspots: 130 mcd/lx/m2			
						LM: Minimum luminance coefficient (daytime) for all other road elements: 100 mcd/lx/m2			
						LM: Minimum retroreflectivity (dry road surface) at hotspots: 150 mcd/lx/m2			
						LM: Minimum retroreflectivity (dry road surface) for all other road elements: 100 mcd/lx/m2			
						LM: Minimum 3:1 contrast ratio between longitudinal pavement markings and surrounding substrate			
		Traffic signs (TS)	No		TS: Traffic signs provided by digital infrastructure	TS: Traffic sign condition without wear			no special road or traffic signs, except the bus stop signs and LIDAR panels have been added for or in relation to the use of the AV:s
						TS: Correct sign positioning without tilting			
						TS: Machine-readability			
						TS: Sign visibility without obstruction			
						TS: Placement of traffic signs in logical sequence without contradicting each other			
		Sight distances (SD)	No			SD: Elimination of visual obstructions at crossroads/intersections			
						SD: Prevention of phantom detections due to reflective surfaces			
		PT Hubs & stations (PTHS)	Yes			PTSH: Provide adequate space for maintenance, storage and charging facilities	Yes		also for shuttle depots
						PTSH: Ensure barrier free accessibility to PT hubs and stations	Yes		The AV bus route has partly its own specially designed station
						PTSH: Provide adequate space for waiting areas in PT hubs and stations	Yes		
		Others	Yes	road side vegetation, road works		OTH: Evaluate safety level at unsignalized intersection	Yes		also around road works
						OTH: Fix pothols and cracks in road surface	Yes		road conditions maintenance due to weather events, organisation of a more rigorous removal of heaps of snow. The internal LIDAR maps could not adapt to the new snowy landscape. Road works: rerouting of the AV due to ongoing constuction areas was neessary
						OTH: Trim trees and bushes along the AV route	Yes		

Test site Thessaloniki: according to our knowledge does not take any adaptations

Test site Mohnheim: due to the late participation in the SHOW project we do not have any in-depth information for this test site yet.

8.2.2 Recommendations to improve HD-Maps

Based on the findings from chapter 7, which deals with the state of the art of HD maps as well as with the development of a workflow for generating a digital dynamic map, specific recommendations were developed to improve the HD maps at the SHOW test sites. These recommendations build on the defined workflow, which states that a HD map should ideally consist of four layers:

- Static information
- Traffic regulations/rules
- Quality information
- Dynamic real-time information

In Table 71, the HD maps at the test sites (information gathered builds on the site overview in chapter 7.1) are shown, including their recommendations and possible reasons for a limited HD map. The description of the map was cut down to the following categories:

- Map type
- Map accuracy
- Fixed virtual track existing
- Map usage
- Map database

Based on these categories, recommendations to improve the maps were given. Each site was given one recommendation, which seemed the most important. Vectorized maps with high accuracy and different usages, without driving on a virtual track were considered as more evolved and got higher level recommendations like including quality information or real-time information. Maps that focus on a depicted area are recommended to be extended to a full-coverage map, because this allows more path flexibility. Another important recommendation was to include updates or generate an update plan, as an up-to-date map is essential to guarantee safe vehicle operation. The four recommendations, of which one was chosen for each site, were:

- Regular update of digital maps
- Include quality information
- Development of HD map (that covers the whole street) for path flexibility
- Integrate real-time information

Given the recommendations, it was clear from the state of the art, that many details for HD maps are still open to discussion, as e.g. different vehicles need and use different maps and information. Because of this, the specific recommendation might not be fulfilled by the test sites, as the vehicle does not need this information, or this information is not available at the site. So, the map will stay limited and won't fulfil the 4-layer-map concept developed in chapter 7.2. The developed reasons for a limited map were:

- Flexible navigation possible through vehicle sensors and GNSS
- Drive on fixed vehicle trajectory
- Real-time information is not used by the vehicle
- Updates are exhaustive
- Quality information is not used by the vehicle.

- None

Nevertheless, the recommendations and reasons for limited HD maps show in an exemplary way how maps are used within current urban pilot projects and connect them to the developed ideal HD map design.

Table 71: Description of HD maps and concluded recommendations for SHOW test sites.

Test site		HD map									
					For what is the map used?						
Country	Site name	Map type	Map accuracy	Fixed virtual track?	Localisation	Predicting other road users' behaviour	Planning/ predicting own behaviour	Simulation	Map database	Recommendations based on the information given for the existing map	Reasons for limited HD map
Austria	**Salzburg**	vectorized HD map	< 10 cm	Can be generated from the map	yes	yes	yes	yes	Vehicle drive	Regular update of digital maps	None
Austria	**Graz**	vectorized HD map	< 10 cm	yes	yes	no	yes	yes	Vehicle drive	Integrate real-time information	N/A
Austria	**Carinthia (Pörtschach and Klagenfurt)**	LiDAR map	< 10 cm	yes	yes	no	no	no	Vehicle drive	Development of HD map (that covers the whole street) for path flexibility	Drive on fixed vehicle trajectory
Germany	**Karlsruhe**	vectorized HD map	< 10 cm	no	no	yes	yes	yes	Merge of existing data bases	Development of HD map (that covers the whole street) for path flexibility	Flexible navigation possible through vehicle sensors and GNSS
Czech Republic	**Brno**	vectorized HD map	> 10 cm	no	yes	no	yes	no	Vehicle drive	Integrate real-time information	Real-time information is not used by the vehicle
France	**Rouen**	LiDAR map	< 10 cm	no	yes	no	yes	no	Vehicle drive	Regular update of digital maps	Flexible navigation possible through vehicle sensors and GNSS
Spain	**Madrid**	vectorized HD map	N/A	no	yes	yes	yes	yes	Merge of existing data bases	Regular update of digital maps	Updates are exhaustive
Finland	**Tampere (map created and used by sensible 4, the vehicle provider)**	LiDAR map	< 10 cm	no	yes	yes	yes	no	Merge of existing data bases	Development of HD map (that covers the whole street) for path flexibility	Flexible navigation possible through vehicle sensors and GNSS
Finland	**Tampere (digital twin)**	vectorized HD map	> 10 cm	no	no	no	no	yes	Merge of existing data bases	Include quality information	Quality information is not used by the vehicle.

Test site		HD map									
					For what is the map used?						
Country	Site name	Map type	Map accuracy	Fixed virtual track?	Localisation	Predicting other road users' behaviour	Planning/ predicting own behaviour	Simulation	Map database	Recommendations based on the information given for the existing map	Reasons for limited HD map
Greece	**Trikala**	other (possibly no HD map)	Road graph	no	no	no	no	no	Merge of existing data bases	Development of HD map (that covers the whole street) for path flexibility	Drive on fixed vehicle trajectory
Netherlands	**Brainport Eindhoven**	other (possibly no HD map)	> 10 cm	no	no	yes	yes	no	Vehicle drive	Regular update of digital maps	Real-time information is not used by the vehicle
Switzerland	**Geneva**	LiDAR map	< 10 cm	Can be generated from the map	yes	no	yes	yes	Vehicle drive	Integrate real-time information	N/A
Germany	**Monheim**	Not known yet.									
Sweden	**Gothenburg**	Not applicable.									
Sweden	**Linköping**	Not applicable.									
Italy	**Turin**	Not applicable.									
Greece	**Thessaloniki**	Not applicable.									

References

[1] Ulrich, S., Kulmala, R., Appel, K., Aiger, W., Tenttinen, M., Laitinen, J., & Deliverable, D. (2020). MANTRA: Making full use of Automation for National Transport and Road Authorities - NRA Core Business. D4.2 Consequences of automation functions to infrastructure.

[2] TRIMIS, https://trimis.ec.europa.eu/

[3] connectedautomateddriving.eu, https://www.connectedautomateddriving.eu/

[4] CORDIS, https://cordis.europa.eu/

[5] Mocanu, I.; Nitsche, P.; Saleh, P. (2015): Highly automated driving and its requirements on road planning and design, 25th World Road Congress, Seoul.

[6] AUSTRIAN STANDARDS (2018): Road marking materials – Road marking performance for road users and test methods, ÖNORM EN 1436, Wien.

[7] CASOL, M.; FIORENTIN, P.; SCROCCARO, A. (2008): On road measurements of the luminance coefficient of paving, 16th IMEKO TC4 Symposium, Sept. 22-24, 2008, Florence, Italy.

[8] AUSTROADS (2020): Implications of pavement markings for machine vision, Research report AP-R633-20, ISBN 978-1-922382-25-2, Sidney.

[9] BABIC, D.; FIOLIC, M.; PRUSA, P. (2014): Evaluation of road markings retroreflection. European Scientific Journal, pp. 105-114.

