MANTRA: Making full use of Automation for National Transport and Road Authorities – NRA Core Business

Consequences of automation functions to infrastructure

Deliverable D4.2

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CEDR Call 2017: Automation

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Author(s) this deliverable:

Sandra Ulrich, ARNDT IDC, DE

Risto Kulmala, Traficon, FI

Kristian Appel, Traficon, FI

Walter Aigner, HiTec, AT

Merja Penttinen, VTT, FI

Jukka Laitinen, VTT, FI

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Executive summary

The development of automated vehicles and road network operation automation is progressing dynamically. However research on effects to physical and digital infrastructure due to automated functions and vehicles is still limited. As amendments to infrastructure are costly and have a long lifetime, there is a strong need for research to ensure that they are planned accordingly. Therefore work-package 4 of project MANTRA analyzes concrete consequences of selected automated vehicle functions to infrastructure up until the year 2040 in response to the CEDR Automation Call 2017.

Building on initial results of the selected use cases together with NRAs regarding their deployment, their operational design domains (ODDs) and penetration rate, we tackle their interplay with infrastructure and following consequences. The field of analysis of infrastructure consequences due to automation is still very open. Therefore, a key pillar of the work was the active engagement with the research community and renowned experts in many interviews and workshops throughout the whole project duration in order to validate results early and continuously. This report now compiles the results of the work and provides recommendations for the National Roads Authorities (NRAs) on the expected impact of highly automated driving and the respective necessary changes to physical and digital infrastructure that can support cooperative, connected and automated road traffic.

Introducing connected and automated mobility on public roads is expected to effectively address several traffic safety, efficiency and environmental problems. While the expected impacts to infrastructure are manifold those resulting from the need to provide the required ODD to ensure safe deployment for those automated functions considered as potentially soon available were identified as most pressing. These obviously provide only recommendations in order to enlarge the automated vehicle's ODD coverage as far as economically feasible. There are some inherent difficulties in supporting the ODDs as the ODDs depend on the capabilities of the sensors and software including artificial intelligence (AI) of the automated vehicles, and these capabilities are improving quite quickly with the evolution of related technologies.

The interdependencies of physical and digital infrastructure are becoming even more visible in a connected and automated future. For instance in the case of road markings and traffic signs the automated vehicles benefit from a "hybrid" combination both the physical markings and signs as well as their digital twins in digital maps.

A highly developed digital infrastructure without an appropriate physical infrastructure is not sufficient to fulfil the mobility needs neither of manually operated nor of automated vehicles. Investments for further development of physical infrastructure need to be made considering the potentials of digitalization and the requirements of future vehicles with various degree of automated functions.

The report provides infrastructure recommendations to support the introduction of those forms of cooperative connected automated mobility (CCAM) supporting the policy goals of NRAs and have been profoundly discussed with the CEDR CAD working group (WG). However the provided recommendations and lists do not in any way indicate the willingness nor commitment of road operators nor other stakeholders to provide these changes and attributes to the infrastructures.

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Glossary of Terms

ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance Systems
aFAS	Acronym for the German project "Automated Unmanned Protective Vehicle for Highway Hard Shoulder Road Works"
AI	Artificial Intelligence
C-ITS	Cooperative Intelligent Transport Systems
CACC	Cooperative Adaptive Cruise Control
CAD	Connected and Automated Driving
CAV	Connected and Automated Vehicle
CCAV	Cooperative Connected Automated Vehicles
CEDR	Conference of European Directors of Road
CEN	French acronym for European Committee for Standardization
CENELEC	French acronym for European Committee for Electrotechnical Standardization
DoRN	Description of Research Needs
DRAGON	Project Acronym: DRiving Automated vehicle Growth On National roads
DSCR	Dedicated Short Range Communication
EETS	European Electronic Toll Service
ERTRAC	European Road Transport Research Advisory Council
ESP	Electronic Stability Control
ETSI	European Telecommunications Standards Institute
EU	European Union
EIP	European Investment Partnerships
FOT	Field Operational Test
GNSS	Global Navigation Satellite System
HCV	High Capacity Vehicle
HD	High Definition
HGV	Heavy Goods Vehicles
ICT	Information and Communication Technology
ISAD	Infrastructure support levels for automated driving
ISO	International Organization for Standardization
LHT	Longer and Heavier Trucks
LKA	Lane Keep Assistance
MANTRA	Project Acronym: Making full use of Automation for National Transport and Road Authorities – NRA Core Business
NRA	National Roads Authority

O&M	Operation and Maintenance
OBU	Onboard Unit
ODD	Operational Design Domain
OEM	Original Equipment Manufacturer
PEB	Programme Executive Board
PMS	Pavement Management System
SAE	SAE International (Society of Automotive Engineers)
TC	Technical Commitee
TEN-T	Trans-European Transport Network
TM	Traffic Management
V2V, V2I	Vehicle-to-Vehicle, Vehicle-to-Infrastructure communications
VRU	Vulnerable Road Users
VMS	Variable Message Sign
WG	Working Group

1 Introduction

The CEDR Transnational Research Programme was launched by the Conference of European Directors of Roads. CEDR is the Road Directors' platform for cooperation and promotion of improvements to the road system and its infrastructure, as an integral part of a sustainable transport system in Europe. Its members represent their respective National Road Authorities or equivalents and provide support and advice on decisions concerning the road transport system that are taken at national or international level.

The participating NRAs in the CEDR Call 2017: Automation are Austria, Finland, Germany, Ireland, Netherlands, Norway, Slovenia, Sweden and the United Kingdom. As in previous collaborative research programmes, the participating members have established a Programme Executive Board (PEB) made up of experts in the topics to be covered. The research budget is jointly provided by the NRAs as listed above.

MANTRA is an acronym for "Making full use of Automation for National Transport and Road Authorities – NRA Core Business". MANTRA responds to the questions posed as CEDR Automation Call 2017 Topic A: How will automation change the core business of NRA's, by answering the following questions:

- 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?
- How will the current core business on operations & services, planning & building and information and communication technology (ICT) change in the future?

An earlier CEDR project DRAGON (Vermaat et al. 2017) already looked at the impacts of three automated driving use cases in specific sites revealing the need to carry out a comprehensive study on the impacts on the road authorities and operators on the European scale.

MANTRA work started with the analysis of vehicle penetrations and Operational Design Domain (ODD) coverage of NRA-relevant automation functions up to 2040. This part is reported in MANTRA Deliverable D2.1. Following, this work-package 3 concentrates on the impacts of connected and automated driving (CAD) and how the impacts relate to the role and policy targets of NRAs. The first deliverable in work-package 3 summarizing a comprehensive state of the art on the impacts of CAD on travel demand, travel behaviour, traffic flow, safety and energy has been also finished as D3.1. In parallel simulations were performed to quantify impacts on policy targets like traffic flow, safety, environmental impacts, etc. which will be published as deliverable D3.2.

Building on these results and digging deeper on infrastructure related matters work-package 4 focuses on the consequences of automated driving to physical and digital infrastructure. Research on impact and consequences to infrastructure is still limited. Following the MANTRA principle of close cooperation with the PEB and the CEDR CAD WG to achieve the expected results, an intermediate deliverable D4.1 was prepared, proposing the structure and explaining the methodology, approach and expected outcome of this work-package to get early feedback on the direction of the work. With this approach of early testing of assumptions valuable contributions of PEB and CEDR CAD WG could be collected and this deliverable D4.2 could be tailored accordingly to meet the expectations of CEDR.

1.1 Objectives

Developments in automation are fast paced and often subject to bold announcements, which makes it difficult also for NRAs to distinguish between developments for which infrastructure provisions need to be taken as soon as possible and pure hype. The ongoing MANTRA project seeks to support in this challenge. Key target of work-package 4 therefore is, to formulate concrete consequences of and necessary changes due to selected automated functions to infrastructure as well as the operation and maintenance (O&M) of it.

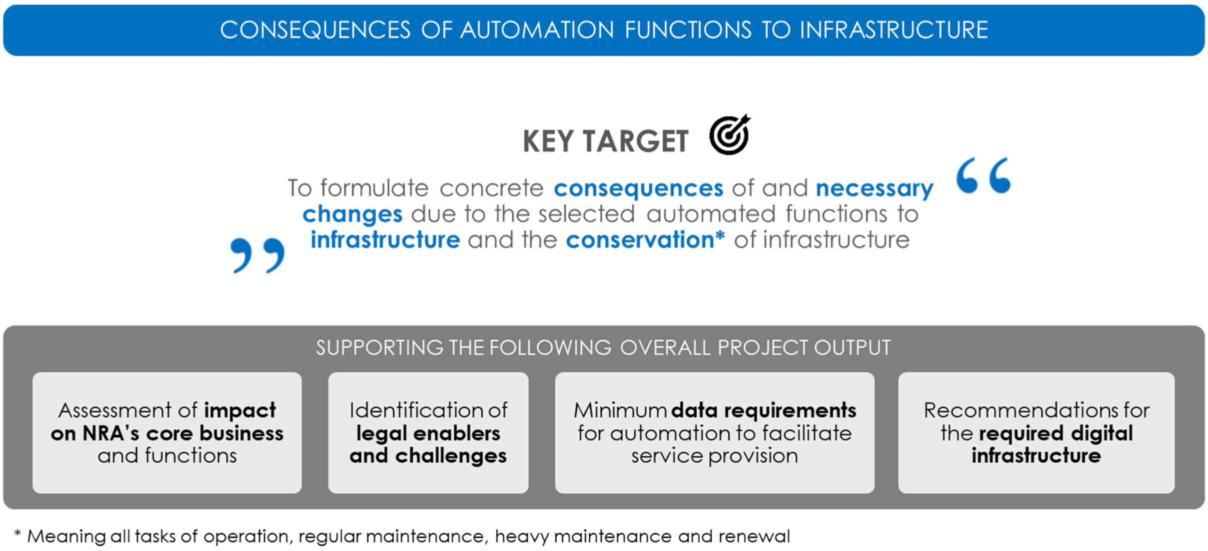


Figure 1. Key target of work-package 4

The results of work-package 4 provide significant input for work-package 5, where the core research question of this project *"How will the current core business on operations & services, planning & building and ICT change in the future?"* to the extend it is possible with the current knowledge will finally be answered. Following Figure 2 provides an overview of NRAs core business.

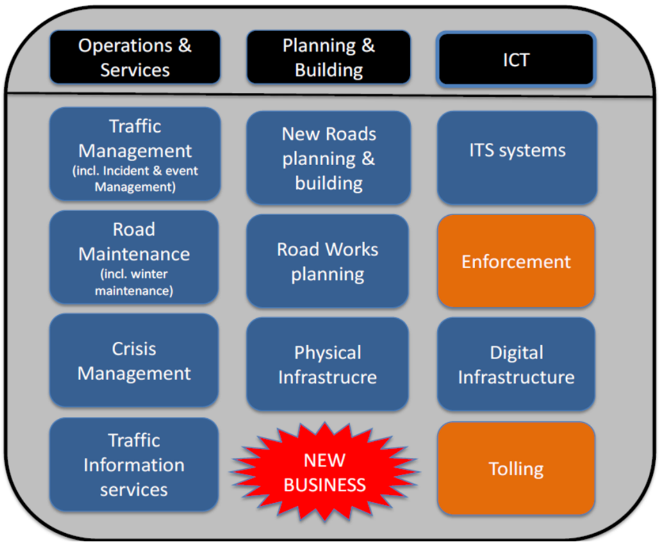


Figure 2. Overview of NRA's core business (DoRN, CEDR Call 2017)

Infrastructure related impacts to these core business fields of Figure 2 are analyzed in this work-package 4 and summarized in chapter 6 for each field.

After the selection of most significant automated functions in a mini-workshop held with CEDR, the impact and consequences of these use cases, their interplay with infrastructure and following consequences were tackled. Potentially new requirements for physical as well as digital infrastructure were collected structurally.

In liaison with work-package 3 close attention was paid on potential effects of infrastructural requirements on NRAs policy targets. The collective results of work-package 3 and this work-package 4 form the basis for the changes to road operator's core businesses in finalising the MANTRA work. Following the approach as described in chapter 1.2, the results feeding into answering the key research question of how NRAs core business will change, are summarized in chapter 6 following the structure of Figure 2.

Today's solutions can quickly become the problem in a tomorrow with automation functions. MANTRA as a whole considers the global impact of automation on infrastructure and the associated changes for NRAs. This deliverable is putting its focus on the technical changes to the infrastructure itself. Construction, maintenance and structural changes during the lifecycle of infrastructure are not only an expensive undertaking for the NRAs, but always comprise impairment to network users at the same time. To minimize consequences on both, costs and traffic, measures are formulated structurally considering timing implications.

On one hand, proposed changes include measures to adapt the physical road geometry as well as road(side) elements. On the other hand, recommendations for digital infrastructure are made that encompass infrastructure-to-vehicle connectivity and different layers of map data. While the necessity to provide the required automated vehicle's ODD as expected by vehicle manufacturers also impose changes to infrastructure which are presented in this report, it is clearly the decision of each NRA whether or not they intend to make those changes happen. As a general recommendation it can be concluded that additional road infrastructure can expand an automated vehicle's ODD, and without the ODD the vehicle cannot operate automatically and provide the expected socio-economic benefits, hence it is an NRAs decision to enable this or not.

1.2 Approach and methodological framework

The overall methodology follows the process as shown in Figure 3. Starting with the current status quo on European highways, inputs from several sources form the basis of the assessment. These are collected in chapter 2 utilizing literature research. Key infrastructure requirements to date for physical and digital infrastructure form the starting point.

With the input of work-packages 2 and 3 impact and consequences are going to be addressed in 3 categories (see Figure 4) as well as the resulting required changes which will then provide the input for work-package 5.

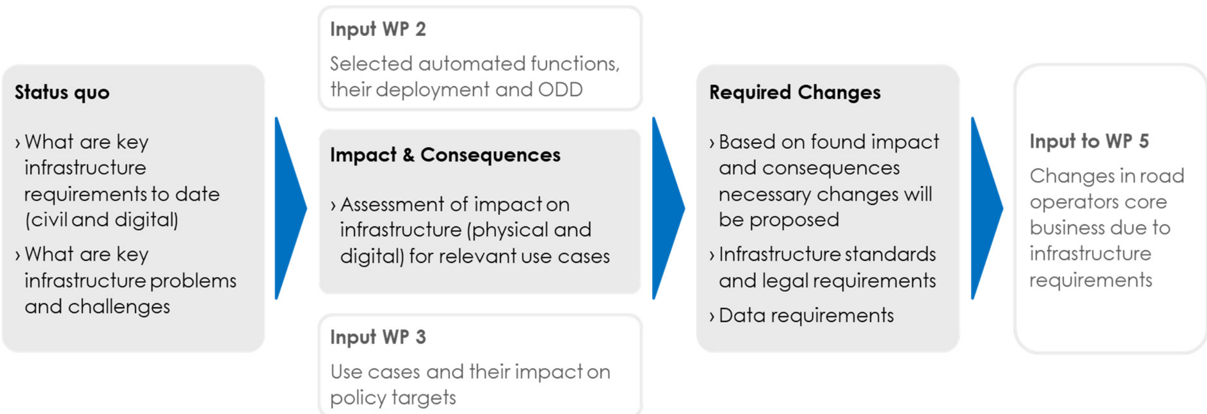


Figure 3. Overall approach work-package 4

The impact and the resulting consequences and therefore necessary changes to infrastructure will have various sources. Analysis is tackled from three directions in order to structurally cover the crucial ones, referred to as impact categories, as shown in Figure 4.

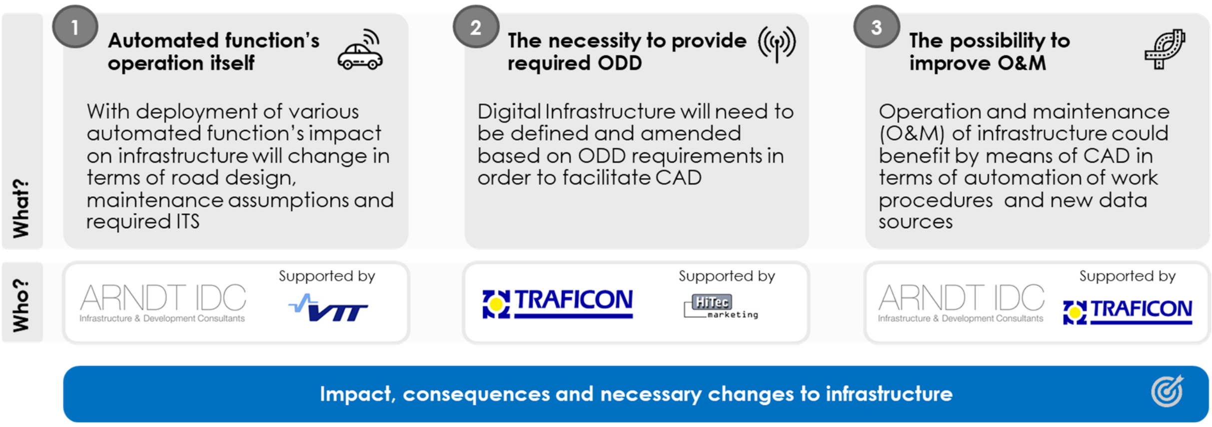


Figure 4. Assessment of impact from three different angles

The assessment of these three impact categories will include literature analysis, expertise of the consortium as well as structured interviews with selected experts, workshops with CEDR CAD WG and a workshop with experts from road authorities, operators, automotive, civil design and construction companies, telecommunications industry and research/academia stakeholders. The approach for each impact category is described in the dedicated respective chapter:

- Impact through automated function's operation itself, approach see chapter 3.1
- Impact by ODD requirements, approach see chapter 4.1
- Impact due to possible O&M improvements, approach see chapter 5.1

The analysis will focus on highways and their physical and digital road-side infrastructure. However, also extended aspects of infrastructure, including the back office and off-roadside infrastructure such as e.g. traffic centre operations, information management systems and databases, cellular networks and base stations, and land stations ensuring the accuracy of satellite positioning will be considered.

After the detailed assessment of consequences to infrastructure for each of the impact categories in chapters 3 to 5, the results and recommendations for necessary technical and legal changes as well as their overall implication for NRAs are described in chapter 6. In case of negative consequences, specific advice will be given in order to mitigate such consequences.

The field of analysis of infrastructure consequences due to automation is still very open. Therefore, a key pillar of the work in work-package 4 is the active engagement with the research community and renowned experts in interviews and workshops throughout the whole time, in order to validate results early and continuously. The following is a selection of the main workshops and engagements with other experts.

- Workshop PEB and CEDR CAD WG, Vienna, 31.08.2018
- 22nd annual meeting international task force on vehicle-highway automation, Copenhagen, 16.09.2018
- ITS world conference 2018, interactive panel discussion within the special interest session on "Systemic impacts from infrastructure-based management of CAD (SIS69)", Copenhagen, 20.09.2018

- Workshop CEDR CAD WG, Oslo, 06./07.11.2018
- Workshop together with ARCADE/ERTRAC, Brussels, 02.2019
- Workshop CEDR CAD WG, Tallinn, 06./07.03.2019
- EU-CAD Conference 2019, Brussels, 02./03.04.2019
- Workshop with project ARCADE Brussels 04.2019
- ITS Europe conference 2019 interactive panel discussion within the special interest session on “Touching the real infrastructure and embracing the unknown (SIS13)”, Eindhoven, 04.06.2019
- Workshop with Asfinags team for ITS, automated and connected driving, Vienna, 06.05.2019
- Kolloquium Future Mobility, Esslingen, 02.07.2019
- Workshop CEDR CAD WG on truck platooning, Stockholm, 12.06.2019
- Workshop in cooperation with Austrian projects on truck platooning Connecting Austria and Spurvariation, Vienna, 08.07.2019
- Workshop with ASECAP, COPER III, Vienna, 24.07.2019
- Expert Workshop, Vienna, 10.09.2019
- Participation/presentation in EU EIP, Action 4.2, Multi-stakeholder workshop on ODD, cost and benefits of automated driving, Turin, 01.-02.10.2019
- Participation/presentation in break-out session on constructs of the ODD of Automated Vehicles, ITS World Congress, Singapore, 22.10.2019

Results and proceedings of all workshops are digested directly in the deliverable. However, detailed documentation is available for each workshop from the authors of the deliverable.

In addition to the workshops expert interviews were done to validate the information. The experts are quoted in the respective chapters.

2 Status quo of road infrastructure in Europe

2.1 Road infrastructure in Europe

Dependent on its importance, demand and location, road infrastructure has to fulfill manifold sets of requirements. There is no such thing as one single standard for road infrastructure throughout Europe that could be easily amended to prepare for automated and connected vehicles. Instead the various road categories, their specific design requirements, traffic loads and complexities have to be assessed individually and from different angels.

Road infrastructure in Europe is heterogeneous for diverse reasons. Not only vary geographic and climate conditions greatly from North to South but also traffic density, volume and need within each of the countries differ depend on location and road category. CEDR members have varying responsibilities for either solely high-level road networks (motorways and highways) or different types of roads from motorways to urban roads and everything in between. However, all CEDR members are responsible for high-level roads, which therefore is MANTRAs main focus when assessing the impact on infrastructure.

CEDR members are also responsible for big parts of the strategically highly important TEN-T network and document the performance of the TEN-T road network within CEDR participating countries in regular reports. The Trans-European Transport Network (TEN-T) is a European Commission policy directed towards the implementation and development of a Europe-wide network of roads, railways, inland waterways, maritime shipping routes, ports, airports, and rail-road terminals. The TEN-T Roads network in the participating CEDR countries is approx. 84,700 kilometres long. Approx. 42% of these roads are Core Roads and 58% of Non-Core Roads and comprises approx. 61% of motorways and 39% of non-motorway roads.

53% of the entire TEN-T Roads network (about 40,280 km) has more than two and up to four lanes, 20% has more than four and up to six lanes, and only about 3% (about 2,073 km) has more than six lanes. The TEN-T network has also about 18,570 km of roads (almost 24% of the total length) with only two lanes or less.

Not surprisingly, most of the TEN-T (Roads) are situated in a rural environment. However, about 6,850 km (i.e. 8.9% of the total network) are located in urban areas and carry more traffic than rural roads. A look at the average annual daily traffic flow (AADT) reveals that 55.5% of the entire TEN-T Roads network carries less than 20,000 vehicle per day, while 41% of the network carries more than 20,000 and less than 100,000 vehicles per day. Only 3.4% of the entire network is very heavily trafficked with more than 100,000 vehicles per day.

Traffic flows vary considerably from country to country: Belgium (Flanders), the Netherlands, and the United Kingdom (England) have the most trafficked TEN-T roads, with more than 20% of their network carrying more than 80,000 vehicles per day. On average, 13.7% of the traffic using the TEN-T network is made up of HGVs, with this share remaining consistent for both motorways and non-motorways (Pettersson et al. 2018).

This confirms that the European road network is indeed large and heterogeneous. MANTRA's objective is to not only scratch on the surface but to provide profound and concrete recommendations for NRAs. Therefore, the focus is on those road categories most relevant to CEDRs members, which are high-level roads and at least for some members, urban roads. This is in line with the selection of use cases that are being addressed in MANTRA. Four different use cases that have been selected together with CEDR CAD WG (Vienna, 31.08.2018) are the basis for MANTRA's work - described in detail in the MANTRA deliverable D2.1 (Aigner et al. 2019). Three of those four use cases are oriented towards high-level roads and one to urban roads.

2.1.1 Road infrastructure network

A brief overview of the road infrastructure network is given below to set the scene for the further work of this report. The definition of road types varies from country to country, which makes the comparison of data difficult and only partially reliable. Comparisons between countries therefore should be done with further detailed analysis. The aim of Table 1 is not to provide absolute numbers comparable between countries but rather to give an impression of scales.

Table 1. Road infrastructure network of CEDR members (Nicodeme et al. 2017)

Country	Road Type [km]		
	Motorways	Highways, Main, National Roads	Secondary, Regional and Rural Roads
Austria	1 719	9 997	112 399
Belgium	1 763	13 229	140 218
Cyprus	257	2 203	7 305
Czech Rep.	776	6 250	123 655
Denmark	1 216	2 646	140 536
Estonia	140	3 873	54 774
Finland	810	12 521	64 762
Germany	12 917	39 389	178 071
Greece	1 558	9 299	106 464
Hungary	1 767	6 824	194 718
Iceland	11	4 919	7 960
Ireland	897	4 531	90 589
Italy	6 751	19 920	229 368
Latvia	-	1 674	68 769
Lithuania	309	6 372	65 910
Luxembourg	152	837	3 782
Malta	-	2 361	4 722
Netherlands	2 678	2 564	133 399
Norway	392	10 562	83 423
Poland	1 482	17 804	395 836
Portugal	3 065	6 454	4 791
Slovenia	770	819	37 285
Spain	14 981	15 041	636 393
Sweden	2 057	13 553	201 366
Switzerland	1 419	393	69 715
UK	3 760	49 074	368 293

Definitions of road types in this overview follow the European Commission (eurostat 2007). In the detailed assessment of impacts for road types later on in this report the distinction of road types follows more functional criteria in order to accommodate the specific requirements of ODDs e.g. for urban roads.

Motorways

A motorway is a road specially designed and built for motor traffic, which does not serve properties bordering on it, and which:

- Is provided, except at special points or temporarily, with separate carriageways for the two directions of traffic, separated from each other, either by a dividing strip not intended for traffic, or exceptionally by other means;
- Has no crossing at the same level with any road, railway of tramway track or footpath;
- Is especially sign-posted as a motorway and is reserved for specific categories of road motor vehicles. Entry and exit lanes of motorways are included irrespective of the location of the sign-posts. Urban motorways are also included.

Highways, Main or National Roads

Highways, main or national roads include kilometer length of A-level roads. A-level roads are roads outside urban areas that are not motorways but belong to the top-level road network. A-level roads are characterized by a comparatively high-quality standard, either non-divided roads with oncoming traffic or similar to motorways. In most countries, these roads are financed by the federal or national government.

Secondary, Regional or Rural Roads

These roads contain roads that are the main feeder routes into - and provide the main links among - highways, main roads or national roads as well as all remaining roads in a country not included in categories listed above. Definitions of secondary, regional and rural roads vary greatly between countries. Therefore, these road types have been summarized in one column. In addition, there is no standardized data on urban roads which are critical further on in this report when it comes to ODDs and specific challenges on urban roads.

2.1.2 Relevant European road infrastructure standardization

In order to allow smooth functioning of road transport it is essential, that physical and digital road infrastructure is maintained effectively and sustainably across the European Union (EU), not only on motorways but also in urban areas. So far a minimum set of EU standards has proven sufficient to enable each country to define their specific regulations best suited for the respective road infrastructure.

Looking at a future with deployment of automated and connected driving use cases, road infrastructure measures could crucially enhance the performance and availability of these systems, thus contributing to an overall increase in road safety and traffic efficiency. Therefore, these standards might need upgrades and even stronger harmonization for preservation, maintenance, restoration and upgrade of existing physical and digital road infrastructure across countries.

CEN TC/226 Road Equipment – WG 12

CEN, the European Committee for Standardization, is one of the central organizations for standardization on EU level. CEN brings together the National Standardization Bodies of 34 European countries and is one of three European Standardization Organizations (together with European Committee for Electrotechnical Standardization (CENELEC) and European Telecommunications Standards Institute (ETSI)) that have been officially recognized by the EU as being responsible for developing and defining voluntary standards at European level. As such various technical bodies of CEN are working on standards relevant to make road infrastructure ready for automated and connected driving.

The most relevant current action is a new WG dedicated to road interaction with Advanced Driver Assistance Systems (ADAS)/automated vehicles led by CEN TC/226.

TC 226 responsible for road equipment has formed a dedicated WG (WG12) for the interaction of road equipment and ADAS/automated vehicles. This includes standardization work on traffic control, horizontal road signs, vertical signs, passive safety of support structures for road equipment, variable message signs (VMS), crash barriers, safety fences, vehicle restraint systems, bridge parapets, clockwork parking meters, automatic car park ticket dispensers and noise reducing devices to improve them for interaction with ADAS/automated vehicles. WG 12 will also inform on how NRAs will accommodate mixed traffic conditions, and ensure consistency between road infrastructure and road vehicles standards enabling safe and interoperable information technology. (Ludovic 2019)

Work has officially started beginning of 2018. The objective of the WG is not to directly define European standards in the short, medium or long term. The work will focus on elaborating technical reports in collaboration with CEN/TC 301 (Road Vehicles) and CEN/TC 278 (Intelligent Transport Systems).

The ongoing main activities include: (Ludovic 2019)

- Better understanding of sensors (including its connectivity). Focus on on-board sensors (i.e. optical, electromagnetic, etc.) and their interaction with road signs/road markings to determine which properties are relevant to sensors. Further, how connectivity can complement optical and electromagnetic sensors
- Synthesis of ongoing European/National research and pilot projects
- Priority use cases that initially include work zones and toll gates
- Supply of road databases and protocols European-wide in order to lead to high definition (HD) Maps in the long run promoting interoperability

In order to ensure progress further cooperation between CEN TC 301, CEN TC 278, ETSI and the relevant International Organization for Standardization (ISO) groups (TC 22 Vehicles and TC 204 ITS) will be key.

ISO TC204 ITS

On an even more international level ISO is the key independent, non-governmental international organization with a membership of 164 national standards bodies. The relevant ISO groups (TC 22 Vehicles and TC 204 ITS) have cooperated in an Automated Driving Ad-hoc group to bring automated driving standardization forward as shown in Figure 5.

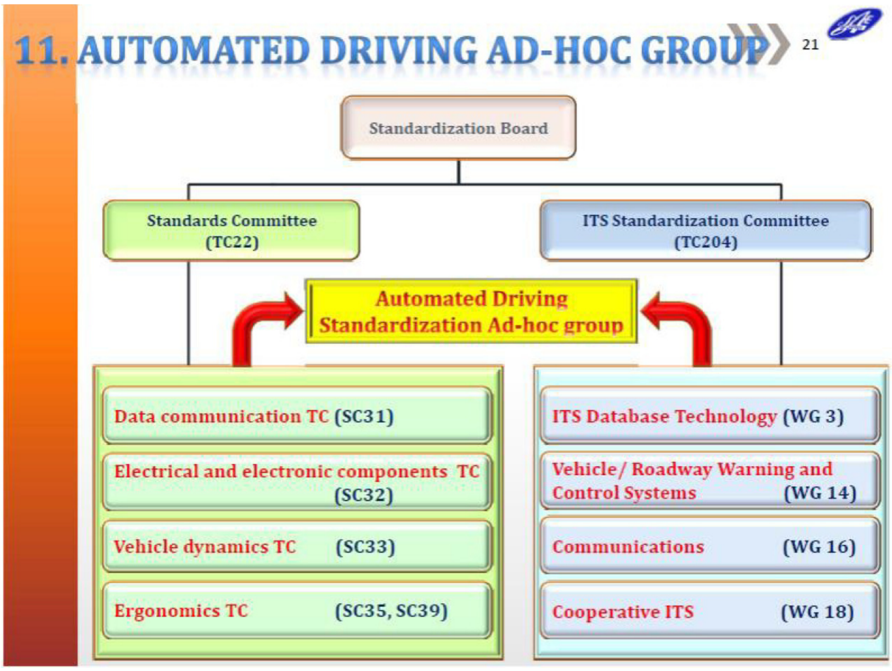


Figure 5. ISO Automated Driving Ad-hoc group (Ludovic 2019)

2.1.3 C-ITS

The aim of Cooperative Intelligent Transport Systems (C-ITS) is to allow road users and traffic managers to share information and use it to coordinate their actions. Opinions on the necessity of connectivity in order to enable automated driving deviate between stakeholders. In Europe however, automation is only seen in connection with connectivity in order to ensure safe and coordinated deployment of automated driving. Also the European Commission is convinced, that C-ITS as cooperative element – enabled by digital connectivity between vehicles and between vehicles and transport infrastructure – is expected to significantly improve road safety, traffic efficiency and comfort of driving, by helping the driver to take the right decisions and adapt to the traffic situation.