[10] NCHRP – NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM: Evaluation of the effects of pavement marking characteristics on detectability by ADAS machine vision, Project No. 20-102(06), Washington DC.

[11] HADI, M.; SINHA, P.; EASTERLING IV, J.R. (2007): Effect of environmental conditions on performance of image recognition-based lane departure warning systems, Transportation Research Record, no. 2000, pp. 114-120.

[12] DAVIES, C. (2017): Effects of pavement marking characteristics on machine vision technology, TRB 2017 Annual meeting, Washington DC.

[13] EuroRAP (2013): Roads that cars can read – a quality standard for road markings and traffic signs on major rural roads, Download: http://www.eurorap.org/wp-content/uploads/2015/04/20110629-Roads-That-Cars-Can-Read-June-2011.pdf, Inquiry date: 23.03.2021

[14] AUSTROADS (2018): Harmonisation of pavement markings and national pavement marking specification, Research Report AP-R578-18, Sydney.

[15] Møgelmose, A.; Trivedi, M.M.; Moeslund, T.B. Vision-Based Traffic Sign Detection and Analysis for Intelligent Driver Assistance Systems: Perspectives and Survey. IEEE Trans. Intell. Transp. Syst. 2012, 13, 1484–1497

[16] Economic Commission for Europe-Inland Transport Committee, ‘‘Convention on road signs and signals,’’ United Nations Treaty Ser., vol. 1091, p. 3, Nov. 1968.

[17] Gamez Serna, Citlalli & Ruichek, Yassine. (2018). Classification of Traffic Signs: The European Dataset. IEEE Access. PP. 1-1. 10.1109/ACCESS.2018.2884826

[18] Lengyel, Henrietta & Szalay, Zsolt. (2018). Traffic sign anomalies and their effects to the highly automated and autonomous vehicles.

[19] ÁDÁM NYERGES, ZSOLT SZALAY, 2017, A new approach for the testing and validation of connected and automated vehicles, 34th International Colloquium on Advanced Manufacturing and Repairing Technologies in Vehicle Industry.

[20] Madani, A.; Yusof, R. Malaysian Traffic Sign Dataset for Traffic Sign Detection and Recognition Systems. J. Telecommun. Electron. Comput. Eng. (JTEC) 2016, 8, 137–143.

[21] Liu, H.; Ran, B. Vision-based stop sign detection and recognition system for intelligent vehicles. Transp. Res. Rec. J. Transp. Res. Board 2001, 1748, 161–166.

[22] Wali, S.B.; Abdullah, M.A.; Hannan, M.A.; Hussain, A.; Samad, S.A.; Ker, P.J.; Mansor, M.B. Vision-Based Traffic Sign Detection and Recognition Systems: Current Trends and Challenges. Sensors 2019, 19, 2093.

[23] Nandi, D.; Saif, A.S.; Prottoy, P.; Zubair, K.M.; Shubho, S.A. Traffic Sign Detection based on Color Segmentation of Obscure Image Candidates: A Comprehensive Study. Int. J. Mod. Educ. Comput. Sci. 2018, 10, 35.

[24] Hannan, M.; Hussain, A.; Mohamed, A.; Samad, S.A.; Wahab, D.A. Decision fusion of a multi-sensing embedded system for occupant safety measures. Int. J. Automot. Technol. 2010, 11, 57–65.

[25] Møgelmose, A.; Trivedi, M.M.; Moeslund, T.B. Vision-Based Traffic Sign Detection and Analysis for Intelligent Driver Assistance Systems: Perspectives and Survey. IEEE Trans. Intell. Transp. Syst. 2012, 13, 1484–1497.

[26] Shao, F.; Wang, X.; Meng, F.; Rui, T.; Wang, D.; Tang, J. Real-time traffic sign detection and recognition method based on simplified Gabor wavelets and CNNs. Sensors 2018, 18, 3192.

[27] Guo, J.; Lu, J.; Qu, Y.; Li, C. Traffic-Sign Spotting in the Wild via Deep Features. In Proceedings of the 2018 IEEE Intelligent Vehicles Symposium (IV), Changshu, China, 26–30 June 2018; pp. 120–125

[28] Zabihi, S.J.; Zabihi, S.M.; Beauchemin, S.S.; Bauer, M.A. Detection and recognition of traffic signs inside the attentional visual field of drivers. In Proceedings of the 2017 IEEE Intelligent Vehicles Symposium (IV), Los Angeles, CA, USA, 11–14 June 2017.

[29] Chang, X.; Yang, Y. Semisupervised feature analysis by mining correlations among multiple tasks. IEEE Trans. Neural Netw. Learn. Syst. 2017, 28, 2294–2305.

[30] Saadna, Y.; Behloul, A. An overview of traffic sign detection and classification methods. Int. J. Multimed. Inf. Retr. 2017, 6, 193–210.

[31] Saxena, P.; Gupta, N.; Laskar, S.Y.; Borah, P.P. A study on automatic detection and recognition techniques for road signs. Int. J. Comput. Eng. Res. 2015, 5, 24–28

[32] Yuan, Y.; Xiong, Z.; Wang, Q. An incremental framework for video-based traffic sign detection, tracking, and recognition. IEEE Trans. Intell. Transp. Syst. 2017, 18, 1918–1929.

[33] Kuang, X.; Fu, W.; Yang, L. Real-Time Detection and Recognition of Road Traffic Signs using MSER and Random Forests. Int. J. Online Eng. (IJOE) 2018, 14, 34–51.

[34] Xu, X.; Jin, J.; Zhang, S.; Zhang, L.; Pu, S.; Chen, Z. Smart data driven traffic sign detection method based on adaptive color threshold and shape symmetry. Future Gener. Comput. Syst. 2019, 94, 381–391.

[35] Convention on Road Signs and Signals (1968 & rev. 2019): Download: http://www.unece.org/fileadmin/DAM/trans/conventn/Conv_road_signs_2006v_EN.pdf, Inquiry date: 07.04.2021

[36] De La Escalera, A.; Armingol, J.M.; Pastor, J.M.; Rodríguez, F.J. Visual sign information ex-traction and identification by deformable models for intelligent vehicles. IEEE Trans. Intell. Transp. Syst. 2004, 5, 57–68.

[37] Gómez-Moreno, H.; Maldonado-Bascón, S.; Gil-Jiménez, P.; Lafuente-Arroyo, S. Goal evalua-tion of segmentation algorithms for traffic sign recognition. IEEE Trans. Intell. Transp. Syst. 2010, 11, 917–930.

[38] Ren, F.; Huang, J.; Jiang, R.; Klette, R. General traffic sign recognition by feature matching. In Proceedings of the 24th International Conference on Image and Vision Computing New Zealand, IVCNZ'09, Wellington, New Zealand, 23–25 November 2009; pp. 409–414.

[39] Fleyeh, H. Shadow and highlight invariant colour segmentation algorithm for traffic signs. In Proceedings of the 2006 IEEE Conference on Cybernetics and Intelligent Systems, Bangkok, Thailand, 7–9 June 2006; pp. 1–7

[40] Maldonado-Bascón, S.; Lafuente-Arroyo, S.; Gil-Jimenez, P.; Gómez-Moreno, H.; López-Ferreras, F. Road-sign detection and recognition based on support vector machines. IEEE Trans. Intell. Transp. Syst. 2007, 8, 264–278.

[41] Gündüz, H.; Kaplan, S.; Günal, S.; Akınlar, C. Circular traffic sign recognition empowered by circle detection algorithm. In Proceedings of the 2013 21st Signal Processing and Communications Applications Conference (SIU), Haspolat, Turkey, 24–26 April 2013; pp. 1–4.

[42] Hu, Q.; Paisitkriangkrai, S.; Shen, C.; van den Hengel, A.; Porikli, F. Fast detection of multiple objects in traffic scenes with a common detection framework. IEEE Trans. Intell. Transp. Syst. 2016, 17, 1002–1014.

[43] Zhu, Z.; Lu, J.; Martin, R.R.; Hu, S. An optimization approach for localization refinement of candidate traffic signs. IEEE Trans. Intell. Transp. Syst. 2017, 18, 3006–3016

[44] Bahlmann, C.; Zhu, Y.; Ramesh, V.; Pellkofer, M.; Koehler, T. A system for traffic sign detec-tion, tracking, and recognition using color, shape, and motion information. In Proceedings of the Intelligent Vehicles Symposium, Las Vegas, NY, USA, 6–8 June 2005; pp. 255–260.

[45] Chiang, H.-H.; Chen, Y.-L.; Wang, W.-Q.; Lee, T.-T. Road speed sign recognition using edge-voting principle and learning vector quantization network. In Proceedings of the 2010 Interna-tional Computer Symposium (ICS), Tainan, Taiwan, 16–18 December 2010; pp. 246–251.

[46] Gu, Y.; Yendo, T.; Tehrani, M.P.; Fujii, T.; Tanimoto, M. Traffic sign detection in dual-focal active camera system. In Proceedings of the 2011 IEEE Intelligent Vehicles Symposium (IV), Ba-den-Baden, Germany, 5–9 June 2011; pp. 1054–1059.

[47] Wang, G.; Ren, G.; Wu, Z.; Zhao, Y.; Jiang, L. A robust, coarse-to-fine traffic sign detection method. In Proceedings of the 2013 International Joint Conference on Neural Networks (IJCNN), Dallas, TX, USA, 4–9 August 2013; pp. 1–5.

[48] Loy, G.; Barnes, N. Fast shape-based road sign detection for a driver assistance system. In Proceedings of the 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems, (IROS 2004), Sendai, Japan, 28 September–2 October 2004; pp. 70–75.

[49] Fu, M.-Y.; Huang, Y.-S. A survey of traffic sign recognition. In Proceedings of the 2010 Inter-national Conference on Wavelet Analysis and Pattern Recognition (ICWAPR), Qingdao, China, 11–14 July 2010; pp. 119–124.

[50] Lafuente-Arroyo, S.; Maldonado-Bascon, S.; Gil-Jimenez, P.; Acevedo-Rodriguez, J.; Lopez-Sastre, R. A tracking system for automated inventory of road signs. In Proceedings of the 2007 IEEE Intelligent Vehicles Symposium, Istanbul, Turkey, 13–15 June 2007; pp. 166–171.

[51] Lafuente-Arroyo, S.; Maldonado-Bascon, S.; Gil-Jimenez, P.; Gomez-Moreno, H.; Lopez-Ferreras, F. Road sign tracking with a predictive filter solution. In Proceedings of the IECON 2006—32nd Annual Conference on IEEE Industrial Electronics, Paris, France, 6–10 November 2006; pp. 3314–3319.

[52] Wali, S.B.; Abdullah, M.A.; Hannan, M.A.; Hussain, A.; Samad, S.A.; Ker, P.J.; Mansor, M.B. Vision-Based Traffic Sign Detection and Recognition Systems: Current Trends and Challenges. Sensors 2019, 19, 2093

[53] Alturki, A.S. Traffic Sign Detection and Recognition Using Adaptive Threshold Segmentation with Fuzzy Neural Network Classification. In Proceedings of the 2018 International Symposium on Networks, Computers and Communications (ISNCC), Rome, Italy, 19–21 June 2018; pp. 1–7.

[54] Khan, J.; Yeo, D.; Shin, H. New dark area sensitive tone mapping for deep learning based traffic sign recognition. Sensors 2018, 18, 3776.

[55] Laguna, R.; Barrientos, R.; Blázquez, L.F.; Miguel, L.J. Traffic sign recognition application based on image processing techniques. IFAC Proc. Vol. 2014, 47, 104–109.

[56] Satılmı¸s, Y.; Tufan, F.; ¸Sara, M.; Karslı, M.; Eken, S.; Sayar, A. CNN Based Traffic Sign Recog-nition for Mini Autonomous Vehicles. In Proceedings of the International Conference on Infor-mation Systems Architecture and Technology, Nysa, Poland, 16–18 September 2018; pp. 85–94.

[57] ČSN 73 6101 Projektování silnic a dálnic. Praha: Český normalizační institut, 2004

[58] ČSN 73 6102 Projektování křižovatek na pozemních komunikacích, ed.2. Praha: Český normalizační institut, 2012.

[59] Arndt, O., R. Cox, D. Barton and G. Veith. Development of the sight distance criteria in the Austroads Guide to Road Design series. Australian Road Research Board | 2010. print version. 18 Geometric road design for heavy vehicles - advancing but still a way to go.

[60] Capaldo, F. Driver Eye Height: Experimental Determination and Implications on Sight Distances. In Procedia - Social and Behavioral Sciences 43: 375–383, 2012. DOI: https://doi.org/10.1016/j.sbspro.2012.04.111

[61] AASHTO. The Green Book: A Policy on Geometric Design of Highways and Streets, 7th Edition, 2018

[62] FRANK H.; REINSBERG, H. (2014): Leitfaden Fahrbahnmarkierung, Deutscher Verkehrssicherheitsrat, Bonn. Download: https://dsgs.de/data/CMM_Contents/files/Publikationen/Leitfaden-Fahrbahnmarkierung-DVR-DSGS-1.pdf, Inquiry date: 07.04.2021

[63] VwV-StVO (2001): Allgemeine Verwaltungsvorschrift zur Straßenverkehrsordnung

[64] KAMPS, M.; WIDLROITHER, H.; LEUTERITZ, J.P. (2020): D7.7: Application guidelines and standardisation, SAFESTRIP Project.

[65] Austrian Standards (1994): Graphic symbols for public information - General principles, Austrian Normative A 3011. Vienna

[66] Austrian Standards (1994): Visual guiding systems for public information - Orientation supported by directional arrows, graphic symbols, text, light and color, Austrian Normative A 3012, Vienna

[67] Austrian Standards (2017): Accessible built environment - Design principles, Austrian Normative B 1600, Vienna

[68] Austrian Standards (2013): Accessible healthcare facilities, assistive housing, and workplaces - Design principles, Austrian Normative B 1601, Vienna

[69] Austrian Standards (2019): Lifts, escalators and passenger conveyors, Austrian Normative 2450-1,-2,-3, Vienna

[70] Austrian Standards (2014): Technical aids for visually impaired and blind persons - Tactile references on control panels for pedestrians, Austrian Normative V 2100, Vienna

[71] Austrian Standards (2015): Acoustical and tactile auxiliary signals for traffic-lights - Technical aids for partially sighted and blind persons, Austrian Normative V 2101, Vienna

[72] Austrian Standards (2018): Tactile walking surface indicators (TWSI) - Technical aids for blind and partially sighted persons, Austrian Normative V 2102, Vienna

[73] Austrian Standards (2020): Remote activation options for acoustics and tactile signals and information - Technic aids for partially sighted and blind people, Austrian Normative V 2103, Vienna

[74] Austrian Standards (2012): Technical aids for visually impaired, blind and mobility impaired persons - Safety devices for construction and dangerous sites, Austrian Normative V 2104, Vienna

[75] Austrian Standards (2011): Technical aids for visually impaired and blind persons - Tactile inscriptions and information systems, Austrian Normative V 2105, Vienna

[76] CITY OF VIENNA (2011): Design manual for the public space (German only). Download: https://www.wien.gv.at/stadtentwicklung/studien/pdf/b008199.pdf, Vienna

[77] City of Vienna (2020): Project Homepage new Metro Lines U2/U5 in the City of Vienna, Download: https://u2u5.wien.gv.at/

[78] McKinsey (2019): A New Look at Autonomous Vehicle Infrastructure, 2019, Download: https://www.mckinsey.com/industries/travel-logistics-and-infrastructure/our-insights/a-new-look-at-autonomous-vehicle-infrastructure#

[79] AONO, S. (2019): Identifying Best Practices for Mobility Hubs, TransLink.

[80] AMBROZ, D.; WILSON, R.; AHN, R. (2012): A Reader's Guide, Download: http://www.urbandesignla.com/resources/docs/MobilityHubsReadersGuide/hi/MobilityHubsReadersGuide.pdf

[81] CROWTHER, J.; MANGLE, K.; ABE, D.; MAINES, K. (2020): Mobility Hub Typology Study, Portland Bureau of Transportation. Download: https://altago.com/wp-content/uploads/PBOT-Mobility-Hub-Typology_June2020.pdf

[82] AVENUE, Figure. At https://h2020-avenue.eu/, first accessed 23rd May 2020

[83] Fournier, G., et al (2018). D2.7 First Stakeholder Analysis and AVENUE strategies. Transport operator's perspectives and research agenda, AVENUE project, available at https://h2020-avenue.eu/wp-content/uploads/2020/07/D2-7-First-Stakeholder-Analysis-and-AVENUE-strategies.pdf, first accessed 23rd May 2020

[84] Morandin, G., et al (2019). HEADSTART D1.2 Stakeholders and user group needs. HEADSTART project, available at https://www.headstart-project.eu/results-to-date/deliverables/, first accessed 28th April 2020

[85] Skoglund, M. et al (2019). HEADSTART D.1.4 Functional requirements of selected use cases, available at https://www.headstart-project.eu/results-to-date/deliverables/, first accessed 23rd May 2020