Therefore, the European Commission has on 30th of November 2016 adopted a European Strategy on C-ITS, a milestone initiative towards cooperative, connected and automated mobility. The objective of the C-ITS Strategy is to facilitate the convergence of investments and regulatory frameworks across the EU, in order to see deployment of mature C-ITS services in 2019 and beyond. This includes the adoption of the appropriate legal framework at EU level to ensure legal certainty for public and private investors, the availability of EU funding for projects, the continuation of the ongoing C-ITS Platform process as well as international cooperation with other main regions of the world on all aspects related to cooperative, connected and automated vehicles (CAV). It also involves continuous coordination, in a learning-by-doing approach, with the C-ROADS platform, which gathers real-life deployment activities in Member States. (EC 2016)

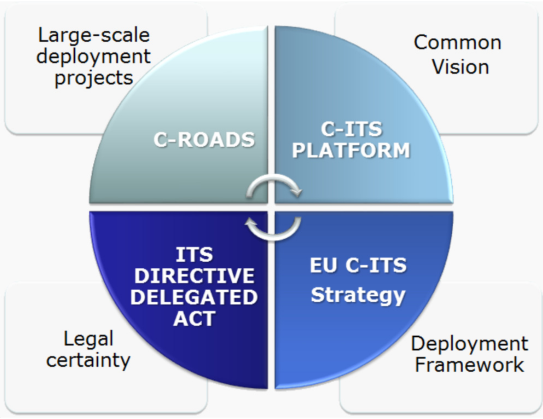


Figure 6. Components of EU Strategy on Cooperative Intelligent Transport Systems (EC 2016)

Due to its aim of supporting automated driving by providing communication options between infrastructure and vehicles, C-ITS have to be a crucial part of the assessment of impacts to infrastructure. In MANTRA communication standards are not discussed in detail but rather what kind of communication infrastructure will be relevant in the coming years. Harmonised C-ITS specifications have been developed between the C-Roads Platform and the CAR 2 CAR Communication Consortium in 2019. They focus on I2V (Infrastructure-to-Vehicle) communication, providing high level C-ITS Day-1 services that are profiled in line with the EC Phase 1 C-ITS Deployment Platform report covering:

- RWW - Road Works Warning
- IVS - In Vehicle Signage
- OHLN - Other Hazardous Location Notifications
- GLOSA - Green Light Optimal Speed Advisory

These specifications form the basis for the roll-out of infrastructure driven C-ITS services all across Europe and shall be extended with following releases. (C-Roads 2019)

2.1.4 European Legislation

The legal framework for enabling automated driving is a broad field. The focus of this report is solely on the impact of automated driving to infrastructure and the following provides an overview of the key European Legislations relevant for infrastructure preparation of automated driving.

EU strategy for mobility of the future

The strategic policy paper of the European Commission entitled "On the road to automated mobility: An EU strategy for mobility of the future" has been published in 2018 with the goal to ensure that future vehicles are embedded in a transport system that favours social inclusion, low emissions and overall efficiency. Enabling the potential benefits of automated driving, the Commission wants to strengthen the links between vehicles and traffic management, public and privately owned data, collective and individual transport and between all transport service providers and modes. According to this new regulatory changes will have to follow in order to build a harmonised, complete and future-proof framework for automation. (EC 2018)

ITS Directive and Delegated Act on C-ITS

The ITS Directive (Directive 2010/40/EU) was adopted in July 2010 as a new legal framework to accelerate the deployment of ITS across Europe. The Directive has been an important instrument for the coordinated implementation of ITS in Europe in establishing interoperable and seamless ITS services while leaving Member States the freedom to decide which systems to invest in. The Directive has stipulated the adoption of specifications (i.e. functional, technical, organisational or services provisions) to address the compatibility, interoperability and continuity of ITS solutions across the EU.

The standards for such specifications have been prepared and published through the C-Roads platform (C-Roads 2019). In order to provide the legal framework the European Commission adopted the Delegated Act for the deployment of C-ITS in March 2019. The act is based on the ITS Directive, which has the intention to accelerate the deployment of ITS across Europe. (EC 2019) The Delegated Act however, was rejected by EU member states in July 2019 primarily due to not being technology neutral. While the standards are there for orientation of all member states they are however not legally binding and still leave the freedom to the member states to decide which systems to adopt.

Tunnel Directive

Directive 2004/54/EC on minimum safety requirements for tunnels in the Trans-European Road Network lays down standards regarding the various organisational, structural, technical and operational aspects of road tunnels longer than 500 metres that form part of designated trans-European transport infrastructure. (European Parliament 2004)

The Tunnel Directive focusses on safety related aspects which might be affected by automated and connected driving or need to be changed to accommodate its safe deployment. Thus the Tunnel Directive needs to be considered as a valuable resource as a European Legislation to ensure that standards for tunnels, as very safety sensitive infrastructure assets, remain appropriate for automated driving.

EU directive on road infrastructure safety management

Directive (EU) 2019/1936 amends Directive 2008/96/EC on road infrastructure safety management following the EUs ambitions to strengthen rules on road infrastructure management in order to make roads safer. The EU wants to reduce road fatalities and serious injuries by making sure that roads, tunnels and bridges are better designed and maintained. With this in mind, the Council adopted revised rules setting out a more systematic approach to safer road infrastructure. The reform is part of the EU's efforts to meet its strategic objectives of halving the number of road deaths by 2020, compared to 2010, and moving close to zero fatalities by 2050. The revised directive will extend the scope of the current rules to motorways and other primary roads beyond the trans-European transport network (TEN-T). Statistics suggest that this will help to make road infrastructure significantly safer across the EU. The rules will also cover roads outside urban areas that are built using EU funding.

Member states will be required to carry out a network-wide road safety assessment at least every five years. The network-wide assessment is a snapshot of the entire road network covered by the directive, and is used to evaluate accident risk. Authorities will use the findings to carry out more targeted road safety inspections or take direct remedial action. The first network-wide road safety assessments are due by 2024 at the latest. It will become mandatory to take systematic account of pedestrians, cyclists and other vulnerable road users in road safety management procedures. (European Parliament 2019a)

2.2 Classifications

2.2.1 SAE Levels

Society of Automotive Engineers (SAE) standard J3016 defines levels of automated driving. It is the industry’s most-cited reference for automated vehicle capabilities. The standard defines six levels of driving automation, from SAE Level Zero (no automation) to SAE Level 5 (full vehicle autonomy).

First deployed in 2016, the summarizing graphic (see Figure 7) has been updated in 2018 to accommodate the developments in the industry. (SAE 2018)

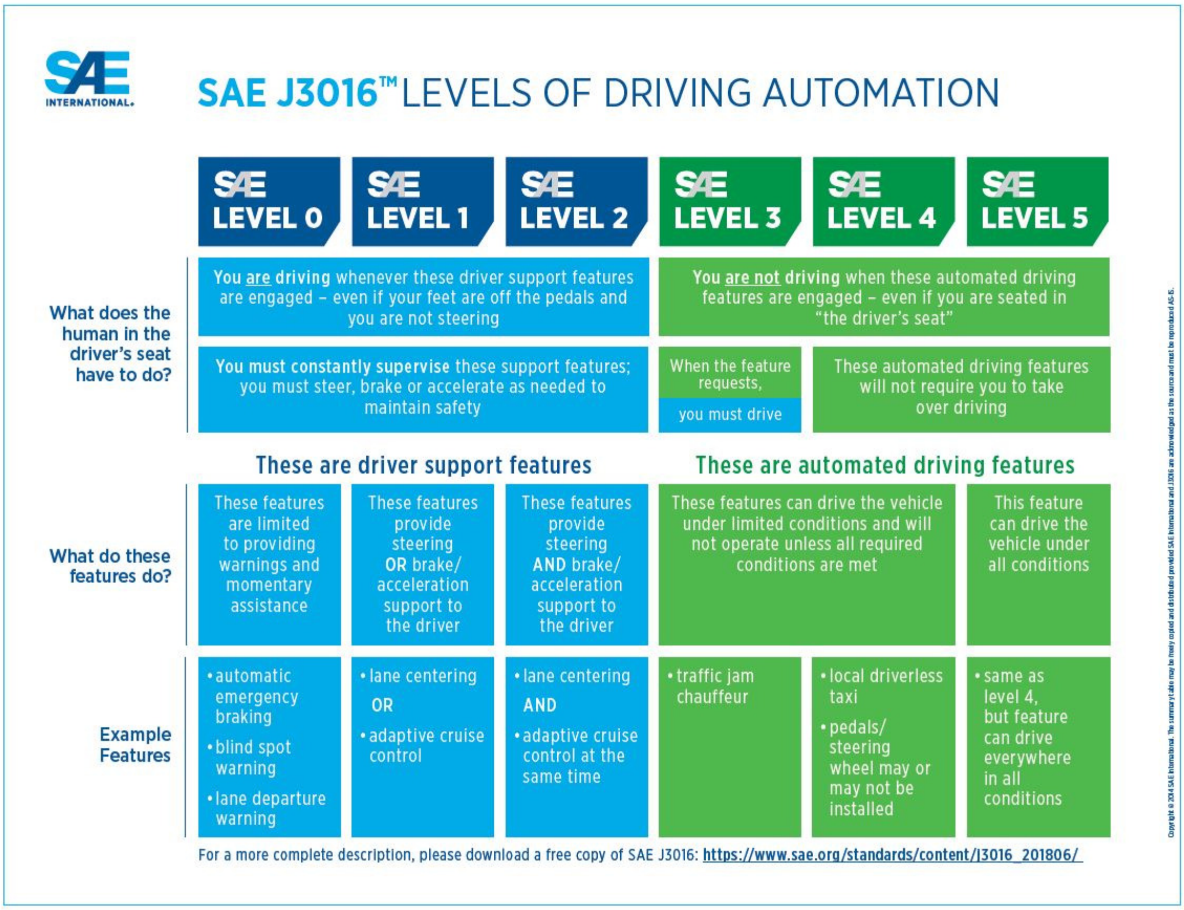


Figure 7. SAE Level according to J3016 (SAE 2018)

While SAE levels provide the industry standard for a common language on the automation functionality, they still lack the information under which conditions the automation level works safely. To close this gap of necessary information, the concept of operational design domains has evolved as described in the following chapter.

2.2.2 Operational Design Domains (ODDs)

ODD is a description of the specific operating conditions in which the automated driving system is designed to properly operate, including but not limited to roadway types, speed range, environmental conditions (weather, daytime/nighttime, etc.), prevailing traffic law and regulations, and other domain constraints. An ODD can be very limited: for instance, a single fixed route on low-speed public streets or private grounds (such as business parks) in temperate weather conditions during daylight hours. (Waymo 2017)

Koopman and Fratrik (2019) point out, that the list of "other" domain constraints can be extensive and difficult to enumerate without significant experience. They have compiled the following list of ODD factors:

- Operational terrain, and associated location-dependent characteristics (e.g., slope, camber, curvature, banking, coefficient of friction, road roughness, air density), including immediate vehicle surroundings and projected vehicle path. It is important to note, that dramatic changes can occur in relatively short distances.
- Environmental and weather conditions such as surface temperature, air temperature, wind, visibility, precipitation, icing, lighting, glare, electromagnetic interference, clutter, vibration, and other types of sensor noise.
- Operational infrastructure, such as availability and placement of operational surfacing, navigation aids (e.g., beacons, lane markings, augmented signage), traffic management devices (e.g., traffic lights, right of way signage, vehicle running lights), keep-out zones, special road use rules (e.g., time-dependent lane direction changes) and vehicle-to-infrastructure availability.
- Rules of engagement and expectations for interaction with the environment and other aspects of the operational state space, including traffic laws, social norms, and customary signaling and negotiation procedures with other agents (both autonomous and human, including explicit as well as implicit signaling via vehicle motion control).
- Considerations for deployment to multiple regions/countries (e.g., blue stop signs, “right turn keep moving” stop sign modifiers, horizontal vs. vertical traffic signal orientation, side-of-road changes).
- Communication modes, bandwidth, latency, stability, availability, reliability, including both machine-to-machine communications and human interaction.
- Availability, correctness and freshness of infrastructure characterization data such as level of mapping detail and identification of temporary deviations from baseline data (e.g., construction zones, traffic jams, temporary traffic rules such as for hurricane evacuation).
- Expected distributions of operational state space elements, including which elements are considered rare but in-scope (e.g. toll booths, police traffic stops), and which are considered outside the region of the state space in which the system is intended to operate.

Special attention should be paid to ODD aspects that are relevant to inherent equipment limitations, such as the minimum illumination required by cameras. (Koopman and Fratrik 2019)

Aigner et al. (2019) concluded that MANTRA will use the ODD attributes agreed by the EU EIP project (Kulmala et al. 2018a), and that does not contradict with the list of Koopman & Fratrik (2019). Table 2 shows the ODD attribute list utilized in MANTRA.

Table 2. ODD attributes (Kulmala et al. 2018a)

ODD attribute	Physical / Digital infra-structure	Static / Dynamic
Road	Physical	Static
Speed range	Physical	Static
Shoulder or kerb	Physical	Static
Road markings	Physical	Static
Traffic signs	Physical	Static
Road equipment	Physical	Static
Traffic	-	Dynamic
Time including light conditions	-	Dynamic
Weather conditions	-	Dynamic
HD map	Digital	Static
Satellite positioning	Digital	Static
Communication	Digital	Static
Information system	Digital	Static

Many attributes are related to infrastructure, mostly the physical infrastructure. Also aspects of the digital infrastructure are relevant for the ODDs.

Concerning the nature of the attributes, most of them are considered as static with regard to the availability of the service behind the attribute. In many cases, the service content itself can be quite dynamic – up-to-date information about a VMS from an information service provided in real time via the communications service to a vehicle accurately located just at the moment utilising a newly updated HD map. (Aigner et al. 2019)

2.2.3 Infrastructure Support levels for Automated Driving (ISAD)

While still a long way from being harmonized, ODDs are the accepted concept of defining the specific operating conditions in which the automated driving system is designed to properly operate. Still, ODDs are somehow the language of the automotive industry to define the requirements of their automated functions towards NRAs and others. NRAs however, so far have no universal language of describing the readiness or status of their road networks to provide the required infrastructure support for the automated functions.

This topic is being addressed in the INFRAMIX project with the proposal of the so called concept of infrastructure support levels for automated driving (Carreras et al. 2018). The ISAD levels could be seen as the NRAs answer to ODDs to provide a clear orientation. The current status of the INFRAMIX projects proposal for the definition of ISAD levels is summarized in Table 3.

Table 3. Levels of the Infrastructure Support for Automated Driving (Carreras et al. 2018)

				Digital information provided to AVs			
	Level	**Name**	**Description**	**Digital map with static road signs**	**VMS, warnings, incidents, weather**	**Microscopic traffic situation**	**Guidance: speed, gap, lane advice**
Conventional infrastructure	**E**	Conventional infrastructure / no AV support	Conventional infrastructure without digital information. AVs need to recognise road geometry and road signs.				
Conventional infrastructure	**D**	Static digital information / Map support	Digital map data is available with static road signs. Map data could be complemented by physical reference points (landmarks signs). Traffic lights, short term road works and VMS need to be recognized by AVs.	X			
Digital infrastructure	**C**	Dynamic digital information	All dynamic and static infrastructure information is available in digital form and can be provided to AVs.	X	X		
Digital infrastructure	**B**	Cooperative perception	Infrastructure is capable of perceiving microscopic traffic situations and providing this data to AVs in real-time.	X	X	X	
Digital infrastructure	**A**	Cooperative driving	Based on the real-time information on vehicle movements, the infrastructure is able to guide AVs (groups of vehicles or single vehicles) in order to optimize the overall traffic flow.	X	X	X	X

The support levels provide significant detail on the information system and address the communication, maps, traffic signs, and road equipmentaspects of the ODD as well. The concept will likely be detailed further in the future and may need to be adapted and/or complemented with regard to specific automated driving use cases. The specification of the infrastructure support levels by the road operators would clearly benefit from a constructive close dialogue with the automated vehicle and driving system manufacturers and developers.

2.3 Research results on effects of CAD on infrastructure

Research on automated driving has increased exponentially in the past years with various real traffic pilot projects, simulation studies and socio-economic studies. In terms of effects of automated driving to infrastructure work has only started. Classification work on ODDs and ISAD levels has increased awareness and has made it clear, that impacts on physical and digital infrastructure are undeniable. In this chapter a quick overview is given on the main research results on a general level which provides the basis for the specific use cases which are in the focus of the MANTRA project (see chapter 3).

2.3.1 Automated driving and infrastructure in general

Though the timeline of automated vehicle development is hotly debated, every major manufacturer and a plethora of start-ups are involved in the race to deliver smarter, more efficient mobility options. Automated vehicles still face some technical challenges that must be solved to allow a safe and efficient journey in this transition period.

Introducing connected and automated mobility on public roads is expected to solve many traffic safety and capacity problems. However, in the ongoing and presumably long-lasting transition period with conventional road users alongside automated vehicles, there are multiple challenges to overcome. In this context, the interplay between vehicles and infrastructure becomes more important than ever. For example, complex junction environments, unexpected or misinterpreted road user behavior, inclement weather conditions or poor road condition or markings constitute potential risk factors for sensor and perception systems. The road infrastructure can contribute to this by supporting automated vehicles in their driving task.

On the one hand, solutions to adapt the physical road geometry as well as road(side) elements in different papers. On the other hand, recommendations for digital infrastructure are made that encompass infrastructure-to-vehicle connectivity and different layers of map data. (EC 2017)

A basic assumption in most projects is, that CAVs are capable to operate robustly and safely within their respective ODD, which defines the functional system boundaries in terms of where and under which conditions the CAV is designed to operate. Additional road infrastructure should not be a necessity for CAV operation. However, infrastructure can help to expand the ODD, e.g. by extending the electronic horizon through infrastructure-to-vehicle (I2V) communication and can thus increase the safety and comfort of CAV passengers. (Czarnecki 2018)

Another important assumption is, that CAVs will operate in mixed traffic alongside non-automated road users. Hence, the safety, comfort or efficiency of conventional road users can at no circumstances be harmed through infrastructure solutions supporting CAV.

The European Commission (2017) states in the C-ITS Platform's II Phase final report that research and standardization work on infrastructure changes related to automated driving should cover the following non-exhaustive list:

Physical infrastructure (EC 2017)

- Decent quality and visibility (contrast) of lane markings, in particular on motorways, dual carriageways and key cross-border routes (TEN-T) to facilitate lateral control for automated driving.
- Clear visibility of road infrastructure for vehicle sensors and the driver – including road signs, speed limit signs, traffic signs indicating change of speed limits via marking entrance to towns and municipalities (maintenance to avoid covered through bushes, or temporarily by snow, and are not clearly recognisable for vehicle systems at the required distance).
- To present static and dynamic traffic rules (or signs) also in digital representation in data bases, in maps and directly on the road. When using both physical road signs and the digital infrastructure, mismatches may occur, especially for dynamic signs. Also, sometimes the regulation becomes effective when physical signs have been installed, and sometimes when the regulatory documents are published. Similarly, the digital representation is sometimes based on the regulatory documents, and sometimes by interpreting the physical signs. A higher quality of data and further harmonization of regulation will benefit CCAM.
- Availability of usable hard shoulders for safe, automated emergency stops.
- Light-signal systems with communication facilities can, in the long run, contribute to the reliability of digital road infrastructure.
- VMS often have scanned LED arrays which are incompatible with vehicle cameras. VMS therefore need standardised triggers (pulsating LEDs and/or short/long range communication).
- Ensuring availability of existing and intact fences where needed on motorways, dual carriageways and TEN-T to minimize risk regarding hazardous situations with large wild life (such as deer, moose, etc.).
- Identification and communication about platooning levels for a specific road segment statically or dynamically assigned (e.g. amount of vehicles allowed in an platoon)

- Allocation of dedicated lanes or areas where economically viable (e.g. automated shuttles are given access to existing bus lanes)

Digital infrastructure (EC 2017)

- The digital infrastructure is composed of data bases and geographical data as well as the related back-office functions. It contains both static and dynamic data and connects and interacts with vehicles through hybrid communication equipment incorporating at least short-range and long-range communication systems. Continuous improvement of cellular coverage for long range communication and deployment of short range communication infrastructure along motorways and urban environments supports tactical and strategic information exchange (e.g. safety and automation related applications)
- Two-way real-time exchange of traffic safety or traffic efficiency related warnings (hazardous situations such as end of traffic jam, dangerous weather conditions, etc.) between vehicles and infrastructure (meaning detection of the hazardous situation and generation of the warning message can come from both).
- Infrastructure-based sensors to detect the different traffic participants and traffic influencing objects, e.g. detecting pedestrians and cyclists at critical intersections and transmitting such information to vehicles. Standardised transmission of short-term road construction or accident situations (position, lane/location concerned, time, speed limit, existing lane markings, passing lanes, etc.) supported by Local Dynamic Map (LDM) and high-definition maps (HDMAPs) concepts.
- Transmission of definitive and binding duration of traffic light status and timing (SPAT) for change to the next signal phase and intersection topology (MAP) info.
- Transmission of right of way rules (traffic light signal, stop, give way, etc.).
- Transmission of (dynamic) speed limits, entrance to urban environments, etc.
- Transmission (forwarding) of the position and operation mode of emergency vehicles and other priority vehicles with right of way permission to ensure traffic prioritisation at intersections, road segments and traffic lights. Transmission of lane closure and traffic light information to influence traffic flow such that prioritized vehicles can benefit from the optimized flow.

According to Vantomme (2019), the automobile manufacturers wish list concerning the infrastructure is similar to the above from EC (2017), although they have labeled many of the physical infrastructure items as digital infrastructure. In addition, he states that “It is essential that road infrastructure (road signs and markings, signal lights, etc.) be adapted ahead of the deployment of autonomous vehicles, in cities, but also in highways and on local roads. Discrepancies between Member States will preclude cross border driving of autonomous vehicles.” (Vantomme 2019)

There are several research projects on specific use cases with some assumptions on infrastructure. A few research projects have set out to define infrastructure requirements and impacts for various types of CAVs. The Austrian research project 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. The requirements of automated driving systems and vehicle sensors were studied, as well as the requirements of infrastructure data concerning availability, quality and up-to-dateness. The underlying work was carried out for three different road types, namely motorways, rural roads and urban roads. The results of via-AUTONOM comprise a set of recommendations for infrastructure measures to support automated driving, a method to identify critical road spots and sections in the Austrian road network as well as a conceptual architecture for the efficient use of data from vehicles, infrastructure and digital maps. (Nitsche et al. 2018)

Carlson, P. & Brown, L. (2019) are working on behalf of the FHWA Office of Infrastructure R&D on a similar objective in North America. Their goal is to assess and understand the demands and potential impacts of AVs on current & future infrastructure assets and to guide and assist DOTs on how to determine their “Readiness” for AV use on their highways.

Results in all cases give general recommendations but face the problem that the developments are shifting quickly and large scale field operational test (FOTs) are not focussed on infrastructure readiness or requirements and therefore results remain theoretical.

2.3.2 Highway autopilot including highway convoy

The highway autopilot including highway convoy provides automated driving up to 130 km/h on motorways or roads similar to motorway from entrance to exit, on all lanes, including overtaking and lane change. The driver must deliberately activate the system, but does not have to monitor the system constantly. The driver can at non-critical times override or switch off the system. There are no requests from the system to the driver to take over when the system is in normal operation area (i.e. on the motorway).Highway autopilot systems are considered as the earliest available automated passenger cars in premium car segment, which could be as early as 2022. (ERTRAC 2019)

The next step would be convoys of electronically linked vehicles of all types on motorways or similar roads in the same lane with minimum distance between each other. Depending on the deployment of cooperative systems, ad-hoc convoys could be created if vehicle-to-vehicle (V2V) communication is available with a real-time performance that allow vehicles of different makes to reduce safety distances far below today´s manually driven distances. By this, especially in large urban areas, highway traffic could develop to be much more efficient (traffic space per person, energy consumption per vehicle). (ERTRAC 2019)

The less automated version, the highway chauffeur (L3), as it is available already now in the premium segment, still depends on clear visibility of lane markings and other signs. In case of the highway autopilot, the current ODDs still require the same. However, preparing for deployment of higher automation functions contains various challenges to put capabilities in place and to synchronise investment cycles (e.g. standardised quality of road markings).

The same applies for other common situations like changing weather conditions or work zones where a highway autopilot has to be able to inform the fallback driver early on to provide sufficient takeover time and to avoid controlled stops ahead of e.g. work zones.

Connectivity can support in this matter to provide the highway autopilot early on with dynamic road situation information.

In work-package 3 simulations were performed using macro simulations in OmniTRANS to assess the mobility and travel behaviour impacts, and using microsimulations with VISSIM to assess the traffic flow and safety impacts. The macro simulation provides a first insight into the impact of AVs at a network level. Since it is expected that AVs are only fully capable of driverless performance on motorways, a 50% AV scenario leads to a shift of trips from local roads toward motorways. This results in usually longer routes, causing an increase in driven vehicle-kms driven. However, due to more efficient driving of AVs this leads to a decrease in total travel time and delay (15-20%) for both AVs and CVs. However, in this way it is assumed that every motorway is occupied by 50% AVs, which might not necessarily be the case. Some routes might have higher AV ratios, and not all vehicles (CVs/AVs) might spread evenly across all road types. A better implementation might be introducing a completely new mode where an AV is modelled as a vehicle with a lower PCU value. The microsimulation showed that decreasing travel times are to be expected with increasing penetration rates, also at small percentages of AVs. The influence of different taper lane lengths or demand levels seems to be marginal. Results of these simulations highly depend on parameter settings. This was shown by using two different parameter sets for modelling CVs: the commonly used default settings and the ones based on extensive calibration using real data. In general, the default parameters resulted in negative influences on travel time and a marginal influence on safety. On the other hand, calibrated parameters resulted in positive influences on travel time as well as a positive influence on the safety. Since every country or area can possibly be recognized by a different driving behaviour, reflected by different (calibrated) parameter settings, it is expected that the influence of AVs on traffic performance may highly be dependent on the country or area of interest. (van der Tuin et al. 2020)Highly automated freight vehicles on open roads (incl. platooning)

Various forms of automated driving are about to influence the logistics industry. Highly automated freight vehicles hold the promise to increase driving times as drivers will need less resting periods or at some point are not needed any more, which is still a distant vision at least for long-distance transport. However, the concept of truck platooning is seen by many as one of the first commercial automated driving use cases to be deployed at a low automation level (SAE level 2) to enable fuel consumption efficiency through the slipstream effect. The platooning concept can be generally defined as a collection of vehicles that travel together, actively coordinated in formation. (Bergenheim et al. 2012)

Truck platooning has been tested on various test tracks and showcases like the European Truck Platooning Challenge (2016) in Europe, North America and Asia. The EDDI project (2019) was the first test with two electronically linked trucks on a highway under real traffic conditions, providing logistics services over a long period with professional drivers rather than test drivers.

Developments in the underlying Cooperative Adaptive Cruise Control (CACC) technology have been ongoing for years, yet wide-scale deployment of truck platooning is a system-wide innovation challenge. Actions are required by policy-makers to contribute supporting legislation and safety-focused type approval methodologies and finally for NRAs it will be important to understand what effects of truck platooning are to be expected on their road networks in order to make the appropriate provisions and amendments. Effects on the high-level road infrastructure are divers and involve not only assessment of entry and exit locations but also potentially necessary amendments to structural bridge design, tunnel design in terms of additional fire protection measures, increased wear and tear of road pavements and many more.

Most ongoing studies and pilot projects deal with the improvement of CACC technology and efficiency effects due to the slipstream effect. However, while it is common understanding that truck platooning potentially could have an impact on all the mentioned infrastructure assets, research is still limited. One project that sets out to understand the systemic effects of truck platooning including impact on road infrastructure is the Austrian project Connecting Austria (Schildorfer et al. 2019) In particular interesting for potentially increased pavement deterioration also little research has been done on the actual achievable CACC accuracy to reach the optimum slipstreaming effect. Further, also only initial research has been done on impact of vehicle lateral offset effects to fuel consumption efficiency. This is particularly important for NRAs as exact lateral track following will possibly lead to increased pavement rutting. The potential for varying lateral offsets might be the solution to avoid pavement lifecycle cost increases due to platooning. While the potential benefits are promising, remaining challenges need to be analyzed in order to take sensible measures. This correlation between lateral track off-set, slipstream effect and pavement deterioration is currently being assessed in the Austrian project “Spurvariation”. (Ulrich et al. 2019)

It is not expected that single highly automated trucks on highways will have significant impact on the road infrastructure compared to conventional ones if they operate within their designated ODD. However this only applies if dimensions and weight restrictions remain the same. Longer vehicles (Gigaliner) can have an impact on entries and exit ramps, junctions and tunnels much like platoons, obviously always dependent on the various country specific design parameters. (Irzik et al. 2016) Heavier vehicles will have an impact on pavement deterioration and bridge structures. While both are not specifically a matter of automation, for the sake of completeness the impact of longer and heavier vehicles will be discussed in chapter 3.4 as they are still a potential future type of freight vehicle. In some European countries so called super-heavy trucks are already a reality today, like in Finland. Since their introduction in 2013 various studies have been conducted on behalf of the Finnish Transport Infrastructure Agency on instrumented test sites which also led to research on effects of truck platooning. Results showed that accurate lateral track following of platoons indeed the rate of distress development, especially rutting, dramatically increases. (Kolisoja 2019)

The impacts of highly automated trucks and truck platooning on traffic flow and environmental policy goals are being discussed in work-package 3 of MANTRA. Following are the major conclusions from the simulation work on automated freight vehicles: (van der Tuin et al. 2020)

- Flow improves as more and more freight vehicles get automated
- There is some non-linearity in the speed and travel time benefits with respect to the share of vehicles automated
- The speed and time benefits are the largest when the motorway is congested
- In a congested situation, the benefits are more egalitarian, i.e. they accrue to all types of vehicles — automated or non-automated; in free-flow conditions, it is the automated freight vehicles which benefit the most, for other vehicles benefits are marginal
- Smaller inter-vehicle gaps allow a slight increase in average freight vehicle speed, but only in congested stretches, with no effect in other stretches
- A larger number of vehicles in the convoy increases average freight vehicle speed, but only in congested stretches, with no effect in other stretches

2.3.3 Commercial vehicles as taxi services

The bold promise of commercial vehicles as taxi services, often referred to as “robot cabs” has collided with reality in the past years. While promises were made in earlier years that companies like Waymo would have their autonomous service ready for commercial use in 2019, it has turned out that bringing robot cabs commercially on every road will take a lot more time and more money than originally expected because a lot more testing is required. (Waymo 2017)

Robot cabs are the use case within the MANTRA project where most driving will be done in the manifold circumstances of urban roads. Compared to highways the variables of driving on urban roads are exponentially bigger. Not only are road design parameters (width, curves, inclinations, traffic control devices) potentially different on each corner, also interaction with other road users is divers. In urban environments it is therefore very unlikely to reach a point where infrastructure is entirely standardized and predictable for robot cabs. Therefore the robot cabs themselves will have to be able to deal with any given challenge in order to reach the promise of being able to operate everywhere, all the time. (Waymo 2017)

Besides the general challenges of visibility and having up-to-date HD maps available, which in case of Waymo are being produced in advance by Waymo itself and are being constantly updated during operation of the robot cabs, are still the many unforeseeable spontaneous disturbances that are common in particular on urban roads. Also Waymo has defined ODDs which include geographies, roadway types, speed range, weather, time of day, and state and local traffic laws and regulations. While Waymo aims to have a broad ODD to cover everyday driving, however if sudden changes (such as a snowstorm) that would affect safe driving within their operational design domain occur, the general solution is to come to a safe stop (i.e. achieve a “minimal risk condition”) until conditions improve. (Waymo 2017)

Taking up the example of the snowstorm and assuming that such an event would force all robot cabs in the area to come to a safe stop, roads would be locally blocked anytime such an unexpected event occurs. Taking this further robot cabs could have a tremendous impact on the availability of urban roads. Hence the systemic impact on urban traffic would be considerable if no other solutions than purely coming to a safe stop are being found.