[86] HEADSTART, Figure. At https://www.headstart-project.eu/, first accessed 28th April 2020

[87] LEVITATE (2017). Website and figure at https://levitate-project.eu/, first accessed 23rd May 2020

[88] L3Pilot, Figure. At www.l3pilot.eu, first accessed 26th May 2020

[89] Metz, B., et al (2019). Deliverable 3.3 Evaluation methods, L3Pilot project, available at https://l3pilot.eu/fileadmin/user_upload/L3Pilot-SP3-D3.3_Evaluation_Methods-v1.0_DRAFT_for_website.pdf, first accessed 26th May 2020

[90] Hibberd, D., (2018). Deliverable 3.1 From Research Questions to Logging Requirements, L3Pilot project, available at https://l3pilot.eu/fileadmin/user_upload/L3Pilot-SP3-D3.3_Evaluation_Methods-v1.0_DRAFT_for_website.pdf, first accessed 26th May 2020

[91] InterACT (2017). Website and figure at https://www.interact-roadautomation.eu/, first accessed 21st November 2020

[92] TrustVehicle, Figure. At https://www.trustvehicle.eu/, first accessed 16th July 2020

[93] Sözen, E., et al (2019). Deliverable 6.4 Traffic Scenarios for Final Validation, TrustVehicle project, available at http://www.trustvehicle.eu/wp-content/uploads/2019/11/TrustVehicle_D6.4_final.pdf, first accessed 16th July 2020

[94] BRAVE (2017). Website and figure at http://www.brave-project.eu/, first accessed 23rd May 2020

[95] VI-DAS (2016). Website and figure at http://www.vi-das.eu/, first accessed 23rd May 2020

[96] ADAS&ME, Figure. At https://www.adasandme.com/, first accessed 16th July 2020

[97] Annund, A. (2020). Deliverable 10.4 – Project Final Report, ADAS&ME project, available at https://www.adasandme.com/wp-content/uploads/2020/04/D10.4-Project-Final-Report.pdf, first accessed 16th July 2020

[98] AUTOMATE (2016). Website and figure at http://www.automate-project.eu/, first accessed 16th July 2020]

[99] CoEXist (2017). Website and figure at https://www.h2020-coexist.eu/, first accessed 16th July 2020

[100] INFRAMIX, Figure. At https://www.inframix.eu/, first accessed 16th July 2020

[101] Manganiaris, S., et al (2019). D5.4 Infrastructure Classification Scheme. INFRAMIX project, available at https://www.inframix.eu/wp-content/uploads/D5.4-Infrastructure-Classification-Scheme.pdf, first accessed 16th July 2020

[102] SAE (2018). Taxonomy and Definitions for Terms Related to Driving Automation Systems for On- Road Motor Vehicles. J3016-101806. Available at https://www.sae.org/standards/content/j3016_201806/, first accessed 14th April 2021

[103] TransAID (2017). Website and figure at https://www.transaid.eu/, first accessed 23rd May 2020

[104] MAVEN (2017). Website and figure at http://www.maven-its.eu/, first accessed 23rd May 2020

[105] GALILEO4MOBILITY (2017). Website and figure at http://www.galileo4mobility.eu/, first accessed 16th July 202

[106] MANTRA, Figure. At https://www.mantra-research.eu/, first accessed 5th August 2020

[107] Ulrich, S., Kulmala, R., Appel, W., Penttinen, M., Laitinen, J. (2020). Deliverable 4.2 – Consequences of automation functions to infrastructure, MANTRA project. Available at https://www.mantra-research.eu/wp-content/uploads/2020/05/MANTRA_Deliverable_D42_Final.pdf, first accessed 5th August 2020

[108] SLAIN, Figure. At https://eurorap.org/slain-project/, first accessed 18th January 2021

[109] Konstantinopoulou, L. and Ljubotina, L. (2020). Road Infrastructure Requirements for Connected and Automated Vehicles (Presentation). SLAIN project. Available at http://www.eurorap.org/wp-content/uploads/2020/12/1_SLAIN-Activity-7-results.pdf, first accessed 18th January 2021

[110] AVINT, Website and figure at www.avint-project.eu, first accessed 19th November 2020

[111] ViaAUTONOM, Figure. At https://www.ait.ac.at/themen/verkehrssicherheit-und-unfallforschung/projects/via-autonom/, first accessed 1st September 2020

[112] Aleksa, M., Nitsche, P., Schwieger, K., Piribauer, T., Rettenbacher, P., Wimmer, P., Beyer, F., Moosbrugger, D. (2019). D6.1 Infrastruktur für automatisiertes Fahren – Empfehlungskatalog. ViaAUTONOM project.

[113] SafeSign (2020). At https://projekte.ffg.at/projekt/3789168, first accessed 18th January 2021

[114] FABULOS (2018). At https://fabulos.eu/, first accessed 19th November 2020

[115] Drive2thefuture (2019). At http://www.drive2thefuture.eu/, first accessed 23rd May 2020

[116] Sohjoa Baltic (2017). At https://www.sohjoabaltic.eu/, first accessed 19th November 2020

[117] STOR - Ruter - SVV(NPRA) – BYM (2019). At https://ruter.no/om-ruter/prosjekter/selvkjorende-kjoretoy/, first accessed 19th November 2020

[118] PIARC – WORLD ROAD ASSOCIATION (2003): „Road Safety Manual", Version 1.00, PIARC Technical Committee on Road Safety (TC13), Paris.

[119] NCHRP – NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM: Evaluation of the effects of pavement marking characteristics on detectability by ADAS machine vision, Project No. 20-102(06), Washington DC.

[120] EUROPEAN COMMISSION (2020): SHOW – Shared automation Operating models for Worldwide adoption, D1.2: Show Use Cases, Not-published.

[121] NHTSA - NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION (2018): A Framework for Automated Driving System Testable Cases and Scenarios, Report No. DOT HS 812 623, Washington DC.

[122] SEER, S. et Al. Higher safety, comfort and efficiency for pedestrian flows. https://www.ait.ac.at/en/solutions/analysis-and-optimization-of-pedestrian-flows/simulate

[123] SEER, S.(2015). A unified framework for evaluating microscopic pedestrian simulation models. Dissertation TU Wien.

[124] Stubenschrott, M., Kogler, C., Matyus, T., & Seer, S. (2014). A dynamic pedestrian route choice model validated in a high density subway station. Transportation Research Procedia, 2, 376-384.

[125] Liu, R., Wang, J., & Zhang, B. (2020). High Definition Map for Automated Driving: Overview and Analysis. In Journal of Navigation (Vol. 73, Issue 2, pp. 324–341). Cambridge University Press. https://doi.org/10.1017/S0373463319000638

[126] Aleksa, M., Nitsche, P., Schwieger, K., Piribauer, T., Rettenbacher, P., Wimmer, P., Beyer, F., & Moosbrugger, D. (2015). viaAUTONOM - Verkehrsinfrastruktur und Anforderungen für autonomen Straßenverkehr. Bericht B6.1. Infrastruktur für automatisiertes Fahren - Empfehlungskatalog.

[127] HERE. (2017). HERE HD Live Map (p. 2). https://www.here.com/sites/g/files/odxslz166/files/2018-11/HERE_HD_Live_Map_one_pager.pdf

[128] Liu, C., Jiang, K., Yang, D., & Xiao, Z. (2017). Design of a Multi-layer Lane-Level Map for Vehicle Route Planning. MATEC Web of Conferences, 124, 03001. https://doi.org/10.1051/matecconf/201712403001

[129] Hausler, S., & Milford, M. (2020). P1-021 : Map creation , monitoring and maintenance for automated driving – Literature Review.

[130] TomTom N.V. (2017). ROADDNA. Robust and scalable localization technology (p. 2). http://download.tomtom.com/open/banners/RoadDNA-Product-Info-Sheet-1.pdf

[131] Chellapilla, K. (2018, October 15). Rethinking Maps for Self-Driving. https://medium.com/lyftself-driving/https-medium-com-lyftlevel5-rethinking-maps-for-self-driving-a147c24758d6

[132] HERE. (2020). HERE Real-Time Traffic. Improve the efficiency of road travel. https://www.here.com/sites/g/files/odxslz166/files/2020-09/20_PLA_PMK_One-Pager_Traffic-Product_NEW.pdf

[133] Jiang, K., Yang, D., Liu, C., Zhang, T., & Xiao, Z. (2019). A Flexible Multi-Layer Map Model Designed for Lane-Level Route Planning in Autonomous Vehicles. Engineering, 5(2), 305–318. https://doi.org/10.1016/j.eng.2018.11.032

[134] Maiouak, M., & Taleb, T. (2019). Dynamic Maps for Automated Driving and UAV Geofencing. IEEE Wireless Communications, 26(4), 54–59. https://doi.org/10.1109/MWC.2019.1800544

[135] ACEA Discussion Paper: Roads of the future for automated driving (Issue June). (2020).

[136] Malone, K., Schreuder, M., Berkers, F., Helfert, K., Radics, L., Boehm, M., Lüpges, C., Kleine, C., Mann, M., Tucker, M., & Kakouris, E. (2019). DIRIZON Deliverable D3.1 Digitalisation and Automation: Implications for use cases, Identification of Stakeholders and Data Needs and Requirements.

[137] Poggenhans, F., Pauls, J. H., Janosovits, J., Orf, S., Naumann, M., Kuhnt, F., & Mayr, M. (2018). Lanelet2: A high-definition map framework for the future of automated driving. IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC, 2018-Novem, 1672–1679. https://doi.org/10.1109/ITSC.2018.8569929

[138] Schindler, J., Leich, A., Saul, H., Wesemeyer, D., Blokpoel, R., Czechowski, A., Rondinone, M., Matheis, D., Walter, T., Bures, P., Damavandpeyma, M., & Finkenflugel, N. (2017). MAVEN (Managing Automated Vehicles Enhances Network). 690727, 1–12. https://doi.org/10.1345/aph.1H502

[139] Ort, T., Paull, L., & Rus, D. (2018). Autonomous Vehicle Navigation in Rural Environments Without Detailed Prior Maps. Proceedings - IEEE International Conference on Robotics and Automation, May, 2040–2047. https://doi.org/10.1109/ICRA.2018.8460519

[140] Artunedo, A., Godoy, J., & Villagra, J. (2019). A decision-making architecture for automated driving without detailed prior maps. IEEE Intelligent Vehicles Symposium, Proceedings, 2019-June(Iv), 1645–1652. https://doi.org/10.1109/IVS.2019.8814070

[141] Joubert, N., Reid, T. G. R., & Noble, F. (2020). A Survey of Developments in Modern GNSS and Its Role in Autonomous Vehicles.

[142] Wilbers, D., Merfels, C., & Stachniss, C. (2019). A Comparison of Particle Filter and Graph-Based Optimization for Localization with Landmarks in Automated Vehicles. 2019 Third IEEE International Conference on Robotic Computing (IRC), 220–225. https://doi.org/10.1109/IRC.2019.00040

[143] Jo, K., Kim, C., & Sunwoo, M. (2018). Simultaneous localization and map change update for the high definition map-based autonomous driving car. Sensors (Switzerland), 18(9), 3145. https://doi.org/10.3390/s18093145

[144] Yu Huang. (2019). A Low Cost Vehicle Localization System based on HD Map. https://medium.com/@yuhuang_63908/a-low-cost-vehicle-localization-system-based-on-hd-map-50d464ba5d8f

[145] Shin, D., Park, K., & Park, M. (2020). High Definition Map-Based Localization Using ADAS Environment Sensors for Application to Automated Driving Vehicles. Applied Sciences, 10(14), 4924. https://doi.org/10.3390/app10144924

[146] inLane - Lane Navigation Technology. (n.d.-o). inLane Solution. Architecture. Precise Positioning. https://inlane.eu/inlane-solution/architecture/

[147] Koppert, A. (2016). inLane D2.1 Sensor Data Fusion.

[148] Barsi, Á., Csepinszky, A., Lógó, J. M., Krausz, N., & Potó, V. (2020). The Role of Maps in Autonomous Driving Simulations. Periodica Polytechnica Transportation Engineering, 48(4), 363–368. https://doi.org/10.3311/PPtr.15852

[149] ISO 20524-2. (2020). ISO 20524-2:2020 Intelligent transport systems — Geographic Data Files (GDF) GDF5.1 — Part 2: Map data used in automated driving systems, Cooperative ITS, and multi-modal transport (p. 589).

[150] Mischinger, M., Nitsche, P., Piribauer, T., Schneider, P., Schwieger, K., & Wimmer, P. (2017). viaAUTONOM - Verkehrsinfrastruktur und Anforderungen für autonomen Straßenverkehr. Bericht B2.1. Dokumentation der Szenarien , Anforderungen und Maßnahmen. 0, 1–95.

[151] ASAM. (2020). ASAM OpenDRIVE Format Specification V1.6.0.

[152] Scholz, M., & Richter, A. (2018). Road2Simulation Guidelines Leitfaden zur Erhebung von. https://www.dlr.de/ts/en/Portaldata/16/Resources/projekte/road2simulation/TD_TS_R2S_Guidelines_v1.2_DE.pdf

[153] Zenzic-UK Ltd. (2020). Geodata report - analysis and recommendations for self-driving vehicle testing. Zenzic consultation findings.

[154] Alkin, T., Amelink, M., Kulmala, R., Jaaskelainen, J., Sacs, I., Narroway, S., Niculescu, M., & Rey, L. (2020). EU EIP SA4.2. Task 3. Road map and action plan to facilitate automated driving on TEN road network - version 2020.

[155] Volkswagen AG. (n.d.-aj). Car2X in the new Golf: A “technological milestone.” https://www.volkswagen-newsroom.com/en/stories/car2x-in-the-new-golf-a-technological-milestone-5919

[156] Ma, L., Li, Y., Li, J., Zhong, Z., & Chapman, M. A. (2019). Generation of horizontally curved driving lines in HD maps using mobile laser scanning point clouds. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 12(5), 1572–1586. https://doi.org/10.1109/JSTARS.2019.2904514

[157] Joshi, A., & James, M. R. (2015). Generation of Accurate Lane-Level Maps from Coarse Prior Maps and Lidar. January.

[158] Ladstädter, R., Luley, P., Ladstätter, S., & Mayer, H. (2019). UHD Mapping von Teststrecken für automatisiertes Fahren. 13. https://www.joanneum.at/en/digital/publications/details/publications/uhd-mapping-von-teststrecken-fuer-automatisiertes-fahren/

[159] Guo, C., Kidono, K., Meguro, J., Kojima, Y., Ogawa, M., & Naito, T. (2016). A low-cost solution for automatic lane-level map generation using conventional in-car sensors. IEEE Transactions on Intelligent Transportation Systems, 17(8), 2355–2366. https://doi.org/10.1109/TITS.2016.2521819

[160] Althoff, M., Urban, S., & Koschi, M. (2018). Automatic Conversion of Road Networks from OpenDRIVE to Lanelets. Proceedings of the 2018 IEEE International Conference on Service Operations and Logistics, and Informatics, SOLI 2018, 157–162. https://doi.org/10.1109/SOLI.2018.8476801

[161] Baidu Apollo, & Elektrobit. (2018). Reliable and safe maps for automated driving.

[162] 5G-MOBIX. (2019). Deliverable D2.1. 5G-enabled CCAM use cases specifications.

[163] Pannen, D., Liebner, M., Hempel, W., & Burgard, W. (2020). How to Keep HD Maps for Automated Driving Up To Date. 2020 IEEE International Conference on

Robotics and Automation (ICRA), 2288–2294. https://doi.org/10.1109/ICRA40945.2020.9197419

[164] Unbehaun, M. (2020): OADF activities. Report for the SIP-adus Workshop 2020 on 10-12 November.

[165] Yoneda, K.; Kuramoto, A.; Suganuma, N.; Asaka, T.; Aldibaja, M. & Yanase, R. (2020) Robust Traffic Light and Arrow Detection Using Digital Map with Spatial Prior Information for Automated Driving, Sensors 20, no. 4: 1181. https://doi.org/10.3390/s20041181

[166] Seif, H.G., &, Hu, X. (2020), Autonomous Driving in the iCity—HD Maps as a Key Challenge of the Automotive Industry,Engineering, 2(2), pp. 159-162, ISSN 2095-8099, https://doi.org/10.1016/J.ENG.2016.02.010.

[167] Shin, D.; Park, K.; Park, M. (2020). High Definition Map-Based Localization Using ADAS Environment Sensors for Application to Automated Driving Vehicles Appl. Sci. 10, no. 14: 4924. https://doi.org/10.3390/app10144924

[168] Neil, J., Cosart, L. & Zampetti, G. (2020) "Precise Timing for Vehicle Navigation in the Smart City: An Overview," in IEEE Communications Magazine, vol. 58, no. 4, pp. 54-59, https://doi.org/10.1109/MCOM.001.1900596.