Research projects like Avenue21 (2019) are therefore analyzing urban roads based on current ODD parameters of robot cabs to assess which ones are useable with their current ODDs. These analyzes result in city maps indicating the urban roads useable for robot cabs. Not surprisingly in particular in historical cities like Vienna the results show very limited options for the safe operation of robot cabs. In addition these analyzes obviously only considers static ODD parameters, so the picture gets worse once weather, temporary road blocks and other daily dynamic changes in cities come into place.

While attempts for urban road design guidelines for physical infrastructure are being made (Transport Systems Catapult 2017), realistically ODDs of robot cabs have become a lot wider to make their large-scale deployment in cities possible. On the digital infrastructure end there are indeed measures that could be realised more easily and support robot cabs. For example, communication with smart connected traffic lights could benefit not only robot cabs in mixed traffic scenarios but also improve traffic flow overall. (Novak et al. 2018)

Many research activities on digital infrastructure to make cities traffic smarter and more easily accessible for robot cabs while encouraging a balanced mix between public mass transport and individual traffic are ongoing. The investigation of how the general availability of robot cabs could affect the attractiveness of traveling by car, how this in turn could affect mode choice, and how changes in mode choice would affect the broader transportation system is tackled in work-package 3 of MANTRA. The simulation results show that the introduction of robotaxis hardly results in any changes in public transport and bicycle usage. Only private car trips are being replaced by robotaxi trips. Because robotaxis need to be relocated after they perform a trip (the so-called empty taxi trips), this results in additional kilometres driven and thereby also additional delays. These delays are also experienced by people not using the robotaxi service. (van der Tuin et al. 2020)

A brighter outlook on the impact of robot cabs to infrastructure: expectations are that robot cabs could significantly redesign the urban environment. For instance, at the neighbourhood and street level, the use and perception of streetscapes can utterly change if parking space is freed up and streets are slowed down. (Avenue21 2019)

2.3.4 Driverless maintenance and road works vehicles on highways

Maintenance and road works often are performed within limited space and right next to traffic. The benefits in terms of safety for road/maintenance workers and efficiency of maintenance work are obvious. However, also these reasons – limited space and fast onward traffic – make the development and use of automated systems difficult. Research and pilot projects around the globe on the one hand reach for the low-hanging fruits of very limited rather simple use cases like driverless safety trailers on emergency ramps. On the other hand complex and cost-intensive tasks are tackled through step-by-step improvements like e.g. winter maintenance operations.

The project “Automated Unmanned Protective Vehicle for Highway Hard Shoulder Road Works”, short aFAS (Schulz et al. 2019; Stolte et al.) developed and tested a self-driving safety trailer on the hard shoulder of German motorways. Mobile road works on the hard shoulder bear an increased accident risk for the crew of the protective vehicle which safeguards road works against moving traffic. The project aimed at the unmanned operation of the protective vehicle in order to reduce this risk. This was also the very first unmanned operation of a vehicle on German roads in public traffic. Besides technical deployment of the very limited use case of hard shoulder road works protection, aFAS also showed the legal adaptions necessary to enable unmanned operation of vehicles in moving traffic.

In terms of highway maintenance and operation one of the more complex applications is the field of winter maintenance. As an extremely safety critical task involving a lot of manpower in rather condensed periods of time but still potentially long shifts, driverless solutions are desirable. However, technical complexity of the driving task itself due to limited visibility as well as the necessary ever-changing strategy adjustments of salting amounts, snow plow shield adjustment make this use case particularly difficult. High-level automated or even driverless snowplows for motorways are therefore a distant vision. In the meantime the step-by-step integration of automated functions is tested with promising results in projects worldwide. Snowplough operators are often tasked with numerous monitoring and operational activities that they need to do simultaneously while removing snow and spreading de-icing agents on the road. In Minnesota (Arabzadeh et al. 2019; Liao et al. 2018) applications for snow plowing convoys and lane boundary guidance were tested using DSRC and GNSS-based lane boundary guidance system. Results showed that the positioning accuracy with DSRC was inadequate for providing the plow operator with sufficient information to maintain spacing between two vehicles. The GNSS-based lane boundary guidance system successfully supports plow operations when visibility is poor and lane boundary cues are limited. Also snow plow operators found the boundary guidance system very helpful and asked for further development in this direction.

In Japan (Abe 2019) pilot tests have been done on a Hokkaido expressway as well as other roads with similar goals. Highly accurate positioning data from a quasi-zenith satellite were combined with high-resolution 3D map data to provide the operator with additional guidance as well as to track the snow removal progress for the traffic management centre.

Another important research field for maintenance improvements is the automated provision of infrastructure condition data through vehicle-to-infrastructure (V2I) communication both ways. Various C-ITS projects tested and provided solutions for communication of condition data into vehicles. From a maintenance perspective the other communication direction – vehicles providing road condition data through V2I communication to the TMC – promise major improvements for predictive maintenance. One project in Germany by Mercedes Benz is testing the provision of data on snowy or icy road conditions through electronic stability control (ESC) and anti-lock braking system (ABS) to enable more efficient winter maintenance planning (next mobility news 2019). Future ambitions involve also the collection of road condition data like cracks, rutting or skid resistance facilitating sensor technology of highly-automated vehicles through V2I communication. However so far it remains unclear if CAV sensors will be suitable for the provision of condition data. Other examples of automated condition data provision include new concepts utilizing drones for difficult to access infrastructure assets like high bridges, gantries or tunnels as tested in projects like e.g. Riskmon. (Bladescanner 2019)

Road works vehicles face similar challenges as maintenance vehicles with the need to work in limited space close to onward traffic. While innovation through automation and digitalization within the construction industry is a huge R&D field, the focus clearly lies on integrated design, construction and asset management through the application of BIM (building information modelling). BIM software programs grant the ability to digitally design a construction project that moves beyond two-dimensional technical drawings and Computer Aided Design. BIM allows professionals at all stages, from architects to engineers to building managers, to collaborate on one construction project.

On another end automation of construction vehicles is progressing but clearly focused on greenfield road or tunnel construction projects with no road traffic interference. Road works vehicles on refurbishment projects under traffic are considered very difficult due to the limited space. The ambitions in this field are also directed towards automated safety trailers for traffic management similar as for O&M.

The impacts of a safety trailer indicating a slow moving work zone (15 km/h), and a winter maintenance truck on traffic flow are simulated in work-package 3 of MANTRA. Different penetration rates (0-100%), different CV driving logics (default and a Dutch calibrated set of parameters), and different communication policies for AVs (adopt a larger headway around the maintenance work, keep the same headway, or not communicating anything) are simulated. Given these factors, the communication policies have the largest effect on smooth traffic flows. Interestingly, a “no communication” scenario where AVs do not receive messages from the maintenance vehicles results on average in the most smooth traffic flows. Changing lanes directly after receiving the message of a work zone ahead results in decreases of capacity on a longer stretch of road, and thereby resulting in longer average travel times. Not only CVs were hindered, also AVs were not able to merge into the correct lane. It might be advised to communicate the same to AVs (e.g. broadcast messages) and CVs (e.g. signs along the road), and let them decide themselves what to do with it. A centralized approach where every AV receives the same advice (“move to the other lane”) doesn’t seem to be the best solution. Obviously, large differences are spotted between the safety trailer and the winter maintenance simulations which are operating in very different speed: 15km/h vs 45 km/h vs 60 km/h. Of course, the business on the road (i.e. f/c ratios) has a high influence on this effect as well: if it gets more crowded, one might not be able to overtake (on time), and as a result it might take longer to find a gap. (van der Tuin et al. 2020)

3 Impacts through automated functions operation itself

In this chapter impacts due to the use of the selected automated functions and their operation themselves are tackled. This involves impacts to pavement lifecycles due to e.g. accelerated rutting by convoy driving as well as additional requirements for emergency bays, tunnel fire protection, additional vehicle restraint systems and such.

3.1 Approach

The initial starting point was a set of candidate automation functions all based on the latest definitions in ERTRAC (2017). The selection of functions and ODDs has been done in work-package 2. Through scientific analysis of deployment and the collective selection with CEDR of most significant automated functions and use cases during workshops (Vienna, 31.08.2018), the following functions shown in Figure 8 have been chosen to be further studied.

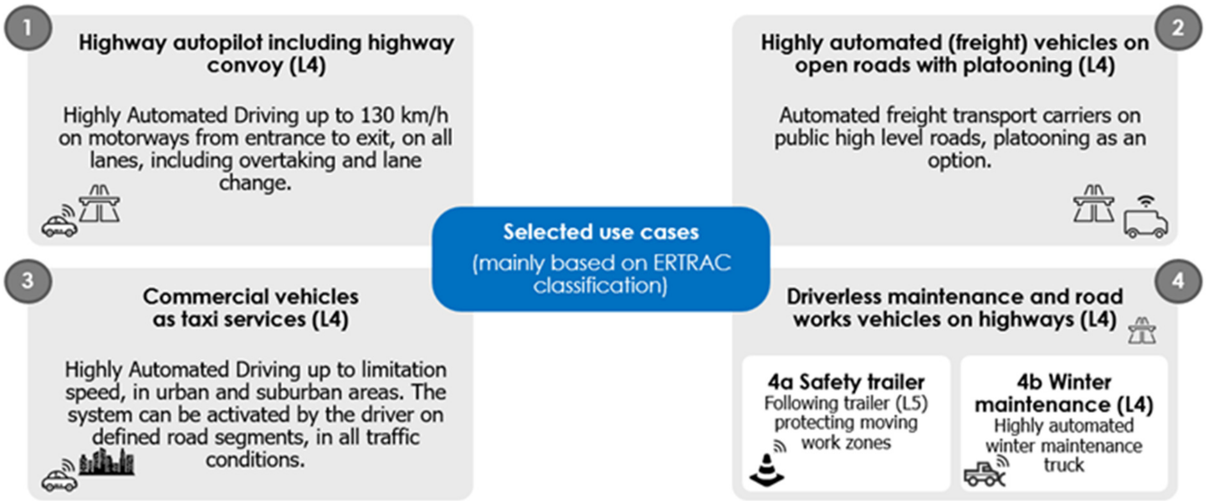


Figure 8. Selected use cases including level according to SAE J3016

The selected use cases are described in detail in the MANTRA Deliverable D2.1 (Aigner et al. 2019), explaining not only the specifics of the use case but also the ODDs and expected penetration rates until 2040.

The process how the use of the selected automated functions and their operation impact infrastructure is shown in Figure 9.

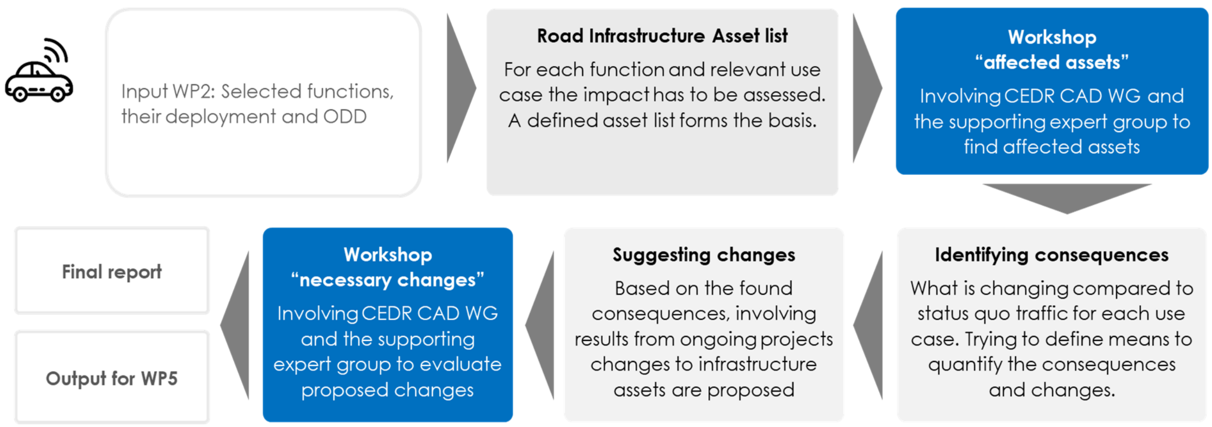


Figure 9. Assessment of impact by automated function itself

In the initial expert workshop with CEDR CAD WG (Tallinn, 07.03.2019) the functions were mapped with physical infrastructure assets to identify which assets are affected by which function the most.

With these results concrete consequences to these identified road infrastructure assets were identified as a desktop study. Results were discussed with selected experts to validate the assumptions. Where possible considering TRL of technologies as well as predictability of developments and economical reasonable necessary changes were developed for respective use cases and affected assets.

Following this, crucial identified changes were discussed and validated in another expert workshop with CEDR CAD WG members and experts in the respective fields (Vienna, 10.09.2019). The results of the workshop were used for validation of the taken assumptions on necessary changes and final suggestions formulated.

3.2 Identifying affected infrastructure assets

3.2.1 Road infrastructure asset list

The starting point to define automated function's impact on road infrastructure is by finding out which types of road infrastructure assets are affected by the selected automated functions. As a basis MANTRA prepared a road infrastructure asset list of primary road infrastructure assets based on typical categorizations. The following primary assets are being analyzed:

The presented asset groups and assets are structured for this project. Commonly the asset road marking is part of the asset group road equipment. However as it has such high importance for CAD it has been discussed as part of the road itself and hence is included in the asset group pavement.

Throughout this document the term road equipment is used for the asset group of guiding, safety and other equipment (except road marking). In many international papers, especially from the US and Australia, the term road furniture is used instead of road equipment. In this report, we use the term road equipment as it is used by the European standardization bodies.

Table 4. Road Infrastructure Assets

Asset Group	Assets	Asset Group	Assets
Pavement	Asphalt pavement	Road equip-ment & Drainage	Road signs (static/non-digi-tal)
	Concrete pavement		Gantries
	Ramps and junctions		Vehicle restraint systems
	Emergency bays		Noise protection walls
	Road marking		Road drainage
	General road design	ITS - Telematics	Toll systems
Bridges	Bridge structures		Surveillance/Cameras
	Joints / Dilatations		Variable Message Signs (VMS)
	Bearings		Traffic lights
	Rails		Speed radar
Tunnels	Tunnel structure		Weather stations
	Tunnel wall finish		C-ITS
	Ventilation		
	Lighting		
	Emergency system (warning lights, fire protection, exits)		

3.2.2 Affected assets by automated functions operation

The asset list in Table 4 was presented to the participants of the expert workshop (Tallinn, 07.03.2019) and discussed in detail for impact due to operation of automated function. Following the discussion, the participants of the workshop described together for each automated function whether or not these have an impact on the individual assets that differs from use of regular vehicles. It should be mentioned that participants were mainly from countries which have to deal with snow and which in general have overall rather good road conditions and effective maintenance management. Therefore the results might not reflect the opinion throughout all EU countries. In the following tables the results are compiled for each asset group.

Pavement

The results of the workshop showed that pavement including the whole topic of road design will be affected by automated functions operation. In general, this means changes to road design as well as to maintenance routines will be a result of the operation of automated functions. Of all functions however automated freight vehicles in platoons are expected to have the biggest impact due to their loads being the critical design factor for pavements. The workshop results are summarized in Table 5.

Table 5. Asset group pavement – affected assets

<table>
<tr><th></th><th></th><th>Highway autopilot</th><th>Automated freight vehicles</th><th>Driverless taxi services</th><th>Maintenance: Driverless safety trailer</th><th>Maintenance: Driverless Winter maintenance truck</th></tr>
<tr><td rowspan="7">Pavement</td><td>Asphalt pavement</td><td>Bigger effects on deterioration (rutting, skid resistance) at least in Northern countries due to spikes</td><td>Bigger effects on deterioration (rutting, skid resistance)</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Concrete pavement</td><td>-</td><td>Potential effects on joints, more maintenance needed</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Ramps and junctions</td><td>Outside of ODD in current definition</td><td colspan="4">Ramps and junctions are considered a very difficult area in terms of dimensions, visibility, etc. It is expected that design parameters of ramps and junctions likely need to change.</td></tr>
<tr><td>Emergency bays</td><td colspan="2">Will be needed. Further investigation in international projects expected. Covered in requirements for ODDs</td><td>Additional passenger drop-off/pick-up locations needed</td><td>-</td><td>-</td></tr>
<tr><td>Road marking</td><td colspan="4">Highly affected asset and big need for detailed evaluation. It is expected that even in 2040 road marking will still be necessary. International/European standardization is deemed critical in terms of machine readability but not in terms of harmonized design. A combination of physical and digital "guiding information" is expected. NRAs shall never be held liable for the condition of road marking. Dealt with in more detail in ODDs.</td><td>Potentially road markings with sensors which will be critical for winter maintenance</td></tr>
<tr><td>General road design</td><td colspan="5">New definitions in terms of visibility distance, inclinations, curve definitions expected. Also impacts on cross sections through increased need for "safe harbours"</td></tr>
</table>

Bridges

The asset group of bridges is not considered to be affected heavily by the use cases highway autopilot and commercial driverless taxi services. Also effects of automated freight vehicles depend more on future load capacities then on automation. However, automated freight vehicles in platoons are considered to have an impact on existing bridges and will require analyzes of bridge design standards.

While working on the driverless maintenance vehicles use cases, it was discussed that bridges might be outside of the safety trailers ODD and that the safety trailers will be used ahead of bridges rather than on them. The biggest consequences are however expected by driverless winter maintenance vehicles. Snow ploughing on bridges is critical, as snow in most cases is not supposed to be simply discarded into the rivers due to environmental regulations. Bridges are therefore also in conventional winter maintenance a challenging part. In addition, bridges are specifically safety critical in terms of black ice and therefore require specific attention in preventive winter maintenance with higher salting amounts. In an automated winter maintenance use case this would therefore mean very accurate positioning information to ensure that right salting amounts are discarded in the appropriate areas. All these are closely related with ODDs of driverless winter maintenance vehicles rather than purely having an impact on the infrastructure itself. The workshop results are summarized in Table 6.

Table 6. Asset group bridges – affected assets

<table>
<tr><th colspan="2"></th><th>Highway auto-pilot</th><th>Automated freight vehicles</th><th>Driverless taxi services</th><th>Maintenance: Driverless safety trailer</th><th>Maintenance: Driverless Winter mainte-nance truck</th></tr>
<tr><td rowspan="4">Bridges</td><td>Bridge struc-tures</td><td>-</td><td>Problems due to higher loads are possible</td><td>-</td><td rowspan="4">Traffic manage-ment require-ments are higher. Might be outside of ODD</td><td rowspan="4">Challenges of snow ploughing on bridges are an additional hurdle for imple-mentation. Spe-cial attention on preventive salt-ing.</td></tr>
<tr><td>Joints / Dila-tations</td><td colspan="2">Convoy / Platooning to have con-densed loads on limited areas</td><td>-</td></tr>
<tr><td>Bearings</td><td>-</td><td>Problems due to higher loads are possible</td><td>-</td></tr>
<tr><td>Rails</td><td>-</td><td>-</td><td>-</td></tr>
</table>

Tunnels

Tunnels are in particular safety critical due to their confined space and the accordingly neces-sary standards for emergency protocols. In particular tunnels longer than 500m have to follow high safety standards which might be affected by automated vehicles operation. (European Parliament 2004)

Similar to bridges it is considered that the biggest effects are to be expected by automated freight vehicles as platoons. Affected will be mainly the emergency system and the ventilation system. Both driverless maintenance use cases are not considered to be used in tunnels. The workshop results are summarized in Table 7.

Table 7. Asset group tunnels – affected assets

<table>
<tr><th colspan="2"></th><th>Highway auto-pilot</th><th>Automated freight vehicles</th><th>Driverless taxi services</th><th>Maintenance: Driverless safety trailer</th><th>Maintenance: Driverless Winter mainte-nance truck</th></tr>
<tr><td rowspan="5">Tunnels</td><td>Tunnel struc-ture</td><td>-</td><td>-</td><td>-</td><td rowspan="5">Traffic manage-ment require-ments are higher. Might be outside of ODD</td><td rowspan="5">Traffic manage-ment require-ments are higher. Might be outside of ODD.

Challenges of snow ploughing at tunnel entry zones are an additional hurdle for implementa-tion. Salting re-quirements in exit/entry zones</td></tr>
<tr><td>Tunnel wall finish</td><td colspan="3">Additional guiding functions might be necessary or different requirements for tunnel wall colourings/re-flection</td></tr>
<tr><td>Ventilation</td><td>-</td><td>Effects of truck platooning to be further assessed</td><td>-</td></tr>
<tr><td>Lighting</td><td colspan="3">New lighting requirements might be possible to avoid problems with tunnel entries/exits (change of bright-ness/glare)</td></tr>
<tr><td>Emergency system (warn-ing lights, fire protection, exits)</td><td colspan="3">Safety critical - needs further investigation in combi-nation with ODD. In particular in long tunnels (tunnel directive) new emergency routing and systems might be required. Fire protection issues due to possible higher number of trucks/cars driving in platoons. Fo-cus area!</td></tr>
</table>

Road equipment and drainage

In terms of road equipment special attention was paid to all kinds of guiding devices like road signs. International standardization was deemed critical for safe implementation of all automation use cases. This will likely require higher standards in terms of visibility and reflectivity. However it would be also possible that requirements on retroreflectivity for machine detection of markings could be also below the minimum level assumed to be suitable for human drivers. This is still an open question. The actual effects due to the operation of automated functions was in general considered unchanged compared to conventional vehicles for road signs once appropriate, harmonized standards are defined.

Actual effects are expected by the operation of automated freight vehicles as platoons in terms of vehicle restraint systems and also noise protection walls. The workshop results are summarized in Table 8.

Table 8. Asset group road equipment and drainage – affected assets

		Highway autopilot	Automated freight vehicles	Driverless taxi services	Maintenance: Driverless safety trailer	Maintenance: Driverless Winter maintenance truck
Road equipment & Drainage	Road signs (non-digital)	International/European standardization is deemed critical - machine readable but still human readable. New requirements are expected. A combination of physical and digital "guiding information" is expected. Focus area				
	Gantries	-	-	-	-	-
	Vehicle restraint systems	-	Higher vehicle restraint systems standards required in case of truck platooning	-	-	-
	Noise protection walls	-	Truck platooning might create increased noise. Evaluation needed but outside of this projects scope.	-	-	-
	Road drainage	-	-	-	-	-

ITS, toll system and telematics

This asset group summarizes the digital road infrastructure. In terms of standardization and necessary changes this is the asset group expected to be mostly affected by automation use cases. However, it became clear during the discussion that in particular digital infrastructure needs to be clarified in the respective automated functions' ODD. It was decided in the workshop that there is no added value to assess the impact on digital infrastructure due to the actual operation of the automated functions themselves and that digital infrastructure impacts need to be assessed holistically through the definition of the necessary ODDs. The workshop results are summarized in Table 9.

Table 9. Asset group ITS – affected assets

		Highway autopilot	Automated freight vehicles	Driverless taxi services	Maintenance: Driverless safety trailer	Maintenance: Driverless Winter maintenance truck
ITS - Telematics	Toll systems	Automated lanes required everywhere. Varies greatly through different countries.			-	-
	Surveillance/Cameras	Biggest changes expected and of high importance. However, most of these are critical for providing the required ODDs - those are being evaluated in task 2 of work-package 4 and will be analysed in detailed in chapter 4.				
	VMS					
	Traffic lights					
	Speed radar					
	Weather stations					
	C-ITS					

3.2.3 Summary of affected assets

The workshop made it very clear that impacts due to the operation of automated functions and the required ODDs for their safe operation are very much interlinked. The discussions made it obvious how important the ODD definition of each function is, also looking specifically into the requirements by each asset. Results of the workshop brought up a lot of aspects that need to be dealt in the analysis of impacts to infrastructure due to ODD requirements which are considered in the assessments of chapter 4.

In order to follow the structure of this work-package 4 the workshop results have been condensed to actual effects to infrastructure due to the automated functions operation. These are summarized in Figure 10 below.

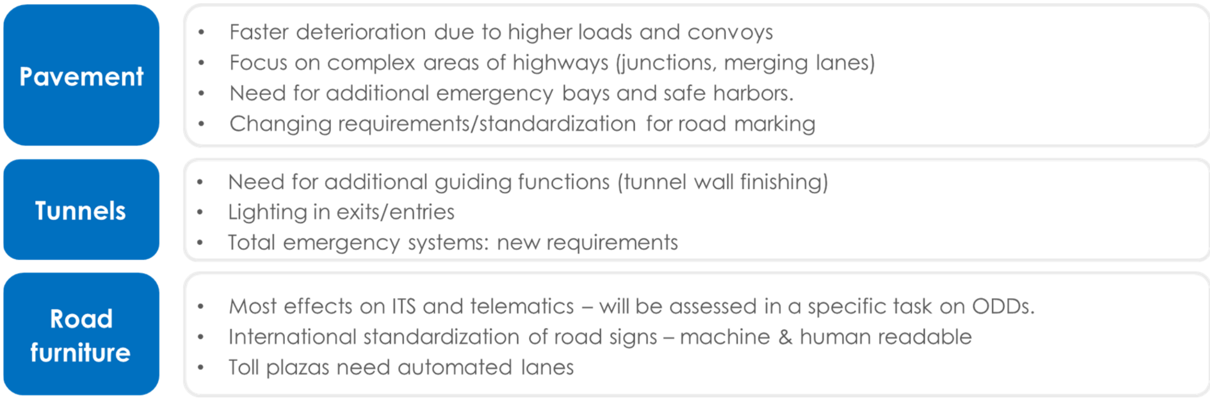


Figure 10. Key results of workshop on affected infrastructure

3.3 Consequences of highway autopilot including highway convoy

The workshop identified major problems with pavement rutting and polishing in the countries, where the use of studded tyres is frequent during winter. Finland, Norway and Sweden are examples of such countries. The increased problems are due to stricter use of the same wheel paths by automated vehicles when compared to human-operated ones. Costs are increased due to shorter repaving cycles.

Emergency bays were discussed from different angles. While motorways already tend to have wide paved shoulders across Europe, some motorways have narrower shoulders, and some have hard shoulder running, making use of the paved shoulder as a driving lane during hours of high traffic volumes. Furthermore, emergency vehicles also need the paved shoulder to reach incident sites even during traffic standing still on all lanes. Thereby, there is likely a need to have wider emergency bays at regular distances to act as safe harbours to stop/park automated vehicles in case of temporary ending of the ODD, and even to be used by all vehicles in case of vehicle breakdowns. Demand and density of such emergency bays need to be further studied.

Well visible, consistent road markings complying with relevant international standards are currently regarded as a necessity for safe automated driving on motorways. The additional costs are due to need to keep them visible, also from snow and ice, renew them more frequently than today, and to ensure their consistency by removing misleading and obsolete markings as well as providing corrections where and when necessary. Also further requirements could be relevant for CAD (e. g. contrast), which are still subject of ongoing research.

Concerning road planning and designs, the workshop agreed about the likely need to specify new definitions in terms of visibility distance, inclinations, and curve definitions.

With regard to bridges, highway convoys might result in condensed loads on limited areas of the bridge surface and structures. The consequences of these could be noteworthy.

The workshop identified tunnels as critical spots also for automated vehicles. New lighting requirements might be possible to avoid problems at tunnel entries/exits with change of brightness/glare especially for vehicles having cameras in a major role in environment sensing. Long tunnels might require new emergency routing and systems. Fire protection regulations and practices might need to be revised due to possible higher number of cars and trucks driving in convoys/platoons.

Tolling systems need to consider automated vehicles, which means that all toll plazas and gates need to have automated lanes.

Biggest changes may target the current ITS systems, which have been designed to provide information and guidance to human drivers. The ODDs of the automated driving systems may need modifications and enhancements in some systems, while some may become totally unused by them.

3.4 Consequences of highly automated freight vehicles on open roads

Highly automated freight vehicles – in particular as platoons – were identified in the expert workshop (Tallinn, 07.03.2019) as the use case with most direct impact on various road infrastructure assets considering only their impact due to operation and not the required ODD. This is in line with latest research results where highway chauffeur or robot cabs are predicted to have tremendous systemic impacts on traffic (traffic flow, density, etc.) but only limited impact on individual infrastructure assets (in accordance with Table 4). The consequences due to the use of highly automated freight vehicles are discussed in further detail in this chapter.

3.4.1 European road freight transport parameters

In the original MANTRA work plan as well as the CEDR CAD WG workshop (Oslo, 06./07.11.2018) where use cases were selected, highly automated freight vehicles had always been tentatively conceived as either one single SAE L4 truck on motorways, highways and main roads. This was based on the assumption that highly automated freight vehicles will still follow current restrictions on weight and dimensions.

In Europe, heavy goods vehicles, buses and coaches must comply with certain rules on weights and dimensions for road safety reasons and to avoid damaging roads, bridges and tunnels. EU Directive 2015/719 (European Parliament 2019b) sets maximum dimensions and weights for international traffic, also ensuring that Member States cannot restrict the circulation of vehicles which comply with these limits from performing international transport operations within their territories.

Technological developments make it possible to attach retractable or foldable aerodynamic devices to the rear of vehicles. For this the maximum lengths permitted under Council Directive 96/53/EC (European Parliament 1996) are exceeded and a derogation from the maximum lengths was therefore necessary. This Directive aims to allow the installation of such devices as soon as the necessary amendments to the technical requirements for type approval of the aerodynamic devices are transposed or applied and the Commission has adopted implementing acts, laying down the operational rules for the use of such devices.

The Directive 2015/7019 (European Parliament 2019b) supplementing the Weights and dimensions Directive (European Parliament 1996) sets maximum vehicle dimensions and weights for national and international road transport in the EU as follows:

- 16.5 metres in length for straight trucks and 18.75 m for road trains
- 2.6 m in width
- 4 m in height
- 40 tonnes (44 t for combined transport, e.g. by rail and water).