[169] Joubert, N., Reid, T.G.R., & Noble, F. (2020) Developments in Modern GNSS and Its Impact on Autonomous Vehicle Architectures, 2020 IEEE Intelligent Vehicles Symposium (IV), Las Vegas, NV, USA, 2020, pp. 2029-2036, https://doi.org/10.1109/IV47402.2020.9304840.

[170] Pannen, D., Liebner, M., Hempel, W. & Burgard, W. (2020) How to Keep HD Maps for Automated Driving Up To Date, 2020 IEEE International Conference on Robotics and Automation (ICRA), Paris, France, 2020, pp. 2288-2294, https://doi.org/10.1109/ICRA40945.2020.9197419.

[171] Jomrich, F., (2020): Dynamic Maps for Highly Automated Driving - Generation, Distribution and Provision. Dissertation, Darmstadt, Technische Universität, DOI: https://doi.org/10.25534/tuprints-00009702

[172] Barsi, Á., Csepinszky, A., Lógó, J. M., Krausz, N., Potó, V. (2020) “The Role of Maps in Autonomous Driving Simulations”, Periodica Polytechnica Transportation Engineering, 48(4), pp. 363-368. https://doi.org/10.3311/PPtr.15852

[173] Poggenhans, F., Pauls, J.H., Janosovits, J., Orf, S., Naumann, M., Kuhnt, F., & Mayr, M. (2018), Lanelet2: A high-definition map framework for the future of automated driving, 2018 21st International Conference on Intelligent Transportation Systems (ITSC), Maui, HI, USA, 2018, pp. 1672-1679, https://doi.org/10.1109/ITSC.2018.8569929.

[174] Genser, A., Nitsche, P. & Kouvelas, A. (2019), Identification of critical ride comfort sections by use of a validated vehicle model and Monte Carlo simulations, 22nd IEEE Intelligent Transportation Systems Conference (ITSC 2019), Auckland, New Zealand

[175] Zaech, J.N., Dai, D., Liniger, A., & Gool, L.V. (2020), Action Sequence Predictions of Vehicles in Urban Environments using Map and Social Context, arXiv 2004.14251

[176] European ITS Platform (2021), https://www.its-platform.eu/, accessed 9.March.2021

[177] Directive 2010/40/EU (2010) ,DIRECTIVE 2010/40/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL, https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32010L0040, accessed 9.March.2021

[178] Buchholz, M., Strohbeck, J., Adaktylos, A.M., Vogl, F., Allmer, G., Barros, SC., Lassoued, Y., Wimmer, M., Hätty, B., Massot, G., Ponchel, C., Bretin, M., Sourlas, V. & Amditis, A. (2020) Enabling automated driving by ICT infrastructure: A reference architecture, arXiv 2003.05229

[179] EUROPEAN COMMISSION Directorate-General Mobility and Transport Unit C3 (2011) ITS ACTION PLAN, FRAMEWORK SERVICE CONTRACT TREN/G4/FV-2008/475/01, D7 –Final Report Action 1.3 - Availability of Public Data for Digital Maps, https://ec.europa.eu/transport/sites/transport/files/themes/its/studies/doc/2011_12-availability-public-data-digital-maps.pdf, 19 December 2011, accessed 17.March 2021

[180] TRB – TRANSPORTATION RESEARCH BOARD (2010): Highway Capacity Manual, Volume 1: Concepts, Washington DC.

[181] FSV – AUSTRIAN RESEARCH ASSOCIATION FOR ROADS, RAILWAYS AND TRANSPORT (2012): RVS 02.02.34 – Road Safety Inspections, Vienna.

[182] FSV – AUSTRIAN RESEARCH ASSOCIATION FOR ROADS, RAILWAYS AND TRANSPORT (2012): RVS 02.02.33 – Road Safety Audit, Vienna.

[183] Via, S., Alonso-Zarate, J., Hetzer, D., Jung, C., Euler, S., Fallgren, M., Kuhn, J., Horst, O., Portalés, M., Streklas, A., Catalán Cid, M., Fabien, C., Kousaridas, A., Spapis, P., Moscatelli, F., Landi, G., Scheidl, W., Le Fur, E., Lacoste, M.-A., Barmpounakis, S. (2020). 5GCroCo. Deliverable D6.1. Intermediate Report on Standardization, Dissemination and Exploitation Activities.

[184] Muehleisen, M., Wendt, S., Schimpe, A., Odinot, J., Munoz, R., Löfede, J., Dizambourg, L., Nilsson, M., Gharba, M., Kousaridas, A., Perraud, E., Henn, R.-W., Euler, S., Allio, S., Moscatelli, F., Landi, G., Jung, C., Vázquez-Gallego, F., Vilalta, R., Alonso-Zarate, J. (2020). 5GCroCo. Deliverable D4.4. Detailed Roadmap of Test Sites – Project Year Two. 825050, 1–104.

[185] SHOW (2020): D1.2 SHOW Use Cases. Deliverable of the Horizon-2020 SHOW project, Grant Agreement No. 875530.

Appendix I

Template for Evaluation of existing infrastructure at pilot sites

The following questions address the current state of the physical infrastructure at your pilot site. If you can't answer a question, please explain. If you have any questions, please contact Andrea Schaub (andrea.schaub@ait.ac.at). Thank you!

Road condition and road markings

- What **pavement conditions** do you have (material and quality e.g. potholes)?
- Do you have **lane markings** on the whole route at the pilot site?
  If not, how large is the percentage of the route with lane markings?
  - ☐ 0-20%
  - ☐ 21-40%
  - ☐ 41-60%
  - ☐ 61-80%
  - ☐ 81-100%
- How would you describe their overall quality?
  0 = really poor (e.g., fringed lines)
  1 = ok, but bad in special conditions (e.g. rain)
  2 = good (sharp lines, good luminance and retroreflectivity)
- What minimum class for luminance (Q_d) and retroreflectivity (R_L) is required by **national regulations for permanent, white** road markings:

	Dry road	Wet road	Rain
Asphalt			
Concrete			

Along the route: Crossings, traffic signs, sight distances

- How many **intersections** do you have along the route? How is right of way given (traffic lights, stop sign, give way sign, roundabout, no rule → right of way)? If they are different, please define which intersections have which characteristics.

Number of intersections	Right of way (e.g. traffic lights, stop sign, give way sign)

- How many **pedestrian/cycling crossings** do you have? How is safety assured there?

Number of pedestrian/cycling crossings	How safety is assured: 0 = the AV has to identify the pdestrians/cyclists and give right of way to cross, 1 = there are additional features (please explain), 2 = traffic lights regulate who can cross when

- Do you have any **traffic signs** along the route? If yes, what role do they play to your AV?
- Do you have along the route traffic signs dedicated only to vehicles, or are there also some **signs dedicated to pedestrians** (e.g. landmark indicators etc.)? If yes, what is their location (e.g. at intersections, along the road etc.)?
- Are there any **abnormally** located signs (e.g. hanging on a wire due to some environmental constraints, etc.)?

- Are there **reflective, shiny, or bright materials** along the road (e.g. glass walls, large windows, etc.)?
- Do you have any **road barriers** along the route (e.g. protective concrete walls for separating pedestrians from the road, etc.)? If yes, what is the percentage of these barriers along the length of the route?
- Do you have any **trees or bushes** close to the route? If yes, how many of them? In what distance from the road? Are they evergreens?
- Do you have any **speed bumps** on the road? If yes, how are they marked? How many of them are there?
- Do you have **parking areas** along the route? (How) do they affect automated driving at your test site?
- Do you have any **fixed infrastructure elements** as reference points **for localisation** along your route?

Public transport stations and terminals

- How do the **PT stations** look like (bus bay, stop within lane, stop within dedicated bus lane, extraordinary design)? If the PT stations do not have a uniform design, please define which stations have which characteristics.
  Are there any other modes of transport (besides the AV) at the PT station/terminal?

Number of PT stations/ terminals	Design (e.g. bus bay, stop within (dedicated bus) lane, other – please describe)	Other modes of transport available (e.g. tram, other local buses, regional buses, car-sharing, bicycle lane, cars, etc.)

- What did you consider when choosing the PT station design?
- Are there any specific infrastructure components at the PT station or terminal?

General

- What **physical infrastructure** characteristics played part in your **route planning**?