However, Member States are able to decide on derogations from these rules for vehicles used only in national transport. So called high-capacity vehicles (HCVs) also known as longer and heavier trucks (LHVs), mega trucks, gigaliners, eurocombis, and ecoliners typically measure 25.25 m in length and are allowed up to 60 t in weight. In the European Union, high-capacity vehicles are allowed and used in Belgium, Denmark, Finland, most German federal states, the Netherlands, Portugal, Spain and Sweden. Concerning the issue of cross-border traffic of vehicles heavier, longer or higher than the limits set in the initial Directive, the debates leading up to the adoption of Directive (EU) 2015/719 ended with the conclusion that the rules of Directive 96/53/EC should not be modified.

A rather different scenario has also been presented by Rosenquist (2019). Deviating from the original assumption of automated trucks which do not differ from currently on the market available trucks in length and size, either as single automated trucks or in platoons, there can be scenarios with platoons of three heavier and longer than normal trucks in either full SAE L4 mode or with the first truck having a driver and the following trucks having no driver (L4). (Rosenquist 2019)

These developments respond to the forecast that significantly rising transport volumes would request an unduly increased number of freight vehicles that would with appropriate following distances significantly reduce the remaining capacity of the European road network. As such a scenario would have a significantly different impact on road infrastructure assets than just normal sized automated trucks. Following discussions with PEB members in the regular steering group conference calls, MANTRA also considered these possible developments about new land transport operational modes in automated freight transport.

Also the European Automobile Manufacturers Association ACEA shares this view calling for policy amendments allowing for HCVs. Claiming the potential of significant carbon emissions reductions ACEA asks for a max. length of 32m to be able to transport 200m³ of load with trucks and trailers with up to 11 axles. (ACEA 2019)

In relation to road infrastructure ACEA has no doubts that HCVs would work in accordance with existing infrastructure as also HCVs must comply with existing road and bridge loading regulations in the same way that all other heavy-duty vehicles must. Given that these high-capacity vehicles, which carry more freight, are longer and the total load is distributed over more axles than it is the case with standard vehicles, HCVs would have the added benefit of causing less road damage per tonne cargo transported than regular trucks. (ACEA 2019)

All the above refers to trucks that are regularly used in road traffic. Special transport high capacity trucks go way beyond those limits. Examples from Finland include 13 axles timber trucks with 104 tons (Kolisoja 2019). The decision to also consider heavier truck examples was further reinforced by such examples.

3.4.2 Overview of parameters and their potential variations

In an effort to filter and digest impacts from such diverse scenarios onto the road infrastructure initially the different parameters of automated freight vehicles are explained. The terminology follows Directive 96/53/EC (European Parliament 1996). Table 10 below also gives an overview of the different possibilities for each parameter which provides the basis for the following scenarios.

Table 10. Variants for highly automated freight vehicle scenarios

Parameters		Description	Possible variations
Truck Type and Dimensions	Type	The type of vehicle, which include straight trucks/motor vehicles, trucks with trailer, articulated trucks and road trains/LHVs	A large number of truck types and hence variations are possible: * Motor vehicle with 2-5 axles (potentially with twin tyres and pneumatic suspension) * Truck with 2-5axles, plus one trailer with 2-3 axles * Articulated trucks with 3-6 axles * Current HCV with up to 7 axles * Future HCV with up to 11 axles
	Length	The length of the truck or the combination of truck and trailer dependent on its type.	A large number of lengths are available and possible. Standard lengths are along the max. lengths: * Motor vehicle: 12m * Truck with trailer: 18,75m * Articulated truck: 16,5m * Current HCV: 25,25m * Future HCV: 32m
	Weight	Max. Transport weight of a truck. Weight restrictions are dependent on number and distance of axles.	A large number of weight variations dependent on the number of axles are possible: * Motor vehicle, 3 axles: 25t * Motor vehicle, 4 axles: 26t * Motor vehicle, 5 axles: 38t * Truck, 3 axles + trailer, 2 axles: 40t * Truck, 4 axles + trailer, 3 axles: 50t * Articulated truck, 4 axles: 38t * Articulated truck, 5 axles: 44t * Articulated truck, 6 axles: 48t * Road train, Current HCV 6 axles: 53 t * Road train, Current HCV, 7 axles: 60t * Future HCV, 11 axles: 80t
Number of Trucks		Single truck or platoon of several trucks	Considering the European road network the max. number of trucks in a platoon is considered to be three. The following variations are possible: * 1 Truck * 2 Trucks * 3 Trucks
Following distance		In case of a platoon, the distance between the trucks	Various distances between trucks from as little as 6m up to 20m are assessed in different projects. In the scenarios the following two categories are assessed: * < 10m * 10 - 20m

Parameters	Description	Possible variations
Level of automation	SAE Automation Level	Highly automated freight vehicles are the focus. In case of truck platoons however also variations with lower automation levels in the lead vehicle are considered: * L4 single truck * L4 platoon * Platoon with L2 lead vehicle and L4 following vehicles

3.4.3 Scenarios for highly automated freight vehicles

As Table 10 clearly shows, there is no single type of automated freight vehicle or truck platoon to be expected but rather a combination of manifold variations. Their operation will have varying impact on infrastructure dependent on their length and loads. However differences between all might be not as big and it will be rather important to look at the most common and most impactful scenarios.

In an attempt to do that, the following scenarios of automated freight vehicles where proposed by MANTRA and confirmed in the expert workshop (Vienna, 10.09.2019) to be assessed in further detail based on their expected future relevance.

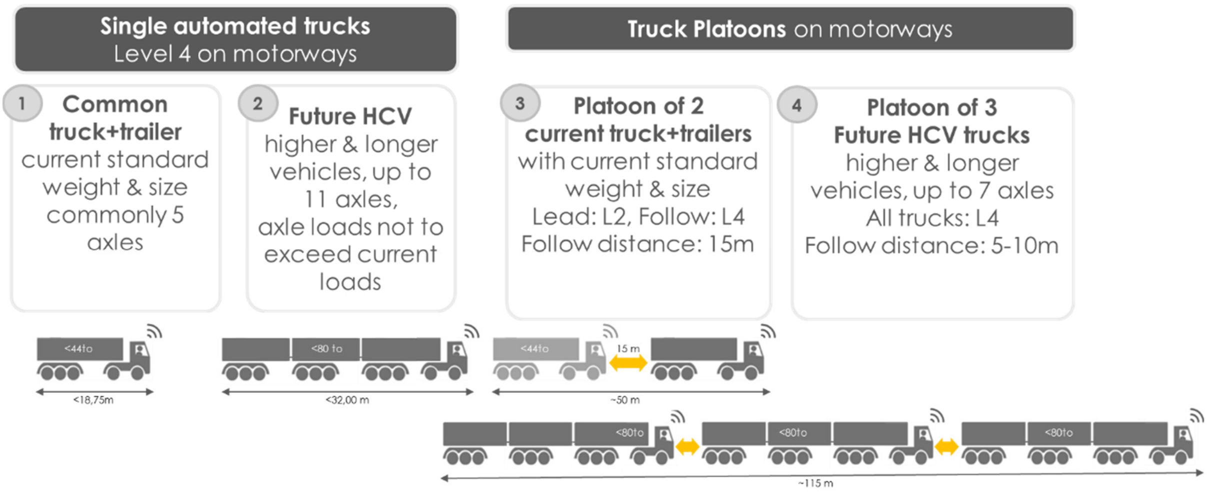


Figure 11. Selected highly automated freight vehicle scenarios

The discussions in the expert workshop (Vienna, 10.09.2019), in particular following the presentation results of Kolisoja (2019), confirmed the chosen approach to also consider HCVs in particular due to the different regulations throughout the CEDR member states. The detailed parameters of those selected scenarios are summarized in Table 11.

Table 11. Highly automated freight vehicle scenarios technical parameters

No.	Short	Description	Truck Type	Length	Weight	No. of Trucks	Follow. distance	SAE Level
1	1xL4 regular	Level 4 automated freight vehicle on Motorways or similar roads with one trailer. Comparable with the most common road freight trucks today in terms of axle, dimension and weight today	2 axle motor vehicle with 3 axle semi-trailer or articulated truck with 5 axles	16,5m - 18,75m	40-44t	1	-	L4

No.	Short	Description	Truck Type	Length	Weight	No. of Trucks	Follow. distance	SAE Level
2	1xL4 HCV future	Level 4 automated freight vehicle on Motorways or similar roads with trailer(s). Dimensions beyond current legislation. Axle weights do not exceed currently allowed axle loads	HCV with up to 11 axles	32m	80t	1	-	L4
3	1xL2 + 1xL4 regular	Truck platoon with 2 vehicles comparable to common road freight truck dimensions today. Lead vehicle level 2 automation, following vehicles level 4 driverless	2 motor vehicles with trailer of same make (e.g. 2 axle motor vehicle + 3 axle semi-trailer)	18,75m each Platoon: ~52m	40t each	2	15m	L2 + L4 + L4
4	3xL4 HCV current	Truck platoon with 3 vehicles with HCV trucks as allowed in some EU countries. All vehicles level 4	HCV with 7 axles	32m each Platoon: ~115m	60t each	3	10m	L4

3.4.4 Consequences and necessary changes due to different scenarios

During the CEDR CAD WG (Tallinn, 07.03.2019) workshop highly automated freight vehicles were identified as the use case with potentially very diverse impact on the existing road infrastructure on motorways. Based on the chosen scenarios of automated trucks, consequences to infrastructure due to their operation on European highways were collected for the different road infrastructures asset categories as described in chapter 3.2 and the results for automated freight vehicles (see Table 5 to Table 9) were further elaborated for the described scenarios.

Those results were discussed interactively within the expert workshop (Vienna, 10.09.2019). The discussions proved very valuable, showing that indeed impact is to be expected by the operation of automated trucks. However, some of the assumptions could be reduced as they are ODD requirements (like visibility of road marking) rather than results of the impact by the operation of the automated vehicles. NRAs highlighted once again that they cannot be held liable for certain condition requirements of road markings or road signs.

In terms of impact due to the operation it also became clear that a kind of an evolution is to be expected with increasing automation. One example were the requirements for safety protection equipment like vehicle restraint systems. For Level 2 platoons vehicle restraint systems will likely require strengthening and therefore Level 2 platooning will probably only be possible on certain routes equipped with the appropriate vehicle restraint systems. However, Level 4 platoons (with automated tire pressure monitoring systems) and no potential for human error should basically not require the passive protection of vehicle restraint systems all together. It also became evident that enforcement will play a more important role in the future. Additionally also enforcement would benefit tremendously from connectivity and automation (e.g. trucks start disabling in case of higher loads). The results of the detailed analysis of consequences as well as the proposals for necessary changes are summarized in Table 12 and Table 13.

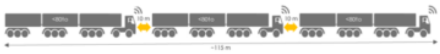
Table 12. Consequences and necessary changes due to single automated trucks operation

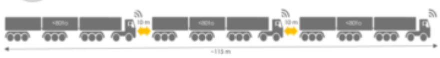
		Common truck+trailer 		Future High-capacity vehicle 	
		Consequences	**Necessary changes**	**Consequences**	**Necessary changes**
Pavement	Asphalt pave-ment	As dimension and weight restrictions are the same as for con-ventional trucks, lim-ited new impact ex-pected. Potentially rutting and fatigue might increase as most LKA systems will use same wheel paths of vehicles could be identical.	Studies are required to analyze rutting and fatigue potential in case of increasing unification of wheel paths (applies al-ready to current LKA systems). Potential of traffic manage-ment measures to be assessed.	Research shows that more axles increase stress on pavement in particular in case of uni-fied wheel paths. So even in case of same axle loads, changes in deterioration are ex-pected	Initial research indicates the potentially positive counter effects of de-fined wheel path offsets might help to level out increased deterioration. This findings need to be further assessed as well as their potential for traf-fic management measures.
	Con-crete pave-ment	As dimension and weight restrictions are the same as for con-ventional trucks, no new impact expected.	No immediate changes identified	Additional axles could lead to increased stress on joints. If axle loads are not exceeded im-pact to concrete pave-ments should not change.	No immediate changes identified
	Ramps and junc-tions	As dimension and weight restrictions are the same as for con-ventional trucks, no new impact expected.	No immediate changes identified	Ramps and junctions are considered a very difficult area in terms of dimensions, visibility, etc. General statements are difficult as each country has their own design guidelines	Each country will need to assess their design parameters of ramps and junctions for 32m long HCVs. Detailed in-formation on their ramp design is needed in or-der to make traffic man-agement provisions al-lowing these trucks only where design parame-ters are ok for them to enter exit.
	Emer-gency bays / Shoul-der	In accordance with ODD requirements, no additional conse-quences due to oper-ation.	To avoid conges-tions and road blocks trucks should be only allowed on routes with neces-sary space for emer-gency stops (wide shoulder or emer-gency bays) so traf-fic management needs to be pre-pared accordingly	In accordance with ODD requirements, no addi-tional consequences due to operation.	To avoid congestions and road blocks trucks should be only allowed on routes with neces-sary space for emer-gency stops (wide shoul-der or emergency bays) so traffic management needs to be prepared accordingly
	Road marking	In accordance with ODD requirements, no additional conse-quences due to oper-ation.	No immediate changes identified	In accordance with ODD requirements, no addi-tional consequences due to operation.	No immediate changes identified

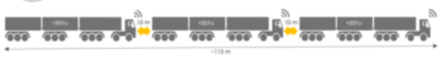
		Common truck+trailer 		Future High-capacity vehicle 	
		Consequences	**Necessary changes**	**Consequences**	**Necessary changes**
	General road design	In accordance with ODD requirements, no additional consequences due to operation.	Road design standards should be adopted to include emergency bays or wide shoulder for new motorways	In accordance with ODD requirements, no additional consequences due to operation. Roundabouts might be challenging, so NRAs with roundabouts on their motorways can expect consequences there.	NRAs will need to have a clear view of their networks in terms of design parameters. Such trucks might not need to be everywhere but rather on certain routes (e.g. transit routes, port connections, etc.). Traffic management will apply
	Rest areas/ service stations	Due to less required resting times space might could be reduced in the very long run.	No immediate changes identified	Length of parking slots are potentially not long enough	Assessment of design guidelines for parking slots (length)
Bridges	Bridge structures	Dimension and weight restrictions are the same as for conventional trucks - no new impact expected.	No immediate changes identified	Necessary strengthening of aged or weak bridges might be possible. If axles loads do not exceed current weight restrictions, impact should be limited	Evaluation of bridges needed based on bridge inspections. Potentially restrictions will be required.
Bridges	Joints / Dilatations	Dimension and weight restrictions are the same as for conventional trucks which implies no new impact. However as most vehicles will use same LKA systems wheel paths of vehicles could be rather identical leading to punctual loads/ faster deterioration expected.	Monitoring of development due to punctual loads. Further research required.	Dimension and weight restrictions are the same as for conventional trucks which implies no new impact. However as most vehicles will use same LKA systems wheel paths of vehicles could be rather identical leading to punctual loads/ faster deterioration expected.	Monitoring of development due to punctual loads. Further research required.
Bridges	Bearings	As dimension and weight restrictions are the same as for conventional trucks, no new impact expected.	No immediate changes identified	Total dynamic load of a moving platoon exceeds existing bridge design scenarios. Aged bridges would potentially need re-calculation and strengthening measures.	Evaluation of bridges needed based on bridge inspections. Potentially restrictions will be required.
Bridges	Rails	None	No immediate changes identified	None	No immediate changes identified
Tunnels	Tunnel structure	None	No immediate changes identified	None	No immediate changes identified

		Common truck+trailer 		Future High-capacity vehicle 	
		Consequences	**Necessary changes**	**Consequences**	**Necessary changes**
	Tunnel wall finish	In accordance with ODD requirements, no additional consequences due to operation.	No immediate changes identified	In accordance with ODD requirements, no additional consequences due to operation.	No immediate changes identified
	Ventilation	None	No immediate changes identified	None	No immediate changes identified
	Lighting	In accordance with ODD requirements, no additional consequences due to operation.	No immediate changes identified	In accordance with ODD requirements, no additional consequences due to operation.	No immediate changes identified
	Emergency system	In accordance with ODD requirements, no additional consequences due to operation.	No immediate changes identified	In accordance with ODD requirements, no additional consequences due to operation.	No immediate changes identified
Road equipment & Drainage	Road signs (non-digital)	In accordance with ODD requirements, no additional consequences due to operation.	No immediate changes identified. TN-ITS standards to ensure digital replications. EU wide standardized signs considered unrealistic and not necessary.	In accordance with ODD requirements, no additional consequences due to operation.	No immediate changes identified. TN-ITS standards to ensure digital replications. EU wide standardized signs considered unrealistic and not necessary.
	Gantries	None	No immediate changes identified	None	No immediate changes identified
	Vehicle restraint systems	None	No immediate changes identified	Strengthening of vehicle restraint systems in particular in critical areas (bridges, dams) and new standards for higher loads would be required for trucks up to L3. This scenario includes L4 trucks therefore typical accidents reasons (tire blowouts, tiredness of driver) are eliminated	Requirement for L4 trucks to have tire pressure monitoring systems. Only certain routes. Further assessment needed
	Noise protection walls	None	No immediate changes identified	Additional noise might goes beyond current noise wall design parameters.	Noise level evaluation to be adapted
	Road drainage	None	No immediate changes identified	None	No immediate changes identified
Toll systems		None	No immediate changes identified	Ability to identify new category to be checked. Impact justifies higher tolls.	New toll category to be incorporated

Table 13. Consequences and necessary changes due to truck platoons

		3 Platoon of 2 common truck+trailers 		4 Platoon of 3 Future HCV trucks 	
		Consequences	**Necessary changes**	**Consequences**	**Necessary changes**
Pavement	Asphalt pavement	Bigger effects on deterioration (rutting, skid resistance) expected due to shorter pavement relaxation periods between axles. In Norther countries additional impact through spikes possible. Lifecycle models and pavement management system to be potentially adapted. Effects on rutting strongly depend on the lateral track following accuracy of the following vehicles	Initial research indicates the potentially positive counter effects of defined wheel path offsets might help to level out increased deterioration. This findings need to be further assessed as well as their potential for traffic management measures.	Bigger effects on deterioration (rutting, skid resistance) expected due to shorter pavement relaxation periods between axles. In Norther countries additional impact through spikes possible. Lifecycle models and pavement management system to be potentially adapted. Effects on rutting strongly depend on the lateral track following accuracy of the following vehicles	Initial research indicates the potentially positive counter effects of defined wheel path offsets might help to level out increased deterioration. This findings need to be further assessed as well as their potential for traffic management measures.
	Concrete pavement	Additional axles could lead to increased stress on joints. If axle loads are not exceeded impact to concrete pavements should not change.	Research on potential of joint strengthening in wheel paths.	Additional axles could lead to increased stress on joints. If axle loads are not exceeded impact to concrete pavements should not change.	Research on potential of joint strengthening in wheel paths.
	Ramps and junctions	Platoons will need to dissolve when entering ramps and junctions. As dimension and weight restrictions are the same as for conventional trucks, no new impact expected.	No immediate changes identified	Platoons will need to dissolve when entering ramps and junctions. The length of individual vehicles (25.5m) still exceeds the max. length of current trucks. Each country will need to assess their design parameters of ramps and junctions for 25.5m long HCVs. Detailed investigation necessary	NRAs need to have a clear picture of their ramp designs in order to make traffic management provisions allowing these trucks only where design parameters are ok for them to enter exit
	Emergency bays / Shoulder	Emergency bays are required in accordance with ODD requirement ideally every 500m or a wide shoulder is present. Emergency bays will need to be at least 200m long.	Each NRA to assess its current network and decide on potential platooning routes	Emergency bays are required in accordance with ODD requirement ideally every 500m or a wide shoulder is present. Emergency bays will need to be at least 400m long.	Each NRA to assess its current network and decide on potential platooning routes
	Road marking	In accordance with ODD requirements, no additional consequences due to operation.	No immediate changes identified	In accordance with ODD requirements, no additional consequences due to operation.	No immediate changes identified

		Platoon of 2 common truck+trailers 		Platoon of 3 Future HCV trucks 	
		Consequences	**Necessary changes**	**Consequences**	**Necessary changes**
	General road design	Roundabouts, inclinations, curves, etc. will potentially provide challenges for platoons.	New definitions in terms of visibility distance, inclinations, curve definitions expected. Also impacts on road cross sections through increased need for emergency bays. However changing all these go too far for whole networks, rather identification of specific transit routes where platoons are beneficial	HCV platoon will not be able to drive everywhere. Roundabouts, inclinations, curves, etc. will in some cases be unpassable for HCV platoons.	Only in specific areas feasible. Evaluation of road network required. Traffic management to organise routes. Might require separate lane.
	Rest areas/ service stations	Due to less required resting times space might could be reduced in the very long run.	No immediate changes identified	Length of parking slots are potentially not long enough	Assessment of design guidelines for parking slots (length)
Bridges	Bridge structures	Total dynamic load of a moving platoon exceeds existing bridge design scenarios. Aged bridges would potentially need re-calculation and strengthening measures.	Evaluation of bridges needed based on bridge inspections. Potentially restrictions will be required.	Total dynamic load of a moving platoon exceeds existing bridge design scenarios. Aged bridges would potentially need re-calculation and strengthening measures.	Evaluation of bridges needed based on bridge inspections. Potentially restrictions will be required.
Bridges	Joints / Dilatations	Additional axles increase stress on joints and dilatations increasing the risk for road defects before/after dilations.	Monitoring of development, further research required.	Additional axles increase stress on joints and dilatations increasing the risk for road defects before/after dilatations.	Monitoring of development, further research required.
Bridges	Bearings	Total dynamic load of a moving platoon exceeds existing bridge design scenarios. Aged bridges would potentially need re-calculation and strengthening measures.	Evaluation of bridges needed based on bridge inspections. Potentially restrictions will be required.	Total dynamic load of a moving platoon exceeds existing bridge design scenarios. Aged bridges would potentially need re-calculation and strengthening measures.	Evaluation of bridges needed based on bridge inspections. Potentially restrictions will be required.
Bridges	Rails	None	No immediate changes identified	None	No immediate changes identified
Tunnels	Structure	None	No immediate changes identified	None	No immediate changes identified
Tunnels	Tunnel wall finish	In accordance with ODD requirements, no additional consequences due to operation.	No immediate changes identified	In accordance with ODD requirements, no additional consequences due to operation.	No immediate changes identified
Tunnels	Ventilation	None	No immediate changes identified	The condensed number of trucks potentially requires re-assessment of emergency ventilation system. Ventilation systems might need an upgrade.	Studies required to assess aerodynamics and flow

		Platoon of 2 common truck+trailers 3 		Platoon of 3 Future HCV trucks 4 	
		Consequences	**Necessary changes**	**Consequences**	**Necessary changes**
	Lighting	In accordance with ODD requirements, no additional consequences due to operation.	No immediate changes identified	In accordance with ODD requirements, no additional consequences due to operation.	No immediate changes identified
	Emergency system	In accordance with ODD requirements, no additional consequences due to operation.	Monitoring system to be checked for suitability	Potentially platoons should be requested to dissolve ahead of tunnels. In particular in long tunnels (tunnel directive and above) new emergency routing and systems might be required. Fire protection issues due to possible higher number of trucks driving in platoons	Traffic management to be put in place and monitoring system to set alarm if platoon does not dissolve
Road equipment & Drainage	Road signs (non-digital)	In accordance with ODD requirements, no additional consequences due to operation.	No immediate changes identified. TN-ITS standards to ensure digital replications. EU wide standardized signs considered unrealistic and not necessary.	In accordance with ODD requirements, no additional consequences due to operation.	No immediate changes identified. TN-ITS standards to ensure digital replications. EU wide standardized signs considered unrealistic and not necessary.
	Gantries	None	No immediate changes identified	None	No immediate changes identified
	Vehicle restraint systems	Strengthening of vehicle restraint systems in particular in critical areas (bridges, dams) and new standards for higher loads will be required. In particular critical in L2 as driver mistakes still happen.	Careful selection of allowed routes. Either improved vehicle restraint systems in danger zones or traffic management measures	Strengthening of vehicle restraint systems in particular in critical areas (bridges, dams) and new standards for higher loads would be required for trucks up to L3. This scenario includes L4 trucks therefore typical accidents reasons (tire blowouts, tiredness of driver) are eliminated	Requirement for L4 trucks to have tire pressure monitoring systems. Only certain routes. Further assessment needed
	Noise protection walls	Additional noise might goes beyond current noise wall design parameters.	Noise studies to be undertaken, potentially additional noise barrier requirements	Additional noise might goes beyond current noise wall design parameters.	Noise studies to be undertaken, potentially additional noise barrier requirements
	Road drainage	None	No immediate changes identified	None	No immediate changes identified
Toll systems		Automated lanes required everywhere. Potentially new toll category to be implemented	Ability to identify new category to be checked. Impact justifies higher tolls.	Automated lanes required everywhere. Potentially new toll category to be implemented	Ability to identify new category to be checked. Impact justifies higher tolls.

3.5 Consequences of commercial vehicles as taxi services

Latest input from high-level safety experts (Schöneburg 2019) suggests that early forms of commercial driverless vehicles as taxi services will take advantage of so called highly regionalised ODDs. These cars will learn specific public roads with little interaction with pedestrians or cyclists in a specific metropolitan area (e. g. business headquarters and airports or train stations). Therefore, this should not be mistaken as generalised ODDs for all urban streets. This specific form of taxis is anticipated to become available before 2025 in Europe and earlier in other regions.

At the February 2019 ARCADE workshop it was anticipated that specific "knowledge" exchange on locally acceptable forms of commercial driverless vehicles such as taxi services might help to provide broader validity ("social networks for automated taxi functions"). (Aigner et al. 2019)

For a more general form of robot taxis, even though a pilot robot taxi service was already started in late 2018 in the Phoenix area in the USA, some experts still doubted that such services would take long time to be allowed in Europe, and that the necessary door-to-door ODD coverage and capability would not be available until early 2030s. As a next step, robot taxis are planned as an urban street service only, but by 2040 this service is anticipated to also cover other roads (ring roads, arterials, highways) around urban areas in order for the taxi service to provide door-to-door service. These services are expected to be available by 2040 in all major cities of at least 0.5 million inhabitants in Europe. (Aigner et al. 2019)

Cooperation between local and national traffic management is necessary for the large area coverage. Likely, specific locations for safe pick-up and drop-off of passengers need to be allocated and designated to the robot taxis, perhaps to be shared with automated shuttles. For 24/7 services, robot taxis should also be able to deal with most weather and road surface conditions. (Aigner et al. 2019)

Biggest impact related to robot-taxis for the pavement are the needs for additional passenger drop-off/pick-up locations. Visibility of road markings was also seen as an important aspect including maintenance (keeping markings clean). New definitions in terms of visibility distance, inclinations and curve definitions are needed for road planning and design.

Bridges are not considered to be affected heavily by the commercial driverless taxi services. For tunnels additional colouring or reflections for walls were identified as well as new lighting requirements to avoid problems when entering or exiting the tunnel. Tunnels emergency systems are safety critical and need further investigation in combination with ODDs. Needs for road equipment and drainage were considered unchanged compared to conventional vehicles. Overall, physical infrastructure should be well-maintained and consistent especially regarding road markings and signage. Tolling systems require automated lanes.

Biggest changes target the current ITS systems. The ODDs of the automated driving systems may need modifications and enhancements in some systems, while some may become totally unused by them.

The following issues also need further consideration for enabling driverless taxis in urban areas:

- Possible needs for specified winter maintained routes (especially for robot taxis in urban areas); visibility of markings, pick-up/drop-off during snowy conditions, snow storage on the road side, etc.
- How to handle the roadwork and other construction work zones and fast changing routings (even on daily basis).
- Accurate positioning with GNSS systems will need RTK land stations or physical stationary landmarks.

- Specific parking area needs for robot taxis when ODD is not effective or low demand period.
- The impact of empty robot-taxis is yet hard to quantify but will potentially have an impact on traffic volume and hence on necessary road capacity adaptions.

Generally all these are necessary to be defined within the ODD requirement rather than being an impact to the infrastructure due to the operation. They are dealt with in greater detail in chapter 4.

3.6 Consequences of driverless maintenance vehicles on highways (safety trailer and winter maintenance)

The workshop (Tallinn, 07.03.2019) identified no real consequences to infrastructure due to the operation of driverless safety trailers or driverless winter maintenance vehicles themselves. While both use cases have the potential to highly benefit the safety and efficiency of the respective maintenance works, both are not expected to effect the infrastructure once their required ODDs are in place. For their safe use infrastructure amendments will be necessary (connectivity to traffic management enabling accurate positioning, etc.) but those are incremental for the ODD definition of both use cases – this is dealt with in chapter 4.2.

The workshop results clearly see limitations for both use cases. Safety trailers are considered to be used only on highways and might be tricky on bridges and in tunnels due to the additional traffic management requirements.

3.6.1 Road work safety trailer

Some automated roadworks trailer ODDs are anticipated to be around soon (successful proof of concept from aFAS project 2016 to 2019; time of commercial roll-out by MAN not yet decided). As already stated above, driverless maintenance vehicles have the potential to significantly reduce safety risk from passing vehicles at higher speeds. Therefore, we anticipate first ODDs to focus on maintenance and road work zone protection on road shoulders of highways. Initial ODDs request a human driver to navigate the vehicle to an area where the ODD is fully covered. As soon as it has arrived within its designated ODD the human driver can switch to an adjoined maintenance vehicle and let the maintenance vehicle go driverless. It will still take time until a wider ODD for protection of various types of O&Mwork zones (on main lanes, combinations of work zones) will be possible to be done by driverless vehicles. The rollout of wider ODD scenarios extended to main lanes will be driven not only by the technical development but rather depends on legal adaptions for use of such work zone protections.

Necessary changes to infrastructure are really limited to the connectivity and interaction with the traffic management center. Other than that most crucial necessary changes for quick deployment are of legal nature which need be adopted in each country individually in order to allow such slow moving autonomous work vehicles on all lanes.

3.6.2 Winter maintenance truck

In countries with snowy/icy winters, the operational works around winter maintenance belong to the most crucial tasks when it comes to providing safe roads. During the winter months, road operators in such countries require a high number of vehicles and drivers on stand-by, ready to start work 24/7. Winter maintenance works on highways are generally divided into preventive salting works performed at speeds of up to 60 km/h independent of snowfall and snow ploughing works performed at speeds of up to 45 km/h during and after snowfall.

Winter maintenance trucks with regular operating speed would profit from smart roads, high-accuracy digital maps and commercially available powerful sensors. The technology is expected to be widely used in zones of minimum interaction (e.g. airports, rest areas) first and depending on the experiences there, a step by step rollout in situations/areas with reduced interaction, low traffic volumes and clear road geometries. Doubts of the regulatory barriers and adverse weather capabilities pushed the low scenario year for automated winter maintenance vehicles to 2030. In 2040, it is likely that the weather-related ODD restrictions will be much smaller than when the systems had entered the market.

While developments in driver assistance systems are progressing (see chapter 2.3.4), the introduction of highly automated winter maintenance vehicles is still far away and makes predictions on their impact on infrastructure due to their operation rather difficult. Infrastructure assets that are sensitive to snow ploughing works now will likely also be challenging in automated cases. One example are road markings that are easily damaged if snow ploughs are not adjusted well. Equally narrow road sections with any kind of barriers like bridge parapets or curbs are challenging. Accurate data on the location of these will be beneficial to avoid damaging.

3.7 Conclusions on suggested changes

The operation of some forms of automated driving functions will have a significant impact on the road infrastructure as we know it today. In this chapter the impact of the selected four use cases – highway autopilot, highly automated freight vehicles, robot taxis and driverless maintenance vehicles (road safety trailer and winter maintenance vehicle) – due to their operation on NRAs roads was assessed. The focus of this analysis was explicitly not on any infrastructural requirements resulting from the ODDs of the vehicles (this is covered in chapter 4) but rather impacts when they are actually used within their defined ODDs. However, it became clear that requirements from ODDs and infrastructural impact during operation are often linked. So in particular for digital infrastructure impact and necessary changes are assessed holistically as part of the ODD analysis in chapter 4.

The selected use cases are quite diverse and will therefore have quite different impacts on infrastructure. Consequently an infrastructure asset list covering the crucial elements of road infrastructure was used to analyze each use case's impact on each of the infrastructure assets. This provided an overall picture which infrastructure assets will be affected the most and which use case will have the greatest impact.

Highly automated freight vehicles – in particular as platoons – were identified as the use case with most direct impact on various road infrastructure assets considering only their impact due to operation and not the required ODD. This is in line with latest research results where highway chauffeur or robot cabs are predicted to have tremendous systemic impacts on traffic (flow, density, etc.) but only limited impact on individual infrastructure assets. However, for each use case some changes are advisable which are summarized here.

The highway autopilot use case was still relevant in particular considering the option of convoys. In northern countries where studded tyres are commonly used during the winter months, highway autopilots potentially increase rutting and fatigue of pavement. Most likely highway autopilots will use lane keep assist systems of the same suppliers, using the same algorithms and therefore following similar wheel paths. This effect is even further increased in case of convoy driving. Those countries are advised to further study the damage models of studs and adopt their pavement design and lifecycle models accordingly to be prepared for additional strengthening. On another end connectivity and the ability for direct traffic management communication into the vehicles with highway autopilot will be necessary to avoid emergency lanes turning into parking lots in case of sudden ODD interruptions (e.g. work zones, etc.). Also for those cases the necessity for additional emergency bays or wider hard shoulders should be assessed by NRAs in critical areas where regular ODD interruptions can be already anticipated (e.g. meteorological divides, etc.).

As already stated above, highly automated freight vehicles are expected to have the biggest direct impact to infrastructure due to their operation purely due to their dimensions and loads. In freight transport not only developments in automation and platooning are expected but also in terms of allowed size and weight. Such scenarios would have significantly different impacts on road infrastructure assets than just normal sized automated trucks. Therefore MANTRA also considered these possible developments about new land transport operational modes in automated freight transport. The use of automated HCVs and truck platoons could have various impacts on infrastructure. First and foremost NRAs are advised to develop strategies for routes where the use of HCVs and HCV platoons is necessary and sensible. Traffic management measures will be required to enforce those routes and to provide additionally necessary information on them. These routes will require adapted pavement design guidelines due to the bigger loads affecting rutting and fatigue of bituminous pavements and/or traffic management measures allowing just certain numbers. Bridges on such routes will need to be evaluated for their bearing capacities and potentially speed limits for those HCVs applied or structures strengthened accordingly. The length of emergency bays, ramps and exit/entry lanes will need to be checked for suitability and potentially extensions are necessary on important routes. This also applies to rest areas and the length of parking spots. Finally, vehicle restraint systems and noise protection walls will need to be reassessed towards their suitability for platoons and HCVs. In a nutshell, NRAs are advised to take measures to strategically decide and control where HCVs and platoons are actually feasible to drive. Only there the potentially cost intensive measures shall be taken to prepare the infrastructure for the additional loads.

Commercial driverless vehicles as taxi services are also considered to be introduced in highly regionalised ODDs and not generally on all public roads. ODD requirements are quite substantial for this use case as chapter 4 clearly shows, so NRAs will again decide strategically where the deployment is most feasible in terms of improving their policy goals. Where ODDs are in place accordingly the actual operation of robot taxis is not expected to add damage potential or other impact to the infrastructure. The biggest impact will be the strategic placement of drop-off and pick-up locations to avoid congestion due to stopping robot taxis on the roads.

Necessary changes due to driverless maintenance vehicles result also mainly from their ODD requirements. Both use cases of driverless safety trailers as well as driverless winter maintenance vehicles have the potential to highly benefit the safety and efficiency of the respective maintenance works but both are not expected to affect the infrastructure significantly once in operation. The biggest necessary amendments will be connectivity to traffic management enabling accurate positioning as a basis for C-ITS services.

Summarizing these findings ________________________

Table 14 shows the key proposals for changes of the most affected asset groups.

Table 14. Summary of proposed changes due to automated functions operation

Asset Group	Proposed necessary changes
General road design	Strategy for routes where the use of HCVs and HCV platoons is necessary and sensible - operation only on these defined corridors (or separated lanes). Necessary changes will involve length of ramps, exits, junctions and parking spaces in rest areas as well as potentially curve radius and inclination. New definitions in terms of visibility distance, inclinations, curve definitions expected. Also impacts on cross sections through increased need for "safe harbours"
Pavement	Rutting and fatigue potential increases due to same wheel paths of convoys and in particular freight platoons. NRAs are advised to further develop and strengthen their pavement design guidelines as well as their pavement lifecycle models.
Bridges	Bridge design standards are different in each country. On routes for HCVs and HCV platoons however structural recalculations of bridges are recommended potentially resulting in the need of strengthening measures.
Tunnels	Traffic management/emergency system to be upgraded and monitoring/CCTV systems need to be able to detect and set alarms if platoons do not dissolve. Fire protection and ventilation systems to be checked and evaluated for suitability of platoons and automated HCVs.
Road equipment	Adaption of standards for vehicle restraint systems on routes for truck platooning. Strengthening will be required as long as truck platoons have any accident potential (human error). Also truck platooning might create increased noise. Evaluation of noise protection walls and standards recommended on truck platooning routes.
ITS	Connectivity to traffic management centre particular in critical areas as well as additional need for VMS signs to enable NRAs to keep control.
Toll systems	Existing systems to be checked for ability to identify new vehicle categories (e.g. HCVs). Automated lanes required on all toll booths.

4 Impacts by ODD requirements

Operational Design Domains are one of the key classification methods used to describe requirements for automated driving. The approach to ODDs and the relevant parameters are described in chapter 2.2.2 to provide an overview of the status quo. In this chapter the impact of ODDs and the resulting requirements as well as their impact on infrastructure are assessed.

4.1 ODD in general

So far, automated driving use cases have been developed and piloted by various stakeholders with only limited coordination. Hence, the stakeholders have made their own decisions concerning the sensor choice, connectivity, positioning options utilised and other factors determining the ODD with only the global, national, and local regulatory frameworks affecting their choices. At the same time, the stakeholders have not published any accurate information about their ODD details as long as the use cases are still not rolled out into the market. (Aigner et al. 2019)

There are also proponents calling for more coordinated and interoperable manner to deploy automated driving. Alonso Raponso et al. (2017) recommend Coordinated Automated Road Transport. Their coordinated automated road transport is meant as an extension of the automated driving concept by adding communication capabilities that connect vehicles in between and with the infrastructure and adding a central coordination player to achieve the full potential of automated driving in terms of social, economic and environmental benefits. Such a coordinated approach would require an additional ODD layer, but on the other hand provide more harmonisation of the ODDs between the stakeholders.

Shladover (2018a) reminds that the ODD may be different for each system. This is due to the fact that an ODD is determined by the capabilities of the sensors, actuators, and software (including AI) of the vehicle's automated driving system.

ODDs are important to road operators as the provision of the physical infrastructure related elements of ODDs are almost solely under the responsibility of the road operators. This also applies to some digital infrastructure elements as well. Also traffic and weather condition aspects can be influenced by road operator actions such as traffic management and winter maintenance, respectively. The provision of ODDs can also be very costly, more than 10 billion euros for the European motorway network in the next ten years (CEDR 2018).

Some of the road operators have already discussed the infrastructure related elements of the ODDs. The concept of infrastructure support levels has been developed in INFRAMIX (Carreras et al. 2018) for cooperative connected automated driving as described in chapter 2.2.3.

4.2 ODD requirements

The chapter will discuss ODD requirements especially with regard to the requirements that can be fulfilled by road operators. Naturally, it is up to the individual road operator to decide whether to meet the ODD requirement – if they are not met, only limited cases of automated driving will be possible on these NRAs roads. It is assumed that the road operators would fulfill ODD requirements if the automated driving use cases in question will provide sufficient financial and socio-economic benefits to justify to related investment, operations and maintenance costs, and if the costs allocated to the road operator can easily be included in their budgets.

4.2.1 ODD requirements today

In MANTRA, the ODD requirements were determined earlier regarding the situation today in Deliverable D2.1 (Aigner et al. 2019). However, the subject of ODD requirements and their definition is currently heavily debated and constantly evolving. Therefore the following Table 15 until Table 19 show the results for the five use cases of MANTRA updated with new data that was gathered since the finalization of Deliverable D2.1.

Table 15. ODD related requirements for highway autopilot based on D2.1 (Aigner et al. 2019)

Highway autopilot incl. highway convoy	
Road	Motorway or similar dual carriageways with separated driving directions, only on line sections not including toll plazas, ramps or intersections, but containing straight driving on weaving sections
Speed range	Up to 130 km/h; some systems do not work below 30-40 km/h; no restrictions 2030-
Shoulder or kerb	Safe stopping for a minimal risk condition requires a wide paved shoulder available for this purpose and not used for, e.g. hard shoulder running. Safe refuges or shoulder areas similar to bus stops could be made available in case of narrow shoulders at intervals of e.g. 500 m on each carriageway
Road markings	Minimum quality of solid or dotted lines painted on the pavement if accurate lateral positioning is based on a camera detecting the location of the lane borders, and if the lines indicate traffic management information (e.g. no overtaking or lane change)
Traffic signs	Needed for vehicle to react to traffic control indicated by traffic signs along its trajectory to select appropriate speed or to take other required action. The sign content can be accessible via cloud, or tags and/or beacons attached to the sign
Road equipment	Wireless radio beacons or physical landmarks possibly with sensor reflectors to support and increase positioning accuracy for AD vehicles. This is most valuable in tunnels and in totally open areas with no fixed objects nearby, or on sections with high likelihood of poor road weather conditions; or when some objects in the environment interfere with the vehicle's sensors.
Traffic	Not in incident situations with people on roadway, or other safety information cases like road work zones
Time incl. light conditions	No specific requirements
Weather conditions	All conditions except for heavy rain or snowing, or road covered with thick layer of snow or water, or in some cases sun glare, heavy fog, or darkness without lighting, 2030- only most severe restrictions apply such as floods, thick snow, etc.
HD map	HD Map of minimum quality needed if the lane identification and accurate lateral lane positioning solution is based on satellite positioning with 3D HD map matching.
Satellite positioning	Needed if the road position, lane identification and accurate lateral lane positioning solution is based on satellite positioning with 3D HD map matching. Satellite positioning accuracy is supported by land stations (e.g. RTK) and possibly also by landmarks on problem sections (tunnels, forests ...) and conditions (weather).
Communication	Needed for end of queue, lane change, and merge situations for negotiations among vehicles and for maintaining a local dynamic map. Short latency V2V communication is a necessity for highway convoy. V2I communication can be used to receive traffic management information in addition to real-time information.
Information system	Real-time traffic information on incidents, roadworks, events, congestion and other disturbances (SRTI) on the road ahead are needed for tactical decisions on route choice, lane selection and safe speed choice. Digital rules and regulations as well as a geofencing database are also needed.

Table 16. ODD related requirements for automated freight vehicles on open roads based on D2.1 (Aigner et al. 2019)

Highly automated (freight) vehicles on open roads	
Road	Motorways or similar dual carriageways with separated driving directions and selected freight-relevant other roads also with single carriageway and on-coming traffic. Restrictions might apply for bridges or tunnels
Speed range	Up to 80 km/h
Shoulder	Safe stopping for a minimal risk condition requires a wide paved shoulder available for this purpose. Safe refuges or shoulder areas similar to bus stops but long enough for freight vehicles could be made available in case of narrow shoulders at intervals of e.g. 500 m on each carriageway
Road markings	Solid or dotted lines painted on the pavement needed if the accurate lateral positioning solution is based on a camera detecting the location of the lane borders, and if the lines indicate traffic management information (e.g. separation of automated freight vehicle lane from the other traffic lanes)
Traffic signs	Needed to indicate any lane use restrictions (automated freight vehicles/other vehicles), either static indicating the times of use or dynamic signs at sufficient intervals. Signs indicating use by automated freight vehicles.
Road equipment	Gantries for overhead lane control signs if dedicated lane(s) for automated freight vehicles. Possible gates for entering and exiting the lanes used for automated freight vehicles, Wireless radio beacons or physical landmarks possibly with sensor reflectors can be used to support and increase positioning accuracy for AD vehicles. This is most valuable in tunnels and in totally open areas with no fixed objects nearby, or in poor road weather conditions.
Traffic	No restrictions on motorways or similar dual carriageways. On other selected freight-relevant roads, only with low traffic volumes.
Time incl. light conditions	No restrictions on motorways. On other roads, sufficiently low traffic volumes only during the night time hours.
Weather conditions	All conditions except for heavy rain or snowing, or road covered with thick layer of snow or water, or in some cases sun glare, heavy fog, or darkness without lighting, 2030- only most severe restrictions apply such as floods, thick snow, etc.
HD map	Needed if the lane identification and accurate lateral lane positioning solution is based on satellite positioning with 3D HD map matching.
Satellite positioning	Needed if the road position, lane identification and accurate lateral lane positioning solution is based on satellite positioning with 3D HD map matching. Satellite positioning accuracy is supported by land stations and possibly also by landmarks.
Communication	V2V and V2I communication needed for vehicles to communicate for safety and to access the dedicated lane or road.
Information system	Real-time traffic information on incidents, roadworks, events, congestion and other disturbances on the road for tactical decisions. Digital rules and regulations as well as a geofencing database.

Table 17. ODD related requirements for robot taxis based on D2.1 (Aigner et al. 2019)

Commercial driverless vehicles as taxi services	
Road	Urban road (meaning any roads in urban region) with not too complicated junctions; 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 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 <5 mm/h, no ice nor snow on road, no fog/steam/smoke/dust hindering vision; 2030- only most severe restrictions apply such as floods, thick snow, etc.
HD Map	Needed as the lane identification and accurate lateral lane positioning solution is based on vision sensors (especially laser scanners) and satellite positioning with 3D HD map matching.
Satellite positioning	Needed to complement the vision sensor system supported by satellite positioning with 3D HD map matching.
Communication	At least 3G needed for V2I communications with operations centre, 4G or higher for remote control of vehicle. Short-range communication for communication in smart intersections. V2V communication at least within fleet.
Information system	Digital traffic rules and regulations, geofenced restrictions

Table 18. ODD related requirements for road work safety trailers based on D2.1 (Aigner et al. 2019)

Road Work Safety Trailer	
Road	Motorway or similar dual carriageways having a paved road shoulder not including toll plazas, ramps or intersections
Speed range	Standing or driving slowly to protect moving work zones with a maximum speed of 20 km/h
Shoulder or kerb	Initial deployment only on road shoulders, so wide shoulder required for early adoption
Road markings	Initial positioning of safety trailer through connectivity to vehicle ahead. For improved lateral positioning cameras are detecting road markings. Optimum functionality in areas with clearly visible solid or dotted lines painted on the pavement. For purely following tasks on the road shoulder no road marking requirements.
Traffic signs	Not needed. Vehicle either follows another vehicle and/or navigates along road marking.
Road equipment	No specific requirements. Wireless radio beacons or physical landmarks possibly with sensor reflectors can be used to support and increase positioning accuracy. This is most valuable in tunnels and in poor road weather conditions. However only if also used for other types of use cases, not required specifically for this one.
Traffic	No specific requirements
Time incl. light conditions	No specific requirements
Weather conditions	All conditions, except for heavy rain or snowing, or road covered with any layer of snow or water.
HD Map	No specific requirements
Satellite positioning	Initial deployment on road shoulder: no satellite positioning required. Advanced version: enabling communication about its position required with land station (e.g. RTK) support accompanying the vision sensor system with 3D HD map matching to provide information to traffic management centre and in turn to road users through VMS/in-car navigational systems.
Communication	CACC, can provide information about position to traffic management centre for further information to road users. V2V communication with other maintenance vehicles, mobile road signs.
Information system	Real-time information of the location and operation of the vehicle to be disseminated to traffic centres and service providers, and finally to other road users; Digital rules and regulations

Table 19. ODD related requirements for automated winter maintenance trucks based on D2.1 (Aigner et al. 2019)

Winter maintenance truck	
Road	Motorway or similar not including ramps or intersections. Not in toll plazas nor road work zones. Limited in areas of noise barriers, depending on height and type of noise barrier.
Speed range	Preventive salting works max. speed 60 km/h (no snowfall) and snow ploughing works max speed 45 km/h (during and after snowfall)
Shoulder or kerb	Safe stopping for a minimal risk condition requires a wide paved shoulder available for this purpose and not used for, e.g. hard-shoulder running. Safe refuges or shoulder areas (emergency bays) could be made available in case of narrow shoulders at intervals of e.g. 5 000m on each carriageway
Road markings	Initial deployment preventive salting: An early adoption of this use case could be the use solely for preventive salting only therefore requiring solid or dotted lines painted on the pavement for accurate lateral positioning solution is based on a camera detecting the location of the lane borders Full deployment snow ploughing: No specific requirements
Traffic signs	No specific requirements
Road equipment	Wireless radio beacons or physical landmarks ideally with sensor reflectors necessary to be used to support and increase positioning accuracy for maintenance trucks.
Traffic	Initial adoption in low traffic volume only.
Time incl. light conditions	No specific requirements
Weather conditions	Initial deployment preventive salting: Initially only when road marking is still visible. All conditions except snow or heavy rain. Full deployment snow ploughing: All conditions
HD Map	Needed for full use - lane identification and accurate lateral lane positioning based on satellite positioning with 3D HD map matching.
Satellite positioning	Needed for full use - road position, lane identification and accurate lateral lane positioning based on satellite positioning with 3D HD map matching. Satellite positioning accuracy is supported by land stations (e.g. RTK) and possibly also by landmarks.
Communication	V2I communication to be used to receive traffic management information in addition to real-time information.
Information system	Real-time traffic information on incidents, roadworks, events, congestion and other disturbances on the road ahead are needed for tactical decisions on route choice, lane selection and coordinated take over procedure to operator.

The next chapters will look separately into each ODD attribute to assess the likely development scenarios for them, based on the possible development of the capabilities of automated vehicle sensors, AI and other software advancements.

4.2.2 Physical infrastructure

The evolution of ODDs is driven by customer demand and enabled by the improvement of vehicle sensors – for instance, sensors being able to deal with different kinds of weather conditions – and vehicle software – for instance, AI being able to deal with safe manoeuvring of the vehicle also in interaction with vulnerable road users in complicated urban environments. The technological development in the areas of sensors and software is currently very fast, and also hard to predict with any certainty. The following tables give always first the 2020 situation – based on current situation (Aigner et al. 2019) – and furthermore prediction of the possible ODD requirements in 2030 and 2040.

Road

Table 20. ODD requirements per road category for parameter road

Road			
road category	**2020 use cases**	**2030 use cases**	**2040 use cases**
motorway	Line sections not including toll plazas, ramps or intersections, but containing straight driving on weaving sections hap, fvor, rst	Line sections, intersection areas and also ramps from one motorway to another hap, fvor, rt, rst	Line sections and ramps hap, fvor, rt, rst, wmt
	Line sections not including ramps, intersections, toll plazas nor road work zones. Limited in areas of noise barriers, depending on height & type of noise barrier. wmt	Line sections and also ramps from one motorway to another. Not in toll plazas nor road work zones. wmt	
highway, main or national road	Roads with separated carriageways fvor	All fvor, rt, rst, wmt	All fvor, rt, rst, wmt
urban road/ street	Urban road with not too complicated junctions rt	All rt	All fvor, rt, wmt
secondary/ rural road	-	Paved roads fvor, rt	Paved roads fvor, rt, rst, wmt
terminal area	Selected port areas, selected areas in logistic terminals fvor	All fvor, rst	All fvor, rt, rst, wmt

Use case abbreviations used: hap=highway autopilot, fvor=freight vehicles open roads, rt= robot taxi, rst=roadworks safety trailer, wmt=winter maintenance truck

Highway autopilot needs to cover all standard motorway sections including connecting ramps by 2030 due to customer demand. In order for the robot taxis to make business, they would need to cover at least the same main roads and streets as human-operated taxis by 2030. The developments for these two use cases will drive similar extensions for other use cases as well.

Speed range

The speed ranges are expected to evolve to reach the speed limits typically allowed for each road category as the automated vehicles are expected to comply with the speed limits. However, the sensors and software solutions of a specific vehicle and automated driving system manufacturer are likely shared with various use cases. Thereby, a robot taxi capable of driving on a motorway could drive faster than 50 km/h on a residential street, but its speed would still be restricted on such streets to 50 km/h or according to posted maximum speed limit by e.g. geofencing.

Table 21. ODD requirements per road category for parameter speed range

Speed range			
road category	**2020 use cases**	**2030 use cases**	**2040 use cases**
motorway	0-130 hap, fvor, rst, wmt	0-130 hap, fvor, rt, rst, wmt	0-130 hap, fvor, rt, rst, wmt
highway, main or national road	0-110 fvor	0-110 fvor, rt, rst, wmt	0-110 fvor, rt, rst, wmt
urban road/ street	0-60 rt	0-70 rt	0-70 fvor, rt, wmt
secondary/ rural road	-	0-80 fvor, rt	0-110 fvor, rt, rst, wmt
terminal area	0-50 fvor	0-50 fvor, rst	0-50 fvor, rt, rst, wmt

Use case abbreviations used: hap=highway autopilot, fvor=freight vehicles open roads, rt= robot taxi, rst=roadworks safety trailer, wmt=winter maintenance truck

Shoulder or kerb

The expected evolutions of requirements for shoulder and kerb space are quite small. This is because these are very basic requirements. Level 4 automated vehicles will need space for a safe stop in case of the termination of ODD, and robot taxis along with e.g. automated shuttles will need a space where to pick up and drop off passengers.

On the other hand, such spaces are widely available already. Most motorways have wide enough shoulders for stopping a vehicle safely. It has to be noted however, that various reports and studies like e.g. the UK report evaluating all lane running (House of Commons, Transport Committee, UK 2016) indicate that stopped vehicles on the hard shoulder provide a significant safety hazard. Therefore, the suitability of using the hard shoulder as a safe harbour needs to be carefully assessed dependent on the road situation. In the case of ODD end, the number of vehicles making a minimum risk manoeuvre can be quite large, and their stopping would practically put the whole road to a standstill. Hence, stopping as the minimum risk manoeuvre should be strongly avoided. Thereby, slowing down and proceeding at a low speed to a large parking area beside the next exit could be a workable solution.

Most city streets have parking space along them, so that adding a sign beside the kerb and prohibiting the use of that particular space for stopping for any other purpose than picking up of dropping off passengers will suffice.

Table 22. ODD requirements per road category for parameter shoulder and kerb

Shoulder or kerb			
road category	**2020 use cases**	**2030 use cases**	**2040 use cases**
motorway	Safe refuges or shoulder areas similar to bus stops in case of narrow shoulders at intervals of e.g. 500 m on each carriageway or an area beside each exit hap, wmt	Safe refuges or shoulder areas similar to bus stops in case of narrow shoulders at intervals of e.g. 500 m on each carriageway or an area beside each exit hap, rt, wmt	Safe refuges or shoulder areas similar to bus stops in case of narrow shoulders at intervals of max 500 m on each carriageway or an area beside each exit hap, rt, wmt
	Safe refuges or shoulder areas similar to bus stops but long enough for freight vehicles with trailers in case of narrow shoulders at intervals of e.g. 500 m on each carriageway or an area beside each exit fvor	Safe refuges or shoulder areas similar to bus stops but long enough for freight vehicles with trailers in case of narrow shoulders at intervals of e.g. 500 m on each carriageway or an area beside each exit fvor	Safe refuges or shoulder areas similar to bus stops but long enough for freight vehicles with trailers in case of narrow shoulders at intervals of max. 500 m on each carriageway or an area beside each exit fvor
highway, main or national road	Safe refuges or shoulder areas similar to bus stops but long enough for freight vehicles with trailers at intervals of e.g. 500-2000 m on each carriageway depending on traffic volumes or an area beside each exit fvor	Safe refuges or shoulder areas similar to bus stops but long enough for freight vehicles with trailers at intervals of e.g. 500-2000 m on each carriageway depending on traffic volumes or an area beside each exit fvor, wmt	Safe refuges or shoulder areas similar to bus stops but long enough for freight vehicles with trailers at intervals of e.g. 500-2000 m on each carriageway depending on traffic volumes or an area beside each exit fvor, wmt
urban road/ street	Roadside parking space, Passenger pick-up/drop-off space at kerb beside public transport terminals, public service, shopping and recreation areas; residential areas at feasible intervals rt	Roadside parking space, Passenger pick-up/drop-off space at kerb beside public transport terminals, public service, shopping and recreation areas; residential areas at feasible intervals rt	Roadside parking space, Passenger/goods pick-up/ drop-off space at kerb in relevant locations; residential areas at feasible intervals fvor, rt, wmt
secondary/ rural road	-	Safe refuges or shoulder areas similar to bus stops but long enough for freight vehicles with trailers at intervals of e.g. 1000-3000 m or areas beside major intersections, passenger pu/do points at relevant spots fvor, rt	Safe refuges or shoulder areas similar to bus stops but long enough for freight vehicles with trailers at intervals of e.g. 500-3000 m or areas beside major intersections, passenger pu/do points at relevant spots fvor, rt, wmt
terminal area	Not relevant	Not relevant	Passenger pick-up/drop-off points at relevant locations rt

Use case abbreviations used: hap=highway autopilot, fvor=freight vehicles open roads, rt= robot taxi, rst=roadworks safety trailer, wmt=winter maintenance truck

Road markings

The case for road markings is the same for all road categories except for ports, rail yards, logistics centres, and other terminal areas, where road markings are used for various logistical purposes, indicating quite exactly where to carry out specific operations such as load or unload. Harmonization of road marking throughout Europe would be desirable but is considered extremely difficult and unrealistic for regulatory reasons. However, technically harmonization is only really required in terms of what is machine readable and to implement this machine readability in all national road marking standards.

Table 23. ODD requirements per road category for parameter road marking

Road markings			
road category	**2020 use cases**	**2030 use cases**	**2040 use cases**
motorway	Consistent and minimum quality of solid or dotted lines and symbols painted on the pavement to distinguish lanes, shoulder, traffic regulations hap, fvor, rst	Consistent and minimum quality of solid or dotted lines and symbols painted on the pavement to distinguish lanes, shoulder, traffic regulations hap, fvor, rt, rst	Perhaps not needed for automated driving hap, fvor, rt, rst
highway, main or national road	as above fvor	as above fvor, rt, rst	as above fvor, rt, rst
urban road/ street	as above rt	as above rt	as above fvor, rt
secondary/ rural road	-	as above fvor, rt	as above fvor, rt, rst
terminal area	as above, in addition markings needed for logistical purposes fvor	as above, in addition markings needed for logistical purposes fvor	as above, possibly markings needed for logistical purposes fvor, rt

Use case abbreviations used: hap=highway autopilot, fvor=freight vehicles open roads, rt= robot taxi, rst=roadworks safety trailer, wmt=winter maintenance truck

Today, and likely in 2030 as well, at least some of the automated vehicle systems rely on cameras just as human drivers on their eyes for lane keeping and following the guidance painted on the road for overtaking prohibitions, channelizing traffic at junctions, etc. The robot taxis may well rely primarily on laser scanners for accurate lateral positioning and other purposes, but it is quite likely that they also utilise cameras for redundancy and other reasons.

Road markings are important also for humanly operated vehicles, but automated vehicles likely place different quality requirements for their consistency and visibility. This requires additional research.

In 2040, all automated vehicles will have connectivity, all traffic management related information should be digitally available, including road markings, whereas accurate positioning of the automated vehicles may not require lane markings. Hence, in 2040 automated vehicles may not need road markings any more.

Traffic signs/signals

Traffic signs are similar to road markings in the ODD evolution. Camera-based sensing requires the signs and signals to be of sufficient quality and clearly visible to be machine-readable, but the information in all permanent signs at least will be available to all automated vehicles via connectivity in 2040. The temporary signs and signals indicating regulations or traffic management information still need to be machine-readable in 2040, assuming that their digital coverage may not be always up to 100%. Carlson & Brown (2019) point out, that machine-readability includes also a refresh/flicker rate of more than 200 Hz for digital sign, and that symbols are preferred against text by the vehicle industry.

Table 24. ODD requirements per road category for parameter traffic signs

Traffic signs/signals			
road category	**2020 use cases**	**2030 use cases**	**2040 use cases**
motorway	Permanent and temporary regulatory and traffic management signs in machine-readable quality hap, fvor	Permanent and temporary regulatory and traffic management signs in machine-readable quality hap, fvor, rt	Temporary regulatory and traffic management signs in machine-readable quality hap, fvor, rt
highway, main or national road	as above fvor	as above fvor, rt	as above fvor, rt
urban road/ street	as above rt	as above rt	as above fvor, rt
secondary/ rural road	-	as above fvor, rt	as above fvor, rt
terminal area	as above fvor	as above fvor	as above fvor, rt

Use case abbreviations used: hap=highway autopilot, fvor=freight vehicles open roads, rt= robot taxi, rst=roadworks safety trailer, wmt=winter maintenance truck

Road equipment

Five kinds of road equipment are likely needed for the highly automated vehicle use cases of MANTRA. First, landmarks to support the accurate positioning of vehicles. These landmarks need to be located by the vehicle sensors, and thereby they can be equipped with radar reflectors and UWB or other radio beacons. These are only needed when the road environment itself does not offer sufficient landmarks (lamp posts, railings, buildings, etc.) already.

Second, the passenger pick-up/drop-off points may be equipped with shelters and waiting areas to increase the level of service of robot taxis (and also automated shuttles likely utilising the same areas) in high passenger volume areas. These may be provided also by the transport operator.

Third, some use cases likely require manoeuvring along streets and roads with only other motor vehicles alongside them, and this would require the separation of VRUs onto the footpath or specific path alongside the road as e.g. bicycle lanes would not be sufficient.

Fourth, even if freight vehicles might be capable of operating on open roads, for safety reasons on some roads, road operators might wish to dedicate a specific lane or a specific time slot for them. This in turn could call for specific signing on gantries or gates providing access to the lanes or roads. The third and fourth kind would likely become unnecessary by 2040, but not the first two of landmarks and passenger pick-up/drop-off point equipment.

Fifth, highly automated vehicles can increase the demand for new game fences or the higher maintenance of the existing fences in order to ensure road safety on sections, where elks, deer and other large animals frequently cross the road.