Appendix II

Survey on infrastructure adaptations at pilot sites

(analysis see Chapter 4.2.2.2)

SHOW D8.1 Chapter 4 Efficient infrastructure adaptations and measures at test sites				
Test Site Name XY (please fill in)				
Infrastructure element/condition	Have you made or are you planning to make any infrastructure adaptations related to the following element/condition… (Yes, No, Not applicable (=does not occur at the test site))	If yes, please describe the adaptation. What is the intention of the measure? E.g. increase safety, optimize communication with other traffic participants, improve localization	Is this a necessary adaptation or a nice to have adaptation?	comments
Example Entry for slope/inclination				
Road condition				
slope/inclination	yes	inclination of 10 % is indicated by a traffic sign limiting access for AVs just on dry road (no rain, no snow, no wet or icy road)	this is a necessary adaption due to safety reasons	
slope/inclination	no			Although there is a road section with increased slope, we do not need any measures as it is within the vehicle's ODD.
slope/inclination	not applicable			Our terrain is flat.
Road				
Road condition				
pavement type/road condition (asphalt, cobblestone, etc.)				
road condition maintenance due to weather events (icy/snowy roads, standing water, etc.)				
pothole cancellation				
slope/inclination				
road geometry				
speed bumps				
Lanes				
width of road/lane width (also on parts)				
separate lane for AVs, safety/priority zones				
lane marking quality (e.g. with reflective paintings)				
street side parking				
bicycle lanes				
narrow lane sections				
longitudinal tram tracks				
parking in second lane				
Crossings				
road junctions				
left turn lanes				
sight distances and visibility at junctions				
pedestrian and bicycle crossings				
tram track and railway crossings				
roundabouts				

Road side				
traffic lights				
road/traffic signs (bus stop signs, warning signs of automated vehicles and informative signs, etc.)				
curbs				
road safety barriers				
road side vegetation				
fixed infrastructure elements as reference points for localisation of the vehicle/Static urban furniture				
buildings along the road (blind spots due to bill board, trees, bus stops, etc.)				
temporary road works				
Public transport terminals and stations				
terminals/stations (layout, design, waiting areas, platforms, etc.)				
terminals/stations interchange areas				
shuttle depots				
Hot spots				
ramp and merging lanes				
tunnel area				
bridges				
areas of schools, hospitals, etc.				
accident hot spots				
Other, please add:				
Other, please add:				
Other, please add:				
Other, please add:				

Appendix III

Segmentation Tool Manual

Segmentation of road features

According to the Highway Capacity Manual (HCM) six main types of roadway system elements are defined to characterize a road network [180]. From smallest to largest, those are points, segments, facilities, corridors, areas and systems (see Figure 70).

Analysing harmonized sections for SHOW pilot sites is primarily based on the second HCM type (road segments), where a segment is defined as a length of roadway between two points. Traffic volumes and physical characteristics generally remain the same over the length of a segment, although small variations may occur (e.g. changes in traffic volumes on a segment resulting from a low-volume driveway).

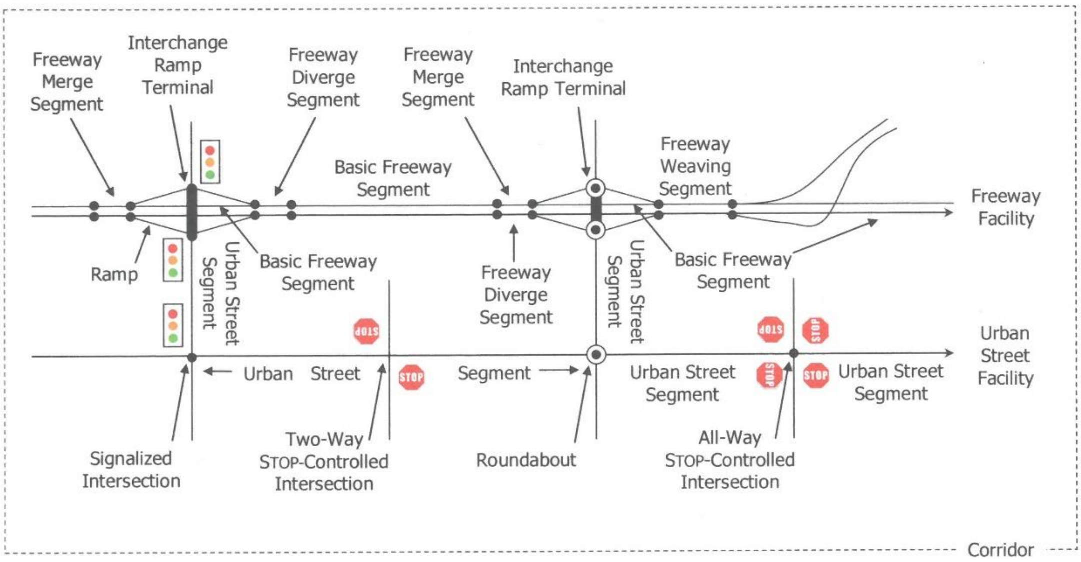


Figure 70: Points, segments, facilities and corridors [180]

The segmentation process starts with a desktop investigation of the pilot site via digital maps (e.g. Google Maps, Open Street Map) to get an overview of the current site conditions, i.e. the layout of the road network and existing road elements (see Figure 71). This quick-scan site assessment also consists of taking pictures of the road and its environment. Images are stored either as photos taken at equal increments (e.g. 10-25m) or on videotape shot from a moving vehicle.

If available, interactive panoramas such as Google Street View (see Figure 72) can also be used considering the recording date of the images. If they are too old, the site investigation runs the risk of being based on old images of the road environment and recent changes not being included in the analysis.

Figure 71: Open Street Map view of the SHOW segmentation tool

Figure 72: Virtual site investigation (e.g. via Google Maps)

After conducting the pilot site overview, the actual segmentation process commences with the first road element to be digitized in the segmentation tool. Initially, a pop-up window asks the user to choose between use case (UC) 1.1 (normal traffic conditions), UC 1.2 (complex traffic conditions) or UC 3.4 before continuing with the actual site investigation. As mentioned above, the different use case scenarios define which road elements are available for the follow-up segmentation process (see Figure 73).

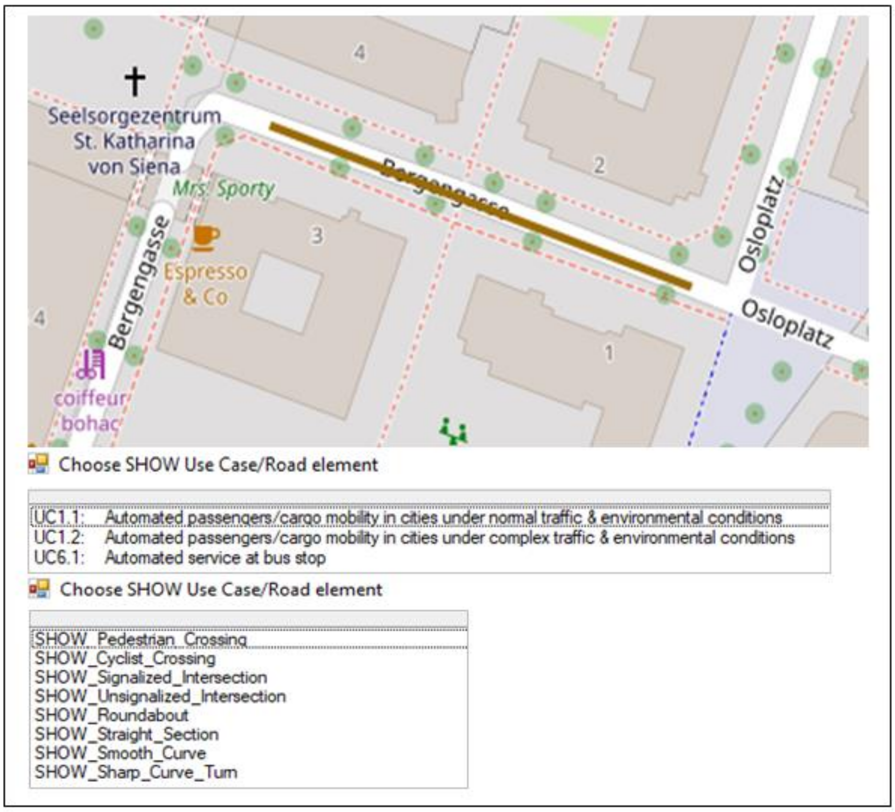


Figure 73: Use case allocation and road feature selection

To finish the segmentation process, each road element must be investigated separately. The test scenario in Figure 74 consists of 6 straight road segments, 2 sharp curves, 2 unsignalized intersections and 2 pedestrian crossings. The actual evaluation process is a repetitive procedure where several checklists concerning the quality of lane markings, traffic signs and sight distances have to be answered for each road segment (see here below "Evaluation of road segments").

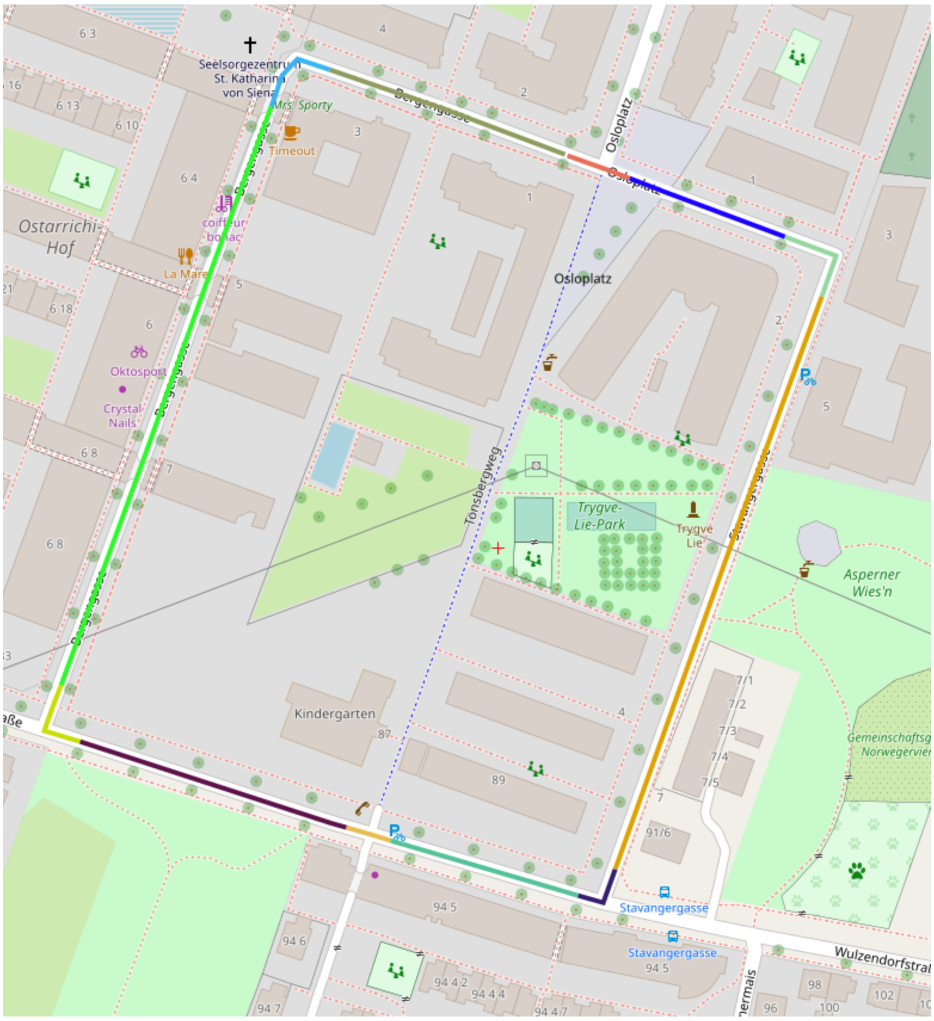


Figure 74: Selection of various road elements in the test scenario

Evaluation of road segments

The basic concept for analysing individual road segments for AD is derived from guidelines concerning road safety inspection (RSI) and road safety auditing (RSA) [181], [182]. These two regulations state that standardized test procedures for the detection and elimination of potential hazards and safety deficits must be conducted both at the beginning of a road building project and at regular intervals after road opening to evaluate potential safety margin at each site. Hence, the main objectives of road evaluations are the identification of vulnerabilities concerning physical infrastructure in the road network to reduce the number of potential traffic conflicts.

The same methodology is used for analysing road segments for automated driving. Several checklists were developed for the evaluation of lane markings (see Figure 75), traffic signs and sight distances. Those checklists allocate individual grades (1-5) according to the personal assessment of the site manager during the test site inspection. If, for example, numerous phantom lane markings exist in a road segment, hazard/risk level 5 will be attributed to this part of the test site.

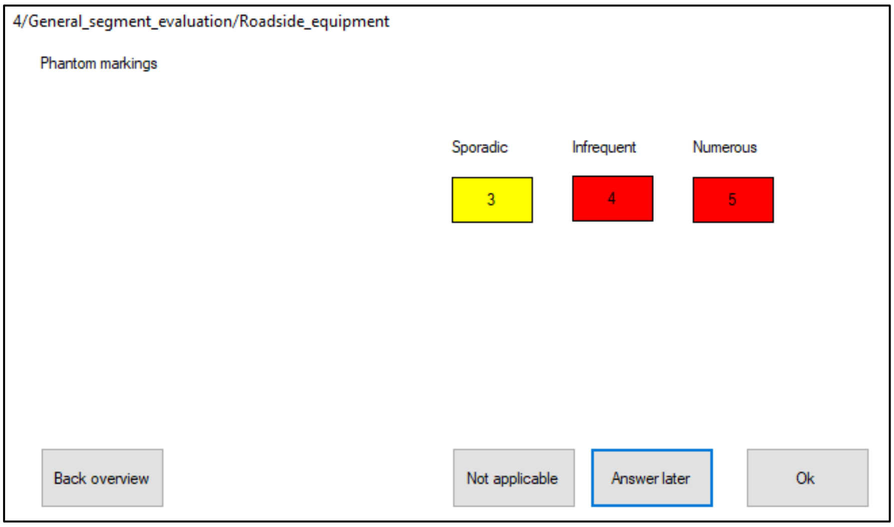


Figure 75: Checklist for phantom lane markings during pilot site evaluation

After completing the checklists for a specific road segment, a summary of the allocated risk levels is given (see Figure 76). The output shows both the individual risk per category (roadside equipment, traffic information and rules etc.) and the highest value in general. A separate indicator for the number of unanswered questions in the checklists is also added to the summary sheet.

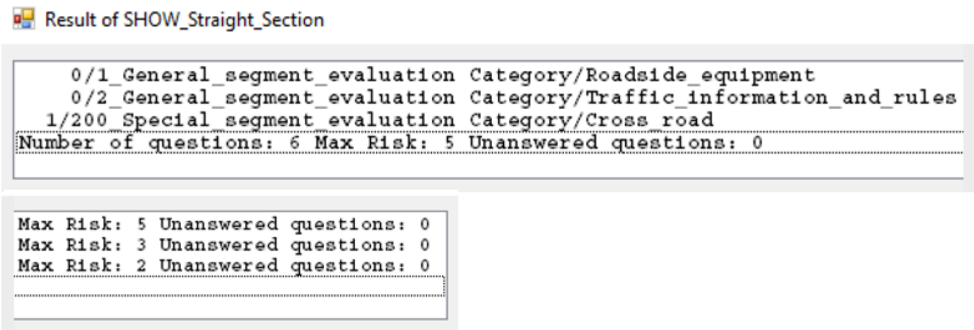


Figure 76: Hazard/risk level for a road segment

The final outcome of the evaluation process is a graphical representation of all road segments investigated including the road element annotation plus the respective hazard/risk level (see Figure 77). The road segments can be saved as a shapefile and imported in any geographic information system (e.g. QGIS, ArcGIS Pro) for further investigation.

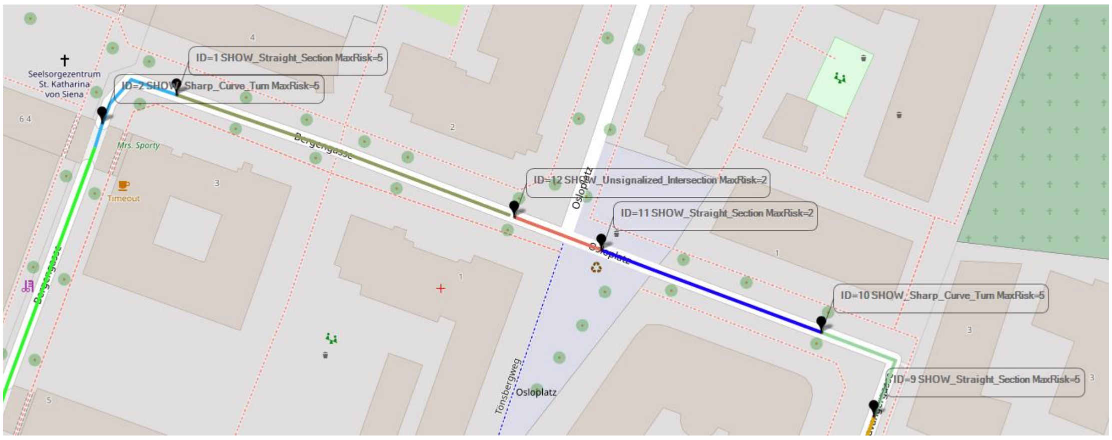


Figure 77: Graphical representation of the investigated road segments