Table 25. ODD requirements per road category for parameter road equipment

Road equipment			
road category	**2020 use cases**	**2030 use cases**	**2040 use cases**
motorway	Wireless and physical landmarks perhaps with sensor reflectors for position support, game fences on high risk sections hap, fvor, rst, wmt	Wireless and physical landmarks perhaps with sensor reflectors for position support, game fences on high risk sections hap, fvor, rt, rst, wmt	Wireless and physical landmarks perhaps with sensor reflectors for position support, game fences on high risk sections hap, fvor, rt, rst, wmt
	Gantries for overhead lane control signs if dedicated lanes. Possible gates for entering and exiting the dedicated lanes. fvor	Gantries for overhead lane control signs if dedicated lanes. Possible gates for entering and exiting the dedicated lanes. fvor	
highway, main or national road	Wireless and physical landmarks perhaps with sensor reflectors for position support fvor	Wireless and physical landmarks perhaps with sensor reflectors for position support, game fences on high risk sections fvor, rt, rst, wmt	Wireless and physical landmarks perhaps with sensor reflectors for position support, game fences on high risk sections fvor, rt, rst, wmt
	Gantries for overhead lane control signs if dedicated lanes. Possible gates for entering and exiting the dedicated lanes. fvor	Gantries for overhead lane control signs if dedicated lanes. Possible gates for entering and exiting the dedicated lanes. fvor	
urban road/ street	Possible shelters and seats for passengers at the pu/do points. Separation of VRUs from motor traffic. rt	Possible shelters and seats for passengers at the pu/do points. Separation of VRUs from motor traffic. rt	Possible shelters and seats for passengers at the pu/do points. fvor, rt, wmt
secondary/ rural road	-	Wireless and physical landmarks perhaps with sensor reflectors for position support. Possible shelters and seats for passengers at the pu/do points, game fences on high risk sections fvor, rt	Wireless and physical landmarks perhaps with sensor reflectors for position support. Possible shelters and seats for passengers at the pu/do points, game fences on high risk sections fvor, rt, rst, wmt

Road equipment			
road category	**2020 use cases**	**2030 use cases**	**2040 use cases**
terminal area	Wireless and physical landmarks perhaps with sensor reflectors for position support fvor	Wireless and physical landmarks perhaps with sensor reflectors for position support fvor, rst	Wireless and physical landmarks perhaps with sensor reflectors for position support fvor, rt, rst, wmt

Use case abbreviations used: hap=highway autopilot, fvor=freight vehicles open roads, rt= robot taxi, rst=roadworks safety trailer, wmt=winter maintenance truck

4.2.3 Digital infrastructure

The digital infrastructure is addressed with regard to HD maps, satellite positioning, communication, and information systems.

HD map

High-Definition (HD) maps provide detailed mapping in a machine-readable format to support a CAVs ability to understand its precise positioning, plan beyond sensor range, possess contextual awareness of the environment and local knowledge of the road rules. Hence, HD maps can assist automated vehicles to optimize their precise positioning and control on the road surface and potentially extend their ODD. (Malone et al. 2019)

All automated vehicles make use of HD maps, which relate to the camera, radar, LIDAR and/or other sensors of the automated vehicle. Vardhan (2017) explains the four levels of the HD maps on top of the base map layer in the following way:

Geometric Map is composed of raw sensor data collected by raw sensor data from LIDAR, various cameras, GPS, and IMUs. The output is a dense 3D point cloud, and this data is post-processed to produce derived map objects that are stored in the geometric map.

Semantic Map Layer is built upon the geometric map layer, by adding semantic objects. Semantic objects can be either 2D or 3D such as lane boundaries, intersections, parking spots, stop signs, traffic lights, etc. that are used for driving safely. These objects contain rich information such as traffic speeds, lane change restrictions etc.

Map priors layer contains dynamic information and human behaviour data. Examples such as the order in which traffic lights change, the average wait times in a typical day at the lights, the probability of a vehicle at a parking spot, the average speeds of vehicles at parking spots etc. Autonomy algorithms commonly consume these priors in models as inputs or features and combined with other real-time information.

Real-time knowledge layer is the top-most layer in the map that is dynamically updated contains real-time traffic information. This data can also be shared in real time between the fleet of autonomous vehicles. (Vardhan 2017) This is further explained as part of the information systems in this chapter.

HD maps for automated vehicles are currently being provided by many actors, such as CARMERA (2019), HERE (2019), NVIDIA (2019) and TomTom (2019). Many of them provide in the HD maps different sets of data depending on the sensor used. Typically, LIDAR maps are the largest containing high definition 3D laser point clouds of the road and its surroundings.

Many road operators have built up their own GiS (Geographical information System) and digital road maps for their own asset management and other purposes. Hence, up-to-date digital maps of their road networks is a strategic asset for them, and many of them are motivated to keep this asset in their own governance. The road operators can provide their data for the HD maps either directly to the HD map providers or via a national access point. (Malone et al. 2019)

Table 26. ODD requirements per road category for parameter HD maps

HD map			
road category	**2020 use cases**	**2030 use cases**	**2040 use cases**
motorway	HD maps for camera, radar and/or ultrasound sensors hap, fvor, wmt	HD maps for camera, radar and/or ultrasound sensors hap, fvor, rt, wmt	HD maps for camera, radar and/or ultrasound sensors hap, fvor, rt, wmt
	HD maps for LIDAR sensors rt	HD maps for LIDAR sensors rt	HD maps for LIDAR sensors rt
highway, main or national road	HD maps for camera, radar and/or ultrasound sensors fvor	HD maps for camera, radar and/or ultrasound sensors fvor, rt, wmt	HD maps for camera, radar and/or ultrasound sensors fvor, rt, wmt
		HD maps for LIDAR sensors rt	HD maps for LIDAR sensors rt
urban road/ street	HD maps for camera, radar and/or ultrasound sensors rt	HD maps for camera, radar and/or ultrasound sensors rt	HD maps for camera, radar and/or ultrasound sensors fvor, rt, wmt
	HD maps for LIDAR sensors rt	HD maps for LIDAR sensors rt	HD maps for LIDAR sensors rt
secondary/ rural road	-	HD maps for camera, radar and/or ultrasound sensors fvor, rt	HD maps for camera, radar and/or ultrasound sensors fvor, rt, wmt
		HD maps for LIDAR sensors rt	HD maps for LIDAR sensors rt
terminal area	HD maps for camera, radar and/or ultrasound sensors fvor	v HD maps for camera, radar and/or ultrasound sensors fvor	HD maps for camera, radar and/or ultrasound sensors fvor, rt, wmt
	HD maps for LIDAR sensors rt	HD maps for LIDAR sensors rt	HD maps for vehicles with LIDAR sensors rt

Use case abbreviations used: hap=highway autopilot, fvor=freight vehicles open roads, rt= robot taxi, rst=roadworks safety trailer, wmt=winter maintenance truck

The TN-ITS platform (TN-ITS 2019) aims to help road users get fresh map data and especially changes in it from the road operators to the vehicle's navigation system, for both automated and human-operated vehicles. Map makers then retrieve, verify and integrate the changes in road data in their platform, and bring this to map users. The platform brings together map makers and public authorities while supporting European Commission policies to update static road data, exchange the updated data, and to ensure a seamless data chain. TN-ITS has defined and maintained a TN-ITS specification in CEN TC278 Working Group 7, and supported the implementation of the national digital map systems according to this specification. The current deployment covers 15 countries. (TN-ITS 2019; Dreher 2019)

According to the DIRIZON project (Malone et al. 2019), the basic process flow HD maps will be established in the short term. This means setting up the national access points or other processes for data provision, and also the specification of the profiles, formats, structures and procedures needed to handle data streams. The processes need to undergo piloting and testing. There will be agreements and digitalisation of road, lane and localization landmark data. HD maps will comprise validated data from various sources/domains that are in standardised computer-readable formats and are queried and linked via suitable web technologies, e.g. SPARQL and RDF. Data can be public and/or private data. Relevant physical infrastructure elements (e.g. road, lane and localization landmarks) have been digitised and are available to HD maps.

By 2040, the feedback loops for maintaining data quality have been established, the digital traffic rules are included, the HD maps localization quality has been reached, most of the physical and digital infrastructure elements have been digitised and are available to HD maps, and HD digital map achieves the data quality levels required for the decision-making process in aCAV. (Malone et al. 2019)

The HD maps are expected to remain an essential part of the ODD at least up to 2040.

Satellite positioning

The automated vehicle needs to be able to position itself with a few cm accuracy to ensure road safety. The vehicles utilise several independent positioning methods, such as satellite positioning and inertial positioning, mobile phone network positioning as well as car sensors and HD map positioning (Koskinen et al. 2018). The accuracy of satellite positioning has been shown to reach the 5 cm accuracy when supported by RTK (Real Time Kinetics) land stations even in the challenging northern latitudes at the Aurora test site in Finland (Koskela 2018).

Table 27. ODD requirements per road category for parameter satellite positioning

Satellite positioning			
road category	**2020 use cases**	**2030 use cases**	**2040 use cases**
motorway	RTK land stations hap, fvor, rst, wmt	RTK land stations hap, fvor, rt, rst, wmt	RTK land stations hap, fvor, rt, rst, wmt
highway, main or national road	RTK land stations fvor	RTK land stations fvor, rt, rst, wmt	RTK land stations fvor, rt, rst, wmt
urban road/ street	RTK land stations rt	RTK land stations rt	RTK land stations fvor, rt, wmt
secondary/ rural road	-	RTK land stations fvor, rt	RTK land stations fvor, rt, rst, wmt

Use case abbreviations used: hap=highway autopilot, fvor=freight vehicles open roads, rt= robot taxi, rst=roadworks safety trailer, wmt=winter maintenance truck

As the positioning satellites such as Galileo and GPS are already in operation, the needed digital infrastructure by the automated vehicles is thereby the network of the RTK land stations enhancing the accuracy of satellite positioning. For this reason, table below is focusing on those. The requirements are not foreseen to change until 2040.

Communication

Communication is developing fast, and will likely do so during the next decades as well. Hence, it is not fruitful to describe things with today's technology names as LTE, 4G, 5G, ITS-G5, DSRC etc.

Table 28. ODD requirements per road category for parameter communications

Communication			
road category	**2020 use cases**	**2030 use cases**	**2040 use cases**
motorway	longer range V2I, short range V2I in tunnels and at roadworks hap, fvor, wmt	longer range V2I, short range V2I in tunnels and at roadworks hap, fvor, rt, wmt	longer range V2I, short range V2I in tunnels and at roadworks hap, fvor, rt, wmt
	V2V hap, fvor, rst	V2V hap, fvor, rst	V2V hap, fvor, rst
highway, main or national road	longer range V2I, short range V2I in tunnels, at roadworks & traffic lights fvor	longer range V2I, short range V2I in tunnels, at roadworks and traffic lights fvor, rt, wmt	longer range V2I, short range V2I in tunnels, at roadworks and traffic lights fvor, rt, wmt
	V2V fvor	V2V fvor, rst	V2V fvor, rst
urban road/ street	longer range V2I, short range V2I at traffic lights rt	longer range V2I, short range V2I at traffic lights fvor, rt	longer range V2I, short range V2I at traffic lights fvor, rt, wmt
		V2V fvor,	V2V fvor
secondary/ rural road	-	longer range V2I, short range V2I in tunnels, at roadworks and traffic lights fvor, rt	longer range V2I, short range V2I in tunnels, at roadworks and traffic lights fvor, rt, wmt
	-	V2V fvor	V2V fvor, rst
terminal area	longer range V2I, short range V2I at traffic lights fvor	longer range V2I, short range V2I at traffic lights fvor	longer range V2I, short range V2I at traffic lights fvor, rt, wmt
	V2V fvor	V2V fvor, rst	V2V fvor, rst

Use case abbreviations used: hap=highway autopilot, fvor=freight vehicles open roads, rt= robot taxi, rst=roadworks safety trailer, wmt=winter maintenance truck

The basic communication types will most likely still be vehicle to vehicle short range, vehicle to infrastructure short range, and vehicle to infrastructure medium/long range. The last mentioned will likely be provided via cellular networks, but the short range V2I communications will need communication beacons beside or over the road, connected to different servers (road operators, vehicle manufacturers, service providers, fleet managers, etc.) via trunk communications such as fibre optic cabling. Short range V2V is essential for highway convoy, truck platooning, automated winter maintenance vehicles and road work safety trailer use cases. The requirements are not foreseen to change until 2040.

Information system

There are basically two kinds of information systems required by the ODD. First, some systems need real-time information on incidents, roadworks, events, congestion and other disturbances on the route ahead as preview information of problems outside the range of the vehicle sensors.

Second, the automated vehicle systems usually also need information of the rules and regulations of any restrictions concerning automated driving, including real time traffic management information, and geofencing information in order to avoid routing through forbidden areas.

Distribution of digital traffic regulation becomes more and more relevant for highly automated vehicles as well as for other areas e.g. smart cities, and is currently being standardized within CEN/TC 278 WG17. It has been found that current legal responsibilities and authorisation schemes vary a lot between countries, states and cities. Rules are time and place referenced similar to a digital map. This means that there will be a need to maintain and encode traffic regulations electronically to be machine readable, processed and correctly interpreted by a highly automated vehicle. (Malone et al. 2019)

The process of creating legislation at different governmental levels (national, regional and local), creating a harmonized digital equivalent for traffic regulations (e.g. normally represented thought physical signs) across Europe, and the enactment of these regulations are prerequisites but not part of the operations of distribution of digital traffic regulations. (Malone et al. 2019)

According to DIRIZON, there are three options for communication of the digital traffic regulations to road users. The first two options require a secure communication and the usage of a Public Key Infrastructure (PKI). The purpose of a PKI is to facilitate the secure electronic transfer of information for a range of network activities. It is required for activities where more rigorous proof is required to confirm the identity of the parties involved in the communication and to validate the information being transferred. (Malone et al. 2019)

- Option 1 is for the implementing authority to provide the regulations to a Trusted Digital Regulation Access Point. These regulations must be picked up by service providers, for use in their (C-)ITS services, integrating the binding information to vehicles and (portable) electronic devices. The application of a PKI should lead the driver or automated vehicle to trust the information and observe the traffic regulation.
- Option 2 is for the implementing authority to provide the regulations via a bidirectional communication with service providers. The further communication is similar to option 1
- Option 3 shows what already takes place: the regulations are displayed via physical infrastructure via static signs or on VMSs.

Specification and standards for the different information items are useful for the provision of the real-time problems as well as regulations and traffic management information. DATEX already has standardised specifications for real-time information with usage related regulation in the delegated regulations for safety-related (EC 2013) and real-time information (EC 2015). Profiles for exchanging such information as C-ITS messages have been produced by C-Roads (2019). The SENSORIS platform is specifying the interface and data format for exchanging information between in-vehicle sensors and dedicated cloud as well as between clouds (Dreher 2019). The NordicWay project has piloted the cloud-based data exchange between vehicles and traffic management centres utilising the DATEX and AMQP standards (Scholliers et al. 2018). For traffic rules, regulations, and traffic management information, similar specifications and standards have not been produced, yet.

It is expected that by 2040, the national road authorities have introduced Trusted Digital Regulation Access Point(s) i.e. a common platform where they can share real-time traffic regulation data. Furthermore, other stakeholders, e.g. digital map providers can exploit that data providing HD maps enriched with dynamic traffic regulations. (Malone et al. 2019)

Table 29. ODD requirements per road category for information system

Information system			
road category	**2020 use cases**	**2030 use cases**	**2040 use cases**
motorway	real-time problem information hap, fvor, wmt	real-time problem information hap, fvor, wmt	real-time problem information hap, fvor, wmt
	information on rules, regulations, geofencing hap, fvor, rst	information on rules, regulations, geofencing hap, fvor, rt, rst	information on rules, regulations, geofencing hap, fvor, rt, rst
highway, main or national road	real-time problem information fvor	real-time problem information fvor, wmt	real-time problem information fvor, wmt
	information on rules, regulations, geofencing fvor	information on rules, regulations, geofencing fvor, rt, rst	information on rules, regulations, geofencing fvor, rt, rst
urban road/ street	-	-	real-time problem information fvor, wmt
	information on rules, regulations, geofencing rt	information on rules, regulations, geofencing rt	information on rules, regulations, geofencing fvor, rt
secondary/ rural road	-	real-time problem information fvor,	real-time problem information fvor, wmt
	-	information on rules, regulations, geofencing fvor, rt	information on rules, regulations, geofencing fvor, rt, rst
terminal area	real-time problem information fvor	real-time problem information fvor	real-time problem information fvor, wmt
	information on rules, regulations, geofencing fvor	information on rules, regulations, geofencing fvor, rst	information on rules, regulations, geofencing fvor, rt, rst

Use case abbreviations used: hap=highway autopilot, fvor=freight vehicles open roads, rt= robot taxi, rst=roadworks safety trailer, wmt=winter maintenance truck

Monitoring and control centres

One part of the digital infrastructure is formed by possible monitoring and control centres, which are needed especially whenever the vehicle encounters the termination of its ODD, and there is no human occupant to take over the driving task of the vehicle. An operations centre can be used to monitor the vehicles and to supervise their control when and where necessary. The need and potential for such operations centres is presented in Table 30.

In case of terminating ODD, the Level 4 vehicle has to move to a state of maximum safety, unless a human driver takes over the driving task. In some cases like the robot taxi, the occupants of the vehicle expect in a problem situation an external supervisor to give guidance to the vehicle about whether a particular manoeuvre can be done safely and to authorize the vehicle to do the manoeuvre (Shladover 2018b). This would be an expected part of the transport service, and thereby the remote operating centre is a key element in the deployment of such services.

In the cases of driverless winter maintenance vehicles, the vehicles do not have a driver in the vehicle for either business case or safety reasons, and again the remote vehicle operating centre is a must in practice.

For the freight vehicle use case, there likely is a driver in the vehicle in many occasions (e.g. when on road) and he/she could take over when and where a human fall-back is useful. In some situations like loading and other terminal operations, the driver may not be in the vehicle. In any case, the freight transport operator with a sizable vehicle fleet usually has a fleet management centre facility with remote monitoring capabilities of some sort, and this may be extended to provide also remote control capabilities. (Kulmala et al. 2018a)

Table 30. Need for and potential implementation of operations centres for the MANTRA automated driving use cases. (utilising Kulmala et al. (2018a))

Automated driving functionality	Need for an operations centre to monitor and supervise vehicles	Potential implementation
Highway autopilot & highway convoy	No real need unless case of a specific fleet	In specific cases only; Not expected very soon.
Highly automated (freight) vehicles on open roads (L4)	The functionality is used for commercial reasons with high economic value but also with safety risks, resulting in need to monitor and supervise.	Ad-hoc centres needed from the start, specific centres set up for normal operations. One operator can manage up to 10 vehicles.
Commercial driverless vehicles (L4) as taxi services	Even short stops for ODD termination are disruptive for customer service, thereby remote supervision is necessary.	From the start of the service. One operator can manage up to 20 vehicles.
Automated winter maintenance vehicles (L4)	Vehicle will likely encounter ODD termination every now and then, while the work needs to be carried out in schedule. When among other traffic, control needs to be taken over quickly.	From the start of the service. One operator can manage up to 10 vehicles.
Roadwork safety trailer (L4)	As the trailer is normally used close to road works personnel, these can take over and/or assist in returning the trailer to automated operation	Not expected until also road works become automated,

For highway autopilot, the remote control service may be needed in the long-term, if sufficient number of customers would need to have such a support service (Kulmala et al. 2018a). In the case of road works safety trailer, these are operated in close proximity with road works personnel, who can take action whenever the safety trailer has to terminate its automated operation.

4.2.4 Traffic Management and Maintenance

In addition to the provision of the physical ODD attributes, the road operators might wish to provide automated vehicles wider ODD by affecting the dynamic attributes of the ODD by traffic management and maintenance activities. The decision to do so will depend on the socio-economic benefits and costs for such ODD provision.

Traffic management to provide ODD

Table 31. ODD requirements per road category to provide traffic management

Traffic management			
road category	**2020 use cases**	**2030 use cases**	**2040 use cases**
motorway	Effective incident management hap, fvor, rst, wmt	Standardized marking and efficient management of road works zones and incident/event sites, adaptation of traffic centres, systems and services to automated driving hap, fvor, rt, rst, wmt	Standardized marking and efficient management of road works zones and incident/event sites, adaptation of traffic centres, systems and services to automated driving hap, fvor, rt, rst, wmt
highway, main or national road	Effective incident management fvor	Standardized marking and efficient management of road works zones and incident/event sites, adaptation of traffic centres, systems and services to automated driving fvor, rt, rst, wmt	Standardized marking and efficient management of road works zones and incident/event sites, adaptation of traffic centres, systems and services to automated driving fvor, rt, rst, wmt
urban road/ street		Standardized marking of road works zones rt	Standardized marking of road works zones fvor, rt, wmt
secondary/ rural road		Standardized marking and efficient management of road works zones and incident/event sites, adaptation of traffic centres, systems and services to automated driving fvor, rt	Standardized marking and efficient management of road works zones and incident/event sites, adaptation of traffic centres, systems and services to automated driving fvor, rt, rst, wmt
terminal area			

Use case abbreviations used: hap=highway autopilot, fvor=freight vehicles open roads, rt= robot taxi, rst=roadworks safety trailer, wmt=winter maintenance truck

Already today to maintain the ODDs for most uses even in daylight, good weather conditions, and not too high traffic volumes, the incident management processes should be effective to mitigate the impacts of incidents and lengthen the time when highly automated vehicles can operate freely. This may need the improvement of these processes for some countries, cities, and road operators.

Standardized marking and efficient management of road works zones has been discussed by e.g. Carlson & Brown (2019), who suggest that the markings for entering the zone and through the lane shifts need to be made with highly visible and continuous materials, not intermittent buttons and reflectors, possibly using orange markings, with a maximum spacing of vertical work zone devices e.g. cones. Concrete walls such as dividers should be marked with highly reflective markers, especially in the beginning of the section. The barrier should provide high contrast from the adjacent road surface. (Carlson, P. & Brown, L. 2019)

Standardized markings would be useful also for incident/event sites. The standardised markings for road works, incident and event sites will likely become needed by 2030 when automated vehicles could constitute about 5-10% of the traffic flow, and the termination of ODDs could produce unacceptable risk of crashes and congestion at these sites. By that point in time, also all major systems, services, and operations at traffic management and control centres probably need to be adapted to consider highly automated vehicles. The same applies to the services directly or indirectly connected to automated vehicles.

The vehicle sensors and systems may not, however, be able to detect and interpret traffic management measures of road works very reliably in all feasible environmental conditions. In that case, the details of temporary traffic management measures need to be communicated to the automated vehicles. Such details should include time of operation and the road layout. Provision of real-time updates when sites have started and finished their work would be valuable. (Transport Systems Catapult 2017)

The actual implementation might involve geo-locating cones or barriers on a site, or setting up a virtual geofence so that the automated vehicle knows exactly where it can and cannot drive. Infrastructure to Vehicle (I2V) communications could likely be used to indicate areas of the road closed for road works. (Transport Systems Catapult 2017)

Maintenance to provide ODD

In some countries (e.g. Finland, Sweden, Norway, etc.) and mountainous regions, mobility is affected by adverse weather conditions for large parts of the year. Hence, there may be a need to provide ODD for automated vehicles at least on some critical routes and roads throughout the year. This would require substantial enhancement of the winter maintenance processes and activities, especially with regard to snow removal and de-icing. Such an enhancement could also result in considerable cost increases, such as doubling of the winter maintenance costs. (Kulmala et al. 2018a)

Thereby the road operators will only make the decision about enhancing winter maintenance as well as the target quality levels for it based on careful assessment of the benefits and costs of the enhancement.

The current maintenance practices for maintaining the condition and quality of road markings and signs as well as their visibility (vegetation etc.) will also likely need to be improved at least for some countries, cities, and road operators.

Neither of these main maintenance requirements are expected to apply any more in 2040. The winter maintenance requirements will vanish due to improved vehicle positioning, sensing and software before 2040, and the road marking and traffic sign maintenance requirements likewise but also due to full connectivity of the automated vehicle fleets.

Table 32. ODD requirements per road category to provide maintenance

Maintenance			
road category	**2020 use cases**	**2030 use cases**	**2040 use cases**
motorway	Enhanced winter maintenance to keep road surface free from snow and ice. Enhanced road maintenance to maintain road marking and traffic sign quality hap, fvor, rst, wmt	Enhanced winter maintenance to keep road surface free from snow and ice. Enhanced road maintenance to maintain road marking and traffic sign quality hap, fvor, rt, rst, wmt	
highway, main or national road	Enhanced winter maintenance to keep road surface free from snow and ice. Enhanced road maintenance to maintain road marking and traffic sign quality fvor	Enhanced winter maintenance to keep road surface free from snow and ice. Enhanced road maintenance to maintain road marking and traffic sign quality fvor, rt, rst, wmt	
urban road/ street	Enhanced winter maintenance to keep road surface free from snow and ice. Enhanced road maintenance to maintain road marking and traffic sign quality rt	Enhanced winter maintenance to keep road surface free from snow and ice. Enhanced road maintenance to maintain road marking and traffic sign quality rt	
secondary/ rural road	-	Enhanced winter maintenance to keep road surface free from snow and ice. Enhanced road maintenance to maintain road marking and traffic sign quality fvor, rt	
terminal area	Enhanced winter maintenance to keep road surface free from snow and ice. Enhanced road maintenance to maintain road marking and traffic sign quality fvor	Enhanced winter maintenance to keep road surface free from snow and ice. Enhanced road maintenance to maintain road marking and traffic sign quality fvor, rst	

Use case abbreviations used: hap=highway autopilot, fvor=freight vehicles open roads, rt= robot taxi, rst=roadworks safety trailer, wmt=winter maintenance truck

4.3 Effects on different road networks

4.3.1 Motorways

Table 33. ODD requirement effects on motorways

ODD attribute	2030	2040
roads covered	Selected core TEN-T roads without severe congestion to mitigate against possible capacity reduction	60% of motorway network covering core TEN-T network and other motorways with highest accident rates
shoulder or kerb	Safe refuges on some of the roads selected, half suitable for freight as well; digital information on all safe refuges, intact game fences on high risk sections	Safe refuges on some of the roads selected, half suitable for freight as well; digital information on all safe refuges, intact game fences on high risk sections
road markings	Harmonised machine readability of road markings. Enhanced maintenance on selected roads to ensure consistent and minimum quality of solid or dotted lines and symbols painted on the pavement	Harmonised machine readability of road markings. 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 in machine-readable quality
road equipment	Wireless or physical landmarks with sensor reflectors on open sections and tunnels requiring them. If parts of motorway dedicated to automated trucks, possibly gantries for indicating and gates for entering and exiting the dedicated lanes.	Wireless or physical landmarks with sensor reflectors on open sections and tunnels requiring them
HD map	HD maps for camera, radar and/or ultrasound sensors on all sections. HD maps for LIDAR sensors based on private investment.	HD maps for camera, radar and/or ultrasound sensors on all sections. HD maps for LIDAR sensors based on private investment.
satellite positioning	RTK land stations	RTK land stations
Communication	longer range V2I full coverage, short range V2I in tunnels and at roadworks	longer range V2I full coverage, short range V2I in tunnels and at roadworks
information system	real-time problem information (incidents, road works, events, disturbances), information on rules, regulations, geofencing	real-time problem information, information on rules, regulations, geofencing
traffic management	Standardized marking and efficient management of road works zones and incident/event sites, adaptation of traffic centres, systems and services to automated driving (all use cases)	Standardized marking and efficient management of road works zones and incident/event sites, adaptation of traffic centres, systems and services to automated driving (all use cases)
maintenance	Enhanced winter maintenance to keep road surface free from snow and ice.	

4.3.2 Highways, main and national roads

Table 34. ODD requirement effects on arterial and ring roads

ODD attribute	2030	2040
roads covered	Selected arterials with no/little severe congestion to mitigate against possible capacity reduction	30% of arterials/ring roads covering the ones with highest accident rates
shoulder or kerb	Safe refuges on some of the roads selected, half suitable for freight as well; digital information on all safe refuges, intact game fences on high risk sections	Safe refuges on some of the roads selected, half suitable for freight as well; digital information on all safe refuges, intact game fences on high risk sections
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 in machine-readable quality
road equipment	Wireless or physical landmarks with sensor reflectors on open sections and tunnels requiring them. If parts of motorway dedicated to automated trucks, possibly gantries for indicating and gates for entering and exiting the dedicated lanes.	Wireless or physical landmarks with sensor reflectors on open sections and tunnels requiring them
HD map	HD maps for camera, radar and/or ultrasound sensors on all sections. HD maps for LIDAR sensors based on private investment.	HD maps for camera, radar and/or ultrasound sensors on all sections. HD maps for LIDAR sensors based on private investment.
satellite positioning	RTK land stations	RTK land stations
communication	Longer range V2I full coverage, short range V2I in tunnels and at roadworks	Longer range V2I full coverage, short range V2I in tunnels and at roadworks
information system	real-time problem information (incidents, road works, events, disturbances), information on rules, regulations, geofencing	real-time problem information, information on rules, regulations, geofencing
traffic management	Standardized marking and efficient management of road works zones and incident/event sites, adaptation of traffic centres, systems and services to automated driving (all use cases)	Standardized marking and efficient management of road works zones and incident/event sites, adaptation of traffic centres, systems and services to automated driving (all use cases)
maintenance	Enhanced winter maintenance to keep road surface free from snow and ice.	

4.3.3 Urban roads/streets

Table 35. ODD requirement effects on city streets

ODD attribute	2030	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 pick-up/drop-off space at kerb beside public transport terminals, public service, shopping and recreation areas	Roadside parking space, Passenger pick-up/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
HD map	HD maps for camera, radar and/or ultrasound sensors on all sections. HD maps for LIDAR sensors based on private investment.	HD maps for camera, radar and/or ultrasound sensors on all sections. HD maps for LIDAR sensors based on private investment.
satellite positioning	RTK land stations	RTK land stations
communication	Longer range V2I full coverage, short randge V2I at traffic lights	Longer range V2I full coverage, short range V2I at traffic lights
information system	information on rules, regulations, geofencing	real-time problem information (incidents, road works, events, disturbances), information on rules, regulations, geofencing
traffic management	Standardized marking of road works zones	Standardized marking of road works zones
maintenance	Enhanced winter maintenance to keep road surface free from snow and ice.	

4.3.4 Secondary and rural roads

Table 36. ODD requirement effects on rural roads

ODD attribute	2030	2040
roads covered	Selected interurban connections with freight relevance	60% of interurban connections of freight relevance and/or of important peri-urban connections of big cities
shoulder or kerb	Safe refuges on some of the roads selected at intervals of e.g. 1000-3000 m, half suitable for freight as well. Digital information on all safe refuges. Passenger pick-up/drop-off points at relevant spots, intact game fences on high risk sections	Safe refuges on some of the roads selected at intervals of e.g. 500-3000 m, half suitable for freight as well. Digital information on all safe refuges. Passenger pick-up/drop-off points at relevant spots, intact game fences on high risk sections
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 in machine-readable quality
road equipment	Wireless or physical landmarks with sensor reflectors on open sections and tunnels requiring them. Shelters and seats for passengers at the pick-up/drop-off points	Wireless or physical landmarks with sensor reflectors on open sections and tunnels requiring them. Shelters and seats for passengers at the pick-up/drop-off points
HD map	HD maps for camera, radar and/or ultrasound sensors on all sections. HD maps for LIDAR sensors based on private investment.	HD maps for camera, radar and/or ultrasound sensors on all sections. HD maps for LIDAR sensors based on private investment.
satellite positioning	RTK land stations	RTK land stations
communication	Longer range V2I full coverage, short range V2I in tunnels, at roadworks and traffic lights	Longer range V2I full coverage, short range V2I in tunnels, at roadworks and traffic lights
information system	real-time problem information (incidents, road works, events, disturbances), information on rules, regulations, geofencing	real-time problem information, information on rules, regulations, geofencing
traffic management	Standardized marking and efficient management of road works zones and incident/event sites, adaptation of traffic centres, systems and services to automated driving (all use cases)	Standardized marking and efficient management of road works zones and incident/event sites, adaptation of traffic centres, systems and services to automated driving (all use cases)
maintenance	Enhanced winter maintenance to keep road surface free from snow and ice.	

4.3.5 Terminal areas

Table 37. ODD requirement effects on terminal areas

ODD attribute	2030	2040
roads covered	Selected terminals at key ports or logistic centres	70% of the import/export ports, major railway terminals, and major logistic centres
shoulder or kerb		Passenger pick-up/drop-off points at relevant spots
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 in machine-readable quality
road equipment	Wireless or physical landmarks with sensor reflectors on open sections and tunnels requiring them.	Wireless or physical landmarks with sensor reflectors on open sections and tunnels requiring them.
HD map	HD maps for camera, radar and/or ultrasound sensors. HD maps for LIDAR sensors based on private investment.	HD maps for camera, radar and/or ultrasound sensors. HD maps for LIDAR sensors based on private investment.
satellite positioning	RTK land stations	RTK land stations
communication	Longer range V2I full coverage, short range V2I in tunnels, at traffic lights	Longer range V2I full coverage, short range V2I in tunnels, at traffic lights
information system	Information on rules, regulations, geofencing	Information on rules, regulations, geofencing
traffic management		
maintenance	Enhanced winter maintenance to keep road surface free from snow and ice.	

4.4 Responsibilities for establishing and operating and maintaining the ODD

Responsibility for making sure that the relevant ODD attributes are available and fully operational belongs to different stakeholders. These responsibilities and potentially interfaces between stakeholders need to be clearly defined to ensure no ODD gaps.

Table 38. Responsibilities for establishing and operating/maintaining the ODD

ODD attribute	motorway, arterial or ring road, city or residential street, rural road	terminal area
shoulder or kerb	road operator	terminal operator
road markings	road operator/ maintenance. contractor	terminal operator
traffic signs	road operator/ maintenance. contractor	terminal operator
road equipment	road operator	terminal operator
traffic management	road operator/ traffic management operator	n. a.
maintenance	road operator/ maintenance. contractor	terminal operator
HD map non-LIDAR	road operator/ other national bodies (different layers)/ digital map providers	terminal operator/ digital map providers
HD map LIDAR	service operator/digital map providers	service operator/digital map providers
RTK stations	land survey agency/ road operator	land survey agency/ terminal operator
longer range V2I	mobile network operator	mobile network operator
short range V2I	road operator	terminal operator
incident, event information	road operator/ TM operator / Original Equipment Manufacturers (OEMs)/ service provider	n. a.
road work information	road operator, road works contractor	n. a.
rules, regulations, geofence	regulatory agency, road operator, TM operator, service provider	regulatory agency, terminal operator, TM operator, service provider
operations centres	OEMs, fleet managers	OEMs, fleet managers

4.5 Costs of establishing ODD

Most of the costs have been estimated based on discussions with Finnish Transport Agency and CEDR experts for the work carried out in CEDR (2018). In addition, the maintenance related costs have been assessed utilising the results of as well as Malmivuo (2010) and Karjalainen (2011), and game fence costs have been obtained from (Finnra 2007). For traffic management related costs, the databases of US DOT (2018a) were used. The pick-up/drop-off costs are estimated based on bus stop related results from Transport for London (2012) and Rintamäki et al. (2013). Traffic management costs were obtained from Highways England (2018). The cellular base station costs are derived from Wisely et al. (2018). The estimated costs are shown in Table 39.

Table 39. Unit deployment costs and annual maintenance cost percentages out of deployment costs for the different ODD features in 2020

ODD attribute	Detailed feature	Unit cost range estimate (deployment)	O&M annually
Shoulder or kerb	Safe "harbours" (broad shoulders, lay-bys etc.)	20-50 k€/safe harbour; or 40-100 k€/km on sections where needed (every 500m)	8 %
	Passenger pick-up/drop-off point (markings, bench, shelter)	2-5 k€/point depending on level of services	10 %
Markings and signs	enhanced maintenance of road markings and traffic signs & signals	0.1-1.0 k€/km/a	included
Road equipment	Landmarks for positioning enhancement	4-6 k€/km (where needed)	10 %
	Signs and/or barriers for access control	30-90 k€/sign; 40-80 k€/gate or barrier; 15-90 k€/km	8 %
	Game fences	20-30 k€/km (both sides of road)	2 %
Traffic management	Standardized marking and efficient management of road works zones, incident/event sites, and toll plazas/gates	3-5 k€/km/a	included
	Adaptation of traffic centres, systems and services to automated driving (all use cases)	10-90 k€/km	8 %
Maintenance	Enhanced snow-removal	winter maintenance cost addition: ca 2-2.5 k€/km /a (2-lane roads) and 3-4 k€/km/a (motorways)	included
HD map non-LIDAR	HD Maps or road areas, infra, equipment	3-4 k€/km	8 %
	HD Maps of road structures for maintenance purposes	5-7 k€/km	8 %
	Road areas & environment for camera, radar, ultrasound sensors	1-3 k€/km/a	included
HD map LIDAR	Road areas & environment with LIDAR point clouds	3-6 k€/km/a (paid by the transport operator)	included
RTK stations	Satellite positioning enhancement with land stations	RTK station 2-10 k€ (depending on the availability of power); 1 station / 5 km; cost 0.4-2 k€/km	8 %
Longer range V2I	Base station (micro or macro)	35-40 k€/station/a (macro) 8-10 k€/station/a (micro)	included

ODD attribute	Detailed feature	Unit cost range estimate (deployment)	O&M annually
Short range V2I	Roadside station	15 k€/km	8%
	Connecting to trunk communication network and servers	fibre optics 20 - 100 k€/km including outtakes	8 %
Problem info and regulation info	High quality real-time situational picture & rules and regulations	0.4-0.8 k€/km/a incl. digitalisation of rules & regulations, back-office; urban 0.1-0.2 k€/km	included
Road works information	VMS/C-ITS warnings: road works, automated road works or maintenance vehicles	0.5-0.9 k€/km/a without new VMS but incl. equipment and marking of road work sites; road works only: 50% of costs	included

Standardization and mass markets will likely reduce the costs for roadside stations, land marks, pick-up/drop-off site equipment. The other costs will likely remain on similar levels as today.

4.6 Conclusions on suggested changes

The ODD-related changes foreseen will mostly deal with the digital infrastructure, which is also otherwise in the development and implementation phase.

The physical road infrastructure is more or less in place already today, and the support that it provides to human-operated vehicles is expected to suffice to highly automated vehicles as well. There are a few exceptions to this:

First, the highly automated vehicles will need to make a minimum risk manoeuvre when the automated driving system realises that the ODD will soon terminate. This can be due to an unexpected weather problem, which could terminate the ODD for multiple vehicles at the same time. If the minimum risk manoeuvre would be stopping on the shoulder, this could cause unacceptable crash risks on high speed roads such as motorways. Furthermore, stopping of a large number of vehicles at the same time would practically force the whole road to a standstill. Hence, other alternatives need to be developed for minimum risk manoeuvres on high speed roads. These could include to continue driving at reduced speed towards safe parking beside next exit or requiring remote supervision of vehicles to a safe refuge. WG 11 of ISO TC204 is working on the specification of the minimum risk manoeuvres.

Second, some use cases such as the robot taxis and automated public transport shuttles require safe passenger pick-up and drop-off spaces by the kerb, resulting in the need to reserve such spaces and also to equip at least the most important ones of them with e.g. shelters and seats to accommodate the waiting passengers.

Third, the accurate positioning of the vehicle likely benefits considerable of fixed landmarks equipped with some kind of sensor reflectors or radio beacons on road sections without any fixed structures or located in tunnels or street canyons. The cost for equipping such landmarks are considered to be not that significant.

For digital infrastructure, accurate positioning is also an important requirement. The satellite positioning needs to be supported by land stations in northern latitudes where most satellites are low in the horizon and radio/cellular beacons in street canyons and tunnels. The deployment and especially constant updating of HD maps including LIDAR point cloud maps will require a lot of resources.

The information system is a very important part of the digital infrastructure. Real-time event and incident information of good quality is needed to provide the extended horizon to the highly automated vehicle beyond the line of sight of its sensors. Such information may be provided directly to the service providers and vehicles or via a national access point. At the same time the vehicle needs to be aware of the rules and regulations applying to the road sections that it is using and approaching. The digital traffic regulations can be disseminated directly to vehicles and/or service providers may be organised to be delivered via a specific Trusted Digital Regulations Access Point to service and HD map providers. The implementation, maintenance, and operation of good quality information system and related access points and dissemination channels will require considerable resources.

Establishing, maintaining and operating the communications between the infrastructure and vehicles will also be quite costly, especially the provision of the trunk communications of the roadside stations and cellular base stations.

Finally, in order to deal with the dynamic non-infrastructure attributes of the ODD such as weather conditions, time of day, and traffic conditions, MANTRA has identified three elements that should likely be added to the road operator relevant list of ODD attributes:

Traffic management – This is especially needed to deal with events and incidents so that the automated vehicles can easily navigate their way through road work zones, event-affected sections, and incident sites. This is the goal towards a spatially comprehensive ODD. In the near future however it can be assumed that road works will be excluded from initial ODDs. Requirements are harmonised traffic management processes, plans, signs, road equipment, and markings. At the same time, the whole traffic management system needs to be digitised.

Infrastructure maintenance – 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 road bed damages and potholes, to maintain the condition of road markings, or to maintain the safe refuges and passenger pick-up and drop-off areas.

Fleet supervision – Evidently, road haulage companies and taxi companies need to have a fleet management centre also in the case of highly automated vehicle fleets. The problems related to sudden ODD termination due to heavy rain, unreported incidents, and other reasons will pause the provision of the transport service, unless the fleet management centre can also remotely supervise the vehicle to retain the ODD or to manually operate the vehicle to a location with ODD.

5 Impacts due to possible O&M improvements

5.1 Approach

Core of this impact category forms the possibility to improve infrastructure related operations as a result of utilizing automated functions or new data provided by these functions. This involves for example improved maintenance and operation carried out by automated vehicles or new ways of data provision on assets' condition. As shown in Fig. 6 this is again tackled through a structured process.

The starting point here is to define the gap which O&M processes are even worth optimizing. O&M of infrastructure could benefit by means of CAD. In a workshop with CED CAD WG (Tallinn, 07.03.2019) the participants define those tasks of O&M that are either big safety hazards for operational workers or road users during road operations works, improve the road availability or reduce cost of O&M. MANTRA has prepared a list of crucial O&M tasks on road networks today. These tasks are rated by the participants in terms of their impact on safety, road availability and cost. The results of this rating provides the ground for the further analysis of potential improvements by automation in O&M.

The following Figure 12 shows the whole process to identify the possibilities to improve O&M by automation. The workshop focuses on the blue box for which flipcharts and handouts listing the crucial operational tasks will be prepared by MANTRA. For those identified potential efficiency improvements a gap analysis was performed to find out which of those improvements could be done with the help of automation.

Figure 12. Assessment of impact due to possible O&M and traffic management improvements

The results of this chapter are closely linked with the results of task 4 in work package 3, where the potential of automation in O&M to reach or improve policy targets, is being addressed. The focus of this chapter is on necessary changes to infrastructure – both physical and digital – due to the improvement potential of O&M as well as improvements to traffic management.

5.2 O&M processes worth optimizing

Significant elements of O&M works will still need to be carried out manually even in 2040. However, for quite a few of these tasks, driverless vehicles could perform the actual driving task.

Highway O&M works traditionally face the challenge to be carried out in an environment with high-speed traffic right next to it and therefore poses enormous safety hazards for the workers. Driverless maintenance vehicles have the potential to reduce this risk tremendously. It will still take time until various types of O&M works will be possible to be done by driverless vehicles. However, there are quite a few use cases where the driverless vehicles could already provide safety and efficiency benefits in the near future. In particular for the initial simple use cases it will be necessary to have a human driver navigate the vehicle to its point of use and only as soon as it has arrived within its designated ODD the human driver can switch to an adjoined maintenance vehicle and let the maintenance vehicle go driverless (e.g. use case safety trailer).

In order to structurally assess the potential O&M tasks to be automated and in turn their implications to infrastructure amendments the following chapter first looks into the key operational tasks.

5.2.1 Critical operational tasks

The following are works and services which are necessary in current highway operation to achieve the best possible results with regard to the availability, reliability and sustainability of a highway. These services are essential to ensure the safety of the road users and for the proper management and communication of all incidents as well as of all planned maintenance works and to ascertain that the condition and status of the highway is maintained. Typical maintenance works include the following major work elements:

- Inspection of the highway condition and inventory
- Safety patrols and inspections
- Detailed visual inspections
- Maintenance and repair of the road elements and equipment
- Cleaning of road surface
- Cleaning and repair of noise barriers, signs and other road equipment
- Debris and litter collection (on highway and off highway)
- Road marking
- Maintenance and repair of road surface
- Maintenance and repair of structures
- Landscaping & grass cutting
- Incident management /emergency responses incl. rescue of broken down vehicles
- Traffic Management
- Environmental / Health and Safety Management

Significant elements of these works will still need to be carried out manually even in 2040. However, for quite a few of these tasks, driverless vehicles could perform the actual driving task. In a next step the typical O&M works have been grouped into task groups. In each task group only tasks are listed that require transportation or a vehicle somehow, leaving out those works that are performed without any vehicles.

Table 40. Critical O&M tasks

Task Group	Task
Winter maintenance	Preventive salting on highway main-carriageway
	Preventive salting on highway ramps
	Snow ploughing and salting on main-carriageway
	Snow ploughing and salting on ramps
Work zone protection	Planned, stationary maintenance works on emergency lane (e.g. tree cutting)
	Planned, stationary maintenance works on first lane (e.g. pothole repair, joint sealing)
	Planned, stationary maintenance works on fast lane (e.g. pothole repair, joint sealing)
	Planned moving maintenance works on emergency lane (e.g. grass cutting shoulder)
	Planned, stationary maintenance works on first lane (e.g. road marking)
	Planned, stationary maintenance works on fast lane (e.g. grass cutting on median)
	Unplanned incidents on emergency lane (accident, litter removal)
	Unplanned incidents on first lane (accident, litter removal)
	Unplanned incidents on fast lane (accident, litter removal)

Task Group	Task
Traffic management	Incident management including removal of debris or cars
	On-highway traffic management (currently VMS, highway patrol vehicles, mobile trailers)
Inspections	General safety patrols and inspections
	Bridge inspections
	Pavement inspections
Operational highway works	Grass cutting on shoulder
	Grass cutting on median
	Maintenance and repair of road assets and equipment
	Cleaning of road surfaces
	Road marking

5.2.2 Identification of O&M tasks worth optimizing

The list of O&M tasks in Table 40 was presented to the participants of the expert work shop (Tallinn, 07.03.2019) and discussed in detail for their impact on safety, cost and operational importance. Following the discussion the participants of the workshop rated the potential of each task in these three categories. Each workshop participant got a set of 10 points for each category and could allocate them to the task. The tasks with the most points are considered most promising for optimization. The results are shown below in Table 41.

Table 41. Workshop result identification of O&M tasks worth optimizing

		Safety Hazard	Cost driver	Operational importance	Total Score
Winter maintenance	Preventive salting on highway main-car-riageway	8	7	6	21
	Preventive salting on highway ramps	3	3	6	12
	Snow ploughing and salting on main-car-riageway	5	5	5	15
	Snow ploughing and salting on ramps	4	3	4	11
Work zone protection	Planned, stationary maintenance works on emergency lane (e.g. tree cutting)	1	0	0	1
	Planned, stationary maintenance works on first lane (e.g. pothole repair, joint sealing)	3	0	2	5
	Planned, stationary maintenance works on fast lane (e.g. pothole repair, joint sealing)	7	0	0	7
	Planned moving maintenance works on emergency lane (e.g. grass cutting shoul-der)	1	3	1	5
	Planned, stationary maintenance works on first lane (e.g. road marking)	1	0	3	4
	Planned, stationary maintenance works on fast lane (e.g. grass cutting on median)	1	2	1	4
	Unplanned incidents on emergency lane (accident, litter removal)	6	2	4	12
	Unplanned incidents on first lane (accident, litter removal)	10	4	5	19
	Unplanned incidents on fast lane (accident, litter removal)	12	5	7	24
Traffic man-agement	Incident management including removal of debris or cars	6	3	4	13
	On-highway traffic management (currently VMS, highway patrol vehicles, mobile trail-ers)	0	0	0	0
Inspections	General safety patrols and inspections	0	6	0	6
	Bridge inspections	1	2	5	8
	Pavement inspections	1	2	0	3
Operational highway works	Grass cutting on shoulder	4	4	2	10
	Grass cutting on median	6	3	0	9
	Maintenance and repair of road assets and equipment	7	4	5	16
	Cleaning of road surfaces	1	5	0	6
	Road marking	5	5	6	16

Based on this the most promising tasks for optimization were identified and are summarized in Table 42.

Table 42. Workshop result: Most promising O&M tasks for optimization

		Safety Hazard	Cost driver	Operational importance	Total Score
Winter maintenance	Preventive salting on highway main-carriageway	8	7	6	21
	Snow ploughing and salting on main-carriageway	5	5	5	15
Work zone protection	Unplanned incidents on first lane (accident, litter removal)	10	4	5	19
	Unplanned incidents on fast lane (accident, litter removal)	12	5	7	24
Operational highway works	Maintenance and repair of road assets and furniture	7	4	5	16
	Road marking	5	5	6	16

5.2.3 Changes to infrastructure to enable O&M task optimization

The identified most promising operational tasks to be optimized through automation are partly already covered through the selected maintenance use cases driverless safety trailer and winter maintenance vehicles. Necessary infrastructure changes to enable these technologies are part of their ODD (see chapter 4).

In order to achieve the automation of the operational task considered to be the biggest safety hazard – work zone protection on the fast lane – the potential for support by infrastructure is limited. Further development of the legal framework to enable this use case as well as an integrated connected traffic management will be key to enable safe deployment of automated safety trailers on fast lanes. In general, the connectivity of automated maintenance vehicles with the traffic management centre in order to provide road users with advanced warnings about location and nature of the operational work to increase traffic safety around work zones or winter maintenance vehicles will be crucial

5.3 Optimization of traffic management through new data sources

The sensors of CAVs will provide a lot of data of the traffic and environmental conditions along their route. Such data would be extremely useful to the road operators and traffic managers. At the same time, the availability of such data would enable road operators to give up large parts of their monitoring infrastructure resulting possibly in cost savings. On the other hand, the vehicle and information service industry is not willing to give for free the data that they have collected via connected and/or automated vehicles. The only type of data, which also the industry needs to share according to European legislation is safety-related information. This information, detailed in eight information types, has to be shared on the basis of the delegated regulation for road safety-related minimum universal traffic information free of charge to users (EC 2013).

Having better and more data throughout the network via vehicles as mobile sensors has been studied and also deployed already for almost 20 years. The pros and cons of FCD (Floating Car Data), mobile phone data, and FVD (Floating Vehicle Data) have been documented widely. The main conclusion seems to be that the penetration rate of “floating vehicles” for single service providers is too low to provide reliable data throughout the day or to detect incidents quickly enough for traffic managers – already highlighted more than 10 years ago by e.g. Brockfeld et al. (2007).

CAVs might change that with reasonable penetrations by 2030, at least if the data on traffic and environmental conditions is shared between the different vehicle and automated driving system manufacturers. Unfortunately there is no certainty of such sharing to take place.

At the same time, the sharing of safety-related information as such can result in breakthroughs on cooperative traffic management, and traffic management will be developed further to accommodate automated vehicles. These topics are discussed in the following two sub-chapters.

5.3.1 Cooperative traffic management

In order for automated vehicles to act and comply accordingly, traffic regulations (static or dynamic; mandatory or advised) need to be digitalised and become 'electronic regulations', able to be coded into the vehicles. The development of advanced automated driving functions depends upon them. (EC 2017)

To better manage traffic, the road manager needs to be able to translate its mobility options into a digitalised standardised language, so that it can be exchanged with the other road sector stakeholders. The split between the governance and the management levels is important to establish, because the definition of the mobility options precedes its operational implementation. (EC 2017)

Deploying circulation network or traffic management plans, along major corridors or urban networks provides the perfect background to realise the potential of cooperative, connected and automated mobility and to understand the impacts on the roles and borders of the road authorities, traffic managers, service providers, vehicle manufactures, and the physical and digital infrastructure stakeholders. (EC 2017)

The basic assumption is, that automated vehicles are also connected vehicles capable of communication with traffic management. Cooperative traffic management has the following basic requirements: (EC 2017)

- Communication – for the purposes of awareness or compliance, the exchange of the appropriate traffic management related data, will be bi-directional.
- Performance – traffic flow conditions will be commonly understood and assessed.
- Collaboration – the actions, from both the public and private sectors, will be complementary, decentralized, and put in place according to pre-arranged agreements.

Cooperative traffic management services will need to be well-orchestrated, as they depend on combined efforts from those involved in the service value-chain, both from the public or private sector. There is a need for scalable and replicable tools to be used across the entire European road network. These tools should provide enough flexibility for city authorities, regardless of their size or mobility policy, and also for traffic managers and road operators, to deploy the services under every possible scenario. (EC 2017)

To help public authorities play the role of the orchestra conductor and translate their mobility plans into 'standardized exchangeable data', the Enhanced Traffic Management WG of the C-ITS Platform conceptualized a specific set of important tools that need to be developed for digital traffic management plans: (EC 2017)

1. The first building block consists of a classification of roads to be done accordingly to network flow hierarchy; not always the shortest path will be fastest, nor the safest. This tool will help public authorities and road managers to conveniently present their views of the main road network hierarchy and the preferred alternatives. These may be useful

for re-routing traffic over an area that is becoming saturated, using green light optimized speed advisory (GLOSA), or for tailoring profiles, targeted to specific road user groups, e.g. freight, electric vehicles or passenger transport.
2. The second building block is a geo-fencing mechanism. This will specially help cities to translate their zoning urban planning into traffic management related data, preventing routing through residential areas or close to hospitals and schools. Service providers can relate to these zones and apply virtual delays on top, so that the routing algorithm proposes an alternative way, more in line with the public's authority expectations.
3. In order to manage traffic, its flow efficiency needs to be monitored and assessed. Establishing a network performance Level of Service (LoS) is therefore the third required building block. LoS will depend of the road classification or type of incident, but it will be assessed under a combination of two more evident key performance indicators; speed and volume. These may be collected by road side units, loops, e.g. or provided, by specific probe vehicle data.
4. The fourth and last building block is the trigger and it is the point in which the acknowledgment of data turns into action. After this point, the need to engage a cooperative traffic management service becomes decisive, to restore adequate safe and flow efficient traffic conditions. The triggering conditions need to be commonly agreed upon, as cooperative traffic management services are the result of a combination of orchestrated actions, from specific actors.

Finally, in order to make the orchestration of cooperative traffic management services possible, there is a need to develop a Common Operational Picture (COP) to provide the involved actors with a standard overview and regional context of a traffic situation. The COP will provide a visual interface, on top of a map, enabling the display of the appropriate traffic management related data, in accordance with the described building blocks layers. The COP can play a major role for re-routing services, e.g., for identifying the need of any additional measures or, for facilitating extra traffic on alternative routes.

The concept of cooperative or Traffic Management 2.0 has been developed by the ERTICO - hosted TM2.0 initiative (TM2.0 2018). An EU research project SOCRATES 2.0 (2018) is developing the interactive traffic management of CAVs further based on the same principles. The aim is a win-win-win situation for all actors in the traffic management eco-system: (SOCRATES 2.0 2018)

- Win for the road user – Effective traffic management depends on the acceptance by an individual traveller. A traveller will only follow traffic management rules well-aligned between the various parties setting up the rules, and also efficiently communicated towards him/her ideally via a “one-stop-shop” of traffic information. The traveller will be able to communicate back to the traffic management operators, giving feedback on current traffic flows and the efficiency of services.
- Win for public traffic management centres – Traffic management centres will be able to substantially optimise traffic management operations addressing a wide range of road users with tailor-made, precise information, utilising new communication channels and sensor/feedback techniques.
- Win for private service providers – The information services will expand to seamless door-to-door traveller assistance. The services will be aligned with public, collective traffic management strategies. However, the specific set-up of services towards the travellers (being their costumers) will remain in the service provider’s freedom in a competitive market.

To reach the win-win-win situation above, some base concepts and common agreements need to be elaborated among the afore-mentioned actors. This was done around three themes: (SOCRATES 2.0 2018)

1. Smart routing
2. Actual speed and lane advices
3. Local information and hazardous warnings

In order to assess how the stakeholders can cooperate to provide the use cases, a theoretical framework was created, describing options for cooperation. The concept of the intermediary was explored, based on the use cases and cooperation models. An intermediary is expected to have a role in data exchange coordination, aggregation, fusion, quality control and common picture. A set of typical options for the intermediary role has been defined and described. (SOCRATES 2.0 2018)

The role of the intermediary is presented also in Figure 13. (SOCRATES 2.0 2018)

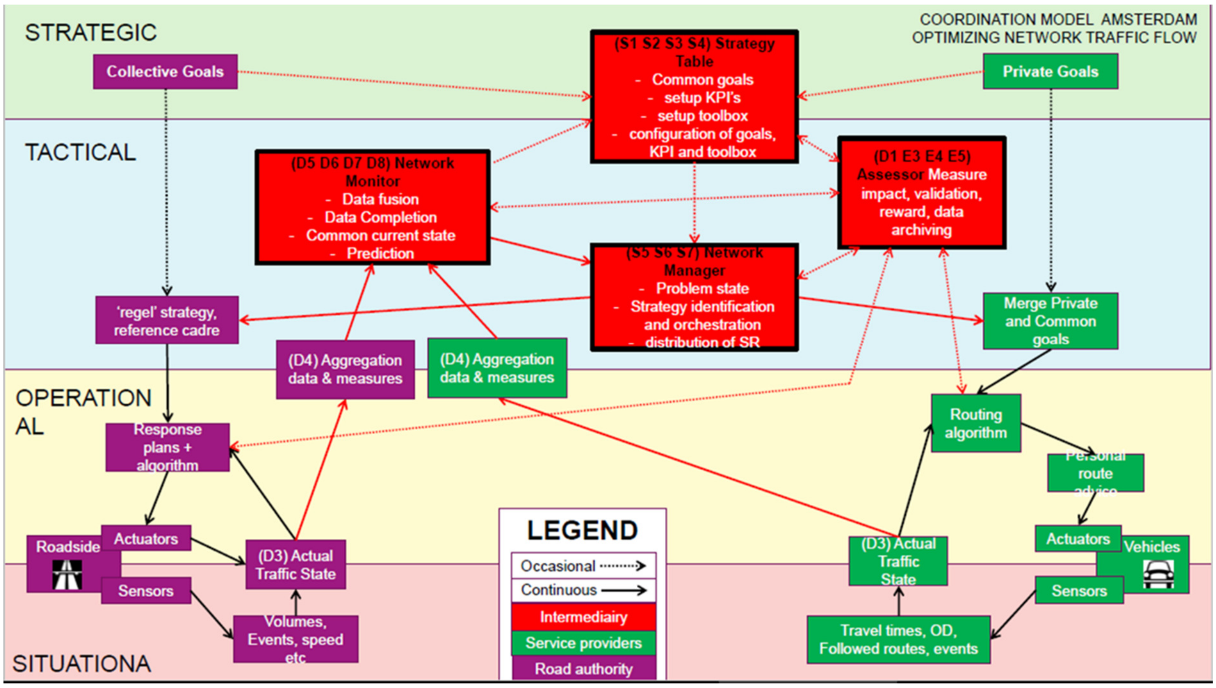


Figure 13. The coordination model for the Amsterdam site of SOCRATES 2.0 (2018).

5.3.2 Traffic management of automated vehicles

Changing situation

Traffic management provides guidance to the European traveller and haulier on the situational picture of the traffic status and condition of the road network. It detects incidents and emergencies, implements response strategies to ensure safe and efficient use of the road network and optimises the existing infrastructure including across borders. Incidents can be unforeseeable or planned: accidents, road works, adverse weather conditions, strikes, demonstrations, major public events, holiday traffic peaks or other capacity overload (EC 2017).

Traditionally, the road operators carry out traffic management by providing information to humans who drive vehicles. With the shift towards providing information to software that drives the automated vehicle this will change significantly. These changes and the impact on the role and responsibilities of road operators were discussed recently in EU EIP 4.2 workshop in Utrecht. (EU EIP 2017)

The main conclusion was that a simple translation of the current messages to humans to messages for machines will not be adequate without rethinking the original purposes of the various traffic management measures. As complex as this may seem, traffic management in a mixed environment may be even more complex when road operators have to consider both (partially) automated vehicles and human driven vehicles. So when considering traffic management for automated vehicles, there are two main challenges: (EU EIP 2017)

- How will the nature of traffic management change when it is directed at automated vehicles?
- What is the transition strategy from the current situation to future situations that include mixed traffic?

Today the over-arching goals are 'no casualties, no congestion and no emissions'. The goals are not likely to change with the introduction of automated driving, but the procedures and methods are likely to change. The roles and responsibilities remain the same, and the road authorities and operators have to set the goals for traffic management. (EU EIP 2017)

Traffic Circulation Plans and Traffic Management Plans will need to be deployed differently in the future. Traffic management has to be seen as an integral part of overall mobility management. Automated vehicles should be supported only if they have positive impact on mobility (safety, environment) i.e. by facilitating new services (MaaS, shared mobility, DRT Public Transport). Traffic management has to be approached from collective perspective, but in best case the collective and individual goals (i.e. travel time from origin to destination, length of the trip) can be aligned. (EU EIP 2017; Kulmala et al. 2018a)

The transitory phase or mixed fleet situation is predicted to be very long. Therefore, the road authorities need to prepare their traffic management for a situation where some of the vehicles are automated and some are not. The instruments and processes have to be developed accordingly, to allow for both manual and automated driving. (EU EIP 2017)

The foreseen development of traffic management processes and methods will have an impact on public acceptance, transportation demand, other road users, interfaces with other transport modes, congestion and network planning. Bodies of traffic management need new systems and new skills, training and new equipment in order to build an efficient traffic management system for CAD, even with new business models.

Evolution of traffic management for automated vehicles

With the introduction of automated driving, new possibilities arise for the traffic management.

Before the trip, the driver could choose the parameters for the route from different variables such as duration, length, scenery and environmental impact, and willingness to use longer routes due to environmental reasons, or a possible reward. The automated vehicle would be directed to a shortest route or route with low occupation or with lower emissions, accordingly. (EC 2017)

It is assumed that for all automated vehicles the origin and destination are known, as this information is present in the vehicle when it commences the trip (the security and privacy issues have to be solved). Knowing the origin and destination is important to facilitate effective routing of the vehicles. (EC 2017)

Data on the origins and destinations as well as improved knowledge of the travel patterns of highly automated vehicles enable the identification of the limiting factors in the current transport system and city or community design. This can be used in new planning methods and in improving the efficiency of automated travel by 2030. New operation models for traffic management will build upon travel pattern insights to improve network efficiency. These models will define the monitoring and compliance requirements as well as routing protocols and their accompanying roles and responsibilities. Dynamic lane management systems and routing optimisation from digital twins are examples of the operational methods that will result in increased network efficiency. (Zencic 2019)

Opening up the discussion and cooperation between the industry and road authorities and operators is a must for securing the desired development of traffic management in the era of automation. The need for harmonisation of traffic management strategies and practises, both on a local and international level, would be beneficial, as well as the digitalisation of the traffic management plans into a standardized exchangeable data. This way the plans can be well communicated, understood and, when required, timely executed. (EC 2017)

The Traffic Managers should develop additional standards which: (EC 2017)

- enable the local policy for traffic management roles and responsibilities to be accessible on a national level;
- are interoperable and trusted for automated driving on a European level;
- combine with other standards under development such as the Traffic Management set of standards from the CEN WG on Urban ITS, METR (Management for Electronic Traffic Regulations), and LDM (Local Dynamic Map);
- will be investigated (standards and specifications) to become (eventually) mandatory or included within a Delegated Regulation.
- will foster cooperation between the different players and enable coopetition for the development of the common tools and building blocks.

It is time to start piloting digital traffic management plans, traffic circulation plans, and the building blocks listed in 5.3.1 on the comprehensive TEN-T Road Network, including urban nodes. Road authorities/operators should be in charge, acting as the 'orchestra conductor', being the only one to have a “global system” view of the road network and its performance, including safety. (EC 2017)

The most harmonised traffic management procedures take place in the motorway network, across borders, along the comprehensive TEN-T Corridors. The tools to develop the Cooperative Traffic Management Services will take stock of the TEN-T ITS Policy, its Regulations and the outcomes of the CEF ITS Corridors and the deployment of the C-ITS Pilots of C-Roads. (EC 2017)

Traffic management procedures can differ from small-medium sized cities to major urban nodes. They can even differ between two similar cities in the same country, depending on the city's strategic mobility. The complexity to operate and maintain ITS applications has implications on budget and resources. To ensure flexibility, the tools to develop the traffic management services for traffic including CAVs should be modular, scalable, replicable and compliant with standards.

The traffic management of automated vehicles can not overlook the ODD issue. Traffic managers need to be aware of the limitations of the highly automated vehicles operating in their networks so that they can prepare for the possible problems at road locations where the ODD of a number of highly automated vehicles will terminate due to static or dynamic conditions affecting the ODD. ODD-aware traffic managers can also provide information of likely ODD termination risks due to events, incidents, weather forecasts or other issues to the automated vehicles and their automated driving systems. Traffic management of the future may also contain ODD management as one functionality as proposed by Kawashima (2019). It can also involve specific real-time ODD service to maintain the real-time dynamic map of the highly automated vehicle as proposed by Park (2019).

5.4 Necessary infrastructure changes

In the field of road operation, maintenance and traffic management automation can certainly contribute to increase safety of operational workers as well as road users, improve traffic flow and optimize operational cost but only in combination with connectivity. The main conclusion on necessary infrastructure changes to improve O&M is therefore the need for integrated connectivity of operational vehicles and work-zones with a traffic management centre, equipped to inform automated and conventional vehicles in real time about such works. With such a traffic management, supported by automation and connectivity, smart routing of road users is just a logical next step. All this together will support the over-arching goals 'no casualties, no congestion and no emissions'. These goals will remain the same with the introduction of automated driving, but the procedures and methods will need to change as explained. The roles and responsibilities remain the same, and the road authorities and operators have to set the goals for traffic management. (EU EIP 2017)

Traditional highway O&M works (inspections, minor repairs, winter maintenance, incident management, etc.) necessary to reach the over-arching goals will also be crusial in the future. Nowadays they are carried out by operational workers who are always at risk by carrying out their work in an environment with high-speed traffic right next to them. Supporting them in the most critical operational tasks, like work zone protection on fast lane and winter maintenance, with automated driverless vehicles will take away main safety hazards. The good news are that such measures are not assumed to need amendments on the physical infrastructure but rather further development of the technological readiness of the systems and the according legal framework. However digital infrastructure enabling the positioning of the vehicles and according standardized, connected communication with the traffic management centre are key for the safe implementation.

Overall, the digital part of an operations management centre and the traffic management centre will need to merge and have integrated communication standards rather sooner than later. The role of the traffic management centre will become increasingly more important in an automated driving future to enable the NRAs to stay in control and to reach their policy goals.

To help public authorities play the role of the orchestra conductor and translate their mobility plans into 'standardized exchangeable data', the Enhanced Traffic Management WG of the C-ITS Platform conceptualized a specific set of important tools that need to be developed for digital traffic management plans: (EC 2017)

1. Classification of roads to be done accordingly to network flow hierarchy; not always the shortest path will be fastest, nor the safest.
2. Geo-fencing mechanism.
3. Establishing a network performance Level of Service (LoS).
4. Defining triggers to engage a cooperative traffic management.

In order to make the orchestration of cooperative traffic management services possible, there is a need to develop a Common Operational Picture (COP) to provide the involved actors with a standard overview and regional context of a traffic situation. The COP can play a major role for re-routing services, e.g., for identifying the need of any additional measures or, for facilitating extra traffic on alternative routes.

The complexity to operate and maintain ITS applications has implications on budget and resources. To ensure flexibility, the tools to develop the traffic management services for traffic including CAVs should be modular, scalable, replicable and compliant with standards.

Finally, future traffic management of automated vehicles can not overlook the ODD issue. Traffic managers need to be aware of the limitations of the highly automated vehicles operating in their networks so that they can prepare for the possible problems at road locations where the ODD of a number of highly automated vehicles will terminate due to static or dynamic conditions affecting the ODD. ODD-aware traffic managers can also provide information of likely ODD termination risks due to events, incidents, weather forecasts or other issues to the automated vehicles and their automated driving systems. Traffic management of the future may also contain ODD management as one functionality.

6 Consequences and recommendations

Recommendations for necessary changes and in case of anticipated potentially negative consequences, advice how to mitigate such consequences, are elaborated in this chapter. They are the summary of the many workshops, expert interviews, literature review and findings from ongoing projects. As this will also provide input to work-package 5, where the core research question of this project *"How will the current core business on operations & services, planning & building and ICT change in the future?"* to the extend it is possible with the current knowledge will be answered, the results are structured in accordance with the core business fields. The anticipated infrastructure impact in the previous chapters is transferred to provide candidate suggestions for making good use from technical and legal consequences for each NRA core business field (see Figure 2) together with recommendations for future time windows up until 2040.

6.1 Traffic management

Technical consequences and recommendations

The concept of cooperative traffic management needs to be fully developed and implemented building on the work carried out among other e.g. in the TM2.0 (2018), SOCRATES 2.0 (2018), and C-ITS Platform (EC 2017). Traffic management will become an integral part of overall mobility management. In an ecosystem enhanced by significant decarbonisation and privacy priorities together with high degrees of digitalisation, traffic management is anticipated to most probably by 2040 become closely integrated with fleet management, at least with regard to ODD management (also with e.g. minimum risk manoeuvres).

Technically, this means establishing real-time two-way connectivity between traffic management and vehicles. The traffic management centres and roadside systems and devices need to be connected to vehicles likely via fleet managers, Original Equipment Manufacturer (OEM) or service provider clouds. In addition, the connectivity should be used to share safety and traffic management related data. The latter will also include traffic rules and regulations as well as ODD-related data such as for example geofences due to or affecting ODD, or incidents, events or conditions affecting the ODD.

Specific access points to digital traffic rules and regulations (e.g. a Trusted Digital Regulations Access Point) and ODDs need likely to be set up to facilitate the cooperative traffic management in practice. High level data security is necessary for these access points. Dynamically evolving cybersecurity awareness and privacy concerns will shape this field of activity far beyond what has been standard now.

The traffic management systems have to be digitized, and the traffic circulation and traffic management plans need to be upgraded to take on board the mobility management and also ODD management aspects. Tools, such as geofencing, are adapted for deployment. Quite likely, the contents of these plans need to be evolving during the whole transition period from fully human-operated to a situation, where close to 100% of the vehicles are highly automated.

The digital traffic management systems will provide real-time information to HD maps and the local dynamic maps in the vehicles via the access points or also directly in specific cases such as e.g. road work zones.

Traffic management for events and incidents including short- and long-term road works should be enhanced and harmonised to maximise efficiency.

Standards need to be developed for the exchange of digital traffic rules, traffic management plans, and ODD management related data as well as the related access points, including the data security solutions. Further standards or similar are needed for the harmonised traffic management and marking of road work zones and incident sites.

Changes in legal framework

In order to reach the goals of 'no casualties, no congestion and no emissions' in the future, transport systems involving highly-automated vehicles with highly varying use cases, capabilities and ODDs determined by different OEMs and automated driving system providers, the status of the road authority and operator as the mobility and traffic manager of the road network needs to be ensured also legally. This means that traffic management plans and digital traffic regulations will be made legally binding to the operators of road vehicles and their automated driving systems. It also means that the vehicle manufactures, automated driving system providers, and fleet managers of highly automated vehicles are mandated to share safety, traffic management and ODD related data to the traffic managers of the networks, which they are using.

Recommendations for implementations of changes

Table 43. Recommendations for traffic management

Action	2021-25	2026-30	2031-40
Management of road works and incident sites	Fine—tuning of processes, proposal for harmonisation	Deployment pilots for harmonised management	Deployment and use
Digitalisation of TMCs	Deployment, including traffic circulation and traffic management plans	In use	In use
Cooperative TM concept	Studies and pilots	Deployments in key urban areas	Deployment and use
Digital traffic regulations	Studies, pilots, standardisation	Deployment; development and standardisation of TDRAP(s)	In use; deployment of TDRAP
ODD management	Research, agreement with OEMs and ADS providers	Studies, pilots, standardisation	Deployment and use, continuous adaptation with ODD evolution
Legal framework	NRA/RO role in traffic management	Mandate of complying to traffic management and circulation plans, and to share traffic management data	Mandate to comply to TDRAP

6.2 Road maintenance

Technical consequences and recommendations

In the field of road operation, maintenance and traffic management automation can certainly contribute to increase safety of operational workers as well as road users, improve traffic flow and optimize operational cost but only in combination with connectivity. The main conclusion on necessary infrastructure changes to improve O&M is therefore the need for integrated connectivity of operational vehicles and road maintenance work-zones with a traffic management centre equipped to inform automated and conventional vehicles in real time about such works. The infrastructural recommendations for road maintenance are therefore closely linked with the recommendations for traffic management in the previous chapter 6.1.

Traditional highway O&M works (inspections, minor repairs, winter maintenance, incident management, etc.) necessary to reach the over-arching goals will also be necessary in the future. Nowadays they are carried out by operational workers who are always at risk by carrying out their work in an environment with high-speed traffic right next to them. Supporting them in the most critical operational tasks, like work zone protection on fast lane and winter maintenance, with automated driverless vehicles will take away main safety hazards. The good news are that such measures are not assumed to need amendments on the physical infrastructure but rather further development of the technological readiness of the systems and the according legal framework. However digital infrastructure enabling the positioning of the vehicles and according standardized, connected communication with the traffic management centre are key for the safe implementation.

Road maintenance can also benefit from new condition data sources made possible through additional vehicle sensors and V2I communication. Various C-ITS projects tested and provided solutions for communication of condition data into vehicles. From a maintenance perspective the other communication direction – vehicles providing road condition data through V2I communication to the TMC – promise major improvements for predictive maintenance. Future ambitions should involve the collection of road condition data like cracks, rutting or skid resistance facilitating sensor technology of highly-automated vehicles through V2I communication. However so far it still remains unclear if CAV sensors will be suitable for the provision of condition data and how the legal barrier of providing such data can be crossed. In any case also road condition data as part of safety relevant data should be somehow made available to service and map providers to increase safety overall.

Overall the digital part of an operations management centre and the traffic management centre will need to merge and have integrated communication standards rather sooner than later.

Necessary changes of legal framework

Unmanned vehicles are legally not allowed on European roads. This also includes maintenance vehicles like safety trailers or mowing robots. While supporting automated functions are helpful in road maintenance, only driverless maintenance vehicles for safety critical tasks are able to provide the actual safety improvements for operational workers. Amendments to legislation are necessary to allow driverless safety trailers in particular on motorways where temporary maintenance works on the fast lane are one of the biggest safety hazard.

In terms of the potential for both-way data exchange on road condition legal provisions have to be made in-line with general data provision and data security legislation.

Recommendations for implementation of changes

Table 44. Recommendations for road maintenance

Action	2021-25	2026-30	2031-40
Integration of operations management center and traffic management center	Definition of data exchange and processes	Integrated processes and communication	Use
Connected road maintenance zones	Data exchange and definition of standardized processes for temporary maintenance zones	Integrated processes and communication	Use
Legal framework for specific use cases of driverless maintenance vehicles	Provision of legal framework for initial use cases like driverless safety trailers, mowing robots	Legal framework for additional use cases	Legal framework for driverless winter maintenance vehicles

6.3 Crisis management

Technical consequences and recommendations

This field is potentially fuelled by (among others) anticipated increases in severe weather conditions in Europe, as well as by increased expectations into adequate management and mitigation activities. Higher degrees of dependability on communication infrastructure add to the criticality.

Crisis management is closely linked to traffic management. This again is important in both directions: informing road users quickly through digital road signs and V2I communication about any crisis and using digital infrastructure of sensors, cameras and vehicles to make the traffic management centre aware of a new incident as quick as possible. Such new data sources can be utilized for even quicker reaction times.

Not just CAD but all new vehicles since 2018 need to be equipped with a so called eCall function which automatically dials Europe's single emergency number 112 in the event of a serious road accident and communicates the vehicle's location to the emergency services. (European Parliament 2015) This information needs to be provided also directly to the responsible traffic management centre to accelerate the crisis management.

The subject of crisis management is an important core business field of NRAs. However consequences to infrastructure through the introduction of CAD beyond the necessary communication as described are limited.

Necessary changes of legal framework

The term of “safety critical data” needs to be further defined and regulations provided accordingly to enable the secure sharing of such data in case of a crisis.

Recommendations for implementation of changes

Table 45. Recommendations for crisis management

Action	2021-25	2026-30	2031-40
Legal adaptations to enable data sharing of safety critical data	Further definitions and harmonization	Use	Use

6.4 Traffic information services

Technical consequences and recommendations

The role of traffic information is changing with the emergence of CAVs. During the last decades policy has relied on providing information on traffic conditions and problems on the road network to the driver and let the driver make the decisions based on. In an ecosystem of decarbonisation and a new EU green deal, there is a need to have traffic management system optimising the transport system at all times. This means that the traffic managers need to make decisions on behalf of the individual drivers and automated vehicles. As Martin Russ (2019) expressed it, “it is not enough to have a dashboard, we need a war room”. This is especially true in large cities and busy peri-urban road networks prone to incidents with considerable consequences to travellers and hauliers.

The role of traffic information is also changing due to its increasing importance to the transport system, because what was desirable for human drivers, is essential for highly automated vehicles (Sweatman 2019). Highly automated vehicles need to be aware of everything happening on the route ahead, also beyond their own sensors. Here CAVs with their sophisticated sensing systems are also part of the solution, providing high-quality information of the conditions, traffic status and incidents that they encounter while driving.

Hence, the quality of traffic information needs to improve from the levels of today. The EU EIP project with its predecessors has defined the quality attributes for traffic information and four quality levels for traffic information, with the “Basic” level to be reached by all EU member states, and the second level “Enhanced” already reached by some member states. The two highest levels are expected to be reached only with high penetration of connected vehicles. (Kulmala et al. 2018b)

Due to the fact that the CAVs will be part of the solution themselves, the quality of the traffic information will gradually improve with increased fleet penetration of connectivity and high-level automation. The prerequisite for the improvement is that the stakeholders involved – Drivers and OEMs governing the data created by their vehicles, service providers and road operators governing the data from their customers and own monitoring stations – are willing to share their data. This could follow from the Data for Road Safety initiative of the European Data Task Force having a 12-month trial of the concept of sharing vehicle originated road safety related data among the stakeholders involving member states, OEMs and service providers. (DTF 2019)

To ensure the quality of traffic information, stakeholders need to use appropriate quality assurance methods and processes. While this is a standard practice for commercial stakeholders, many road authorities and operators do not have such quality assurance in place.

In the future, the road users (drivers, automated vehicles, vulnerable road users) will receive information in addition to roadside variable and dynamic message signs also via their onboard devices. The latter can be devices embedded in the vehicle by the OEMs or aftermarket or nomadic devices attached to the dashboard of the vehicle. Unfortunately, today the OEMs, service providers and app developers use a large variety of pictograms and message content in presenting the information to the user of the device. Often the contents and pictogram differ considerably from that shown by the road operator. (Haspel 2019)

For the safety of the road users, it would be good to harmonise at least the pictograms used by the different stakeholders, but preferably the whole message content (Kamalski and Rytkönen 2015). This would require some time as the road signs and vehicles have a long life-cycle, although the apps and nomadic devices have much shorter ones. On one hand, if highly automated driving will take over, the pictograms will have a decreasing significance as harmonised pictograms are more important for human drivers than for automated driving systems capable of connecting a number of pictograms to the same type of message/warning. On the other hand, the use of pictograms may be misleading. The pictogram used to indicate slipper road used by in many road operators' signs is applied in some cars as indicators of the Electronic Stability Control, while the slipperiness of the road can be indicated by a snow flake pictogram used in some road operators' signs to indicate slipperiness but also snowing. Hence, the automated driving systems would also benefit from a harmonised, consistent use of the pictograms.

Security is also important for traffic information to avoid false alarms and otherwise to ensure road safety.

Changes in legal framework

While data sharing can be accomplished based on voluntary cooperation, specific mandating to share vehicle-based safety-related data is likely required. Traffic information is the key commodity for the business of especially some service providers. Such mandating could be carried out as updates of the current delegated regulations on safety-related traffic information SRTI (EC 2013) and real-time traffic information RTTI (EC 2014). These updates could also specify the minimum quality requirements for such data utilising the results of EU EIP and similar projects and initiatives. Mandating of key pictograms for road safety related warnings could be needed.

Recommendations for implementations of changes

Table 46. Recommendations for traffic information system

Action	2021-25	2026-30	2031-40
Enhancing traffic information content	Research on optimal, smart routing and guidance	Pilots in major cities and peri-urban networks	Deployment and use with continuous learning
Improving information quality	Development and take-up of quality assurance processses for traffic info	Deployment and use	In use
Sharing of data	Agreements between stakeholders, deployment of SRTI	Mandation of sharing of safety-related and TM related data	Deployment and use
Harmonisation of pictograms	Discussion and hopeful agreement between stakeholders	Standardisation of pictograms for warnings and info	Possible mandation of pictograms; Deployment and use

6.5 New roads planning & building

Technical consequences and recommendations

Differences of road networks between countries are obvious, the total road length and type of roads, their equipment, the traffic regulation, economic wellbeing, the weather conditions, and also the responsibilities of NRAs are manifold. However, new road construction and strategic development of necessary road networks has been done successfully throughout Europe in the past decades. This means that most countries have their necessary road network more or less in place, shifting the focus and monetary resources from new road construction to rehabilitation and maintenance of the existing roads. Unlike emerging cities and countries (e.g. Arab region) EU countries and their road networks are not newly designed on the drawing board providing the possibility for perfectly suitable infrastructure requirements.

It is crucial to consider this fact as the planning of new roads obviously needs to consider and make provisions for mixed traffic and CAD. These new roads however will only be a very minor network part on which CAD will be driving. Therefore it is even more important to define standards for rehabilitation and extensions of existing roads considering the necessary equipment. This way road networks will be upgraded step by step as part of the continual maintenance program.

Infrastructure support levels (ISAD) as developed in the project Inframix (Carreras et al. 2018) should be further defined to provide very clear guidelines for necessary digital and physical infrastructure a like. The ISAD levels are meant to describe road or highway sections rather than whole road networks. In order to structure the various means of support that infrastructure can provide towards automated vehicles, 5 levels are proposed which are based on the idea of the SAE levels for vehicle capabilities. It is important to put both pillars into the picture, ISAD and ODD requirements, to consider their interplay and mutual dependencies. New road planning in the future needs to involve the assessment of the new sections and dependent on their importance and segment a categorization in those ISAD level. The first pillar of new requirements for new road planning should result from those ISAD level requirements.

The second pillar results from the ODD requirements as described in this report. Dependent on the respective NRAs strategy and willingness to support and widen the ODDs of different use cases, these ODD requirements should be built into the design guidelines for new roads planning. Both ISAD level requirements and ODD requirements should be applied equally not only for new roads planning but also for rehabilitations.

As described earlier prioritization in terms of road types and relevant routes are crucial based on what NRAs can afford to do. However, new road construction makes the integration of digital infrastructure much easier compared to upgrades during rehabilitations of existing roads. NRAs are advised to use this opportunity and plan the digital infrastructure requirements defined as part of the ISAD levels as well as the ODD requirements.

Design guidelines considering all this will need to be developed for planning of new roads as well as for upgrades of existing ones. Some countries already started to develop such guidelines for infrastructure (e.g. U.S. DOT 2018b; Zencic 2019) but also admit that it is an ongoing approach also facing the challenges of limited, concrete exchange with CAD developers in terms of ODDs.

One element that would have a tremendous impact on new road planning standards but also budget is the decision whether or not dedicated lanes should be provided anywhere or for any use case. For obvious reasons it will be neither feasible nor possible to provide dedicated lanes everywhere. Design guidelines should therefore provide indications in which areas, road types, use cases and/or traffic volumes this could be a recommended solution.

Relevant for new roads planning will also be the shift of needs for stationary traffic. While needs for parking spaces will decrease over time, additional areas for deliveries of all kinds and sizes will increase. What bus stops are nowadays will need to be multi modal switching hubs in the future providing variable room for traffic mode switches.

One element of new road planning and construction is the application of the BIM (building information modelling) methodology to ensure the parallel development of a so called digital twin of the new road that includes all necessary design, material and operational data for each asset. This will also provide the basis for NRA's information exchange and provisions for HD maps.

Necessary changes of legal framework

The manifold European and local technical standards for road planning will need to undergo continuous assessments and updates in the coming years to make the according provisions for mixed traffic and CAD.

Recommendations for implementation of changes

Table 47. Recommendations for new roads planning & building

Action	2021-25	2026-30	2031-40
Road categorization ISAD levels also for digital and physical infrastructure	Further specification and official introduction of ISAD levels for digital and physical infrastructure	Consideration of vehicle sensor evolution in further development of infrastructure specifications. Annual review of new roads design guidelines	Consideration of vehicle sensor evolution in further development of infrastructure specifications. Annual review of new roads design guidelines
Provision of digital twin and digital data of new road	BIM approach and data structure to be clearly defined and applied already in planning of all new roads planning	Use	Use

6.6 Road works planning

Technical consequences and recommendations

Planned road works as part of routine maintenance works, rehabilitation or even new roads are not only core business of NRAs but also heavily affect traffic flow and road safety. Key policy goals of NRAs are maximum availability of their roads, smooth traffic flow and safe roads. It is evident that potential improvements of road works planning are of biggest interest for NRAs.

A huge potential for smoother traffic flow and increased safety around road works is a defined communication standard with traffic management. Starting with a network analysis to avoid conflicting road work zones in close vicinity the exact location, planned layout, duration and any other relevant technical information needs to be exchanged with the traffic management centre following a standardized process. During planning of road work zones – in particular in safety critical areas – cooperative connected safety trailers and temporary sensors should be considered to enable continuous live communication with the TMC. This way any changes to the road work zone layout, position of or incidents around the road work zone are communicated directly to the TMC and further on to the road users. Road works planning of the future therefore goes beyond picking right time slots and planning the local traffic management layout. The standardized information exchange on location and layout together with defined communication protocols have to be compulsory. Guidelines for necessary sensors in road work zones need to be developed and lane layouts, temporary marking and other guiding elements described in greater detail.

Furthermore road works planning as part of bigger rehabilitation works need to follow also the BIM approach as for new roads to provide NRAs with the necessary asset data sets required for HD maps.

Necessary changes of legal framework

No changes foreseen.

Recommendations for implementation of changes

Table 48. Recommendations for traffic management

Action	2021-25	2026-30	2031-40
Standardized communication protocols with TMC	Development of standardized communication protocols, work zone layouts and use of sensors.	In use	In use

6.7 Physical infrastructure

Technical consequences and recommendations

Physical infrastructure solutions are defined as measures or adaptations to the static road infrastructure where, in comparison to digital infrastructure, there is no (electronic) flow of data. However, there are many hybrid elements such as VMS that require both physical (e.g. poles, mountings) and digital (e.g. display, information) elements. As consequences of CAD and recommendations rather effect the digital part, these hybrid forms are allocated to the digital infrastructure. Technical consequences and recommendations in this section give a brief overview with details in the respective chapters 3 to 5 in this deliverable.

In particular consequences to the physical infrastructure are either due to new CAD use cases having an impact (e.g. truck platooning) or requirements that result from such new CAD use cases ODDs. In both cases NRAs are partly able to influence whether or not such use cases are going to be allowed on their networks and which adaptions are necessary. Physical infrastructure adaptions are very costly, need to be planned far ahead and are also heavily regulated in each country with technical standards. Amendments therefore need to be well thought through. The elements most affected are either the road guidance systems (signs, markings, etc.) which are crucial for the ODD of the selected CAD use cases or the more extensive elements related to the road geometry and structural adaptations.

If NRAs want to enable the potentially positive effects of CAD in terms of safety, traffic flow and such they are advised to make according provision so their infrastructure supports the ODD. Most required infrastructure support will be on the digital part (see chapter 6.9 and 6.10) and physical infrastructure amendments should be very carefully selected. In the most recent workshop on ODD related infrastructure requirements as part of the ITS world conference in

Singapore (Vreeswijk 2019) it has been agreed that it is necessary to try to limit the dependence on physical infrastructure because of the cost. It has been also agreed that the ODD has to be defined by CAD developers based on the technical capabilities that they have been able to verify.

This information unfortunately is still limited due to market competitiveness excuses of CAD developers. Therefore, the identified ODD requirements of the report are based on MANTRAs multi-stakeholder workshops and expert views. In any case prioritization in terms of road types and relevant routes are crucial based on what NRAs can afford to do. The evolution of the ODDs is driven by customer demand, and enabled by the improvement of vehicle sensors – for instance, sensors being able to deal with different kinds of weather conditions – and vehicle software – for instance, AI being able to deal with safe manoeuvring of the vehicle also in interaction with vulnerable road users in complicated urban environments. The technological development in the areas of sensors and software is currently very fast, and also hard to predict with any certainty. The overarching recommendation to NRAs is however to analyze their networks and prioritize where deployment of CAD use cases is most suitable and sensible. As a further step, design guidelines will need to be developed for planning of new roads as well as for upgrades of existing ones. Some countries already started to develop such guidelines for infrastructure (e.g. U.S. DOT 2018b; Zencic 2019) but also admit that it is an ongoing approach also facing the challenges of limited, concrete exchange with CAD developer in terms of ODDs.

Recommendations for changes to the physical infrastructure for those routes and road types where NRAs are willing to support the ODD provision Table 49 lists some recommendations for the physical infrastructure.

Necessary changes of legal framework

Physical infrastructure is regulated through manifold European and local technical standards. As explained CAD introduction will make it necessary to audit those standards and provide them with updates for road categories and routes where CAD are introduced. This includes structural bridge standards (where deployment of use cases of HCVs or truck platooning are foreseen) as well as harmonized standards throughout Europe for the machine-readability of the whole road guidance system. International/European standardization is deemed critical in terms of machine readability but not in terms of harmonized design of road markings and signs. However, NRAs shall not be held liable for the condition of road marking as this is subject to manifold factors ranging from maintenance to adverse weather. CADs therefore will need to be able to react accordingly if road markings and other guiding systems are suddenly not in accordance with their ODD requirements. A combination of physical and digital "guiding information" is expected, which will need to be regulated also legally in cases of discrepancies. (Expert workshop, Vienna, 10.09.2019)

Recommendations for implementation of changes

The following recommendations provide a summary of chapters 3 to 5 and are generalized throughout road types. In particular ODD requirements are specified in more detail for different road types in chapter 4.

Table 49. Recommendations for physical infrastructure

Action	2021-25	2026-30	2031-40
Uniform wear of pavement enabled by wheel path alteration in cross-section	Research on methods to alter horizontal lane positioning to ensure even wheel path distribution across lane; Research on safety aspects of "asymmetric driving"	Piloting; Negotiations, agreements with OEMs and ADS providers; Possible mandating	Take-up in all new highly automated vehicles
Pavement design and maintenance standards review and adaption	Studies are required to analyze rutting and fatigue potential in case of increasing unification of wheel paths. Empirical data collection on pilot project routes for truck platooning as a basis for pavement design and maintenance amendments	Pavement enforcements and increased maintenance budgets for routes with truck platooning, HCVs or car platooning with studs (Nordic countries)	Design and maintenance guidelines based on empirical data.
Pavement enforcement on truck platooning routes	Additional pavement maintenance provisions for truck platooning routes	Strengthening of pavements on truck platooning routes as part of necessary rehabilitations	Strengthening of pavements on truck platooning routes as part of necessary rehabilitations
Additional emergency bays, wide shoulders and safe harbours	Provision of safe harbours in pilot projects and evaluation of necessity. Safe refuges or shoulder areas similar to bus stops but long enough for freight vehicles with trailers every e.g. 500m on pilot sides.	Safe refuges or shoulder areas similar to bus stops in case of narrow shoulders at intervals identified during pilots and ahead of tunnels.	Safe refuges or shoulder areas similar to bus stops in case of narrow shoulders at intervals identified during pilots and ahead of tunnels.
Safe minimum risk manoeuvre specification considering also cases of very large AV fleets	Sharing of operational practices; Agreement with OEMs, ADS providers, NRAs and other ROs; Pilots and their evaluation	Establishment of cross-sector practices; Standardisation (if sufficient maturity); Take-up in development	Roll-out and use

Action	2021-25	2026-30	2031-40
Safe passenger pick-up and drop-off points for automated shuttles and robot taxis	Piloting of different solutions for different road environments (urban areas, highways, rural roads). Design specifications for passenger pick-up and drop-off points	Deployment in areas with relevant use cases (e.g. robot taxis, automated shuttles)	Deployment in areas with relevant use cases (e.g. robot taxis, automated shuttles)
General road design	New definitions in terms of visibility distance, inclinations, etc. to be defined based on findings in pilot projects.	Upgrade and amendment of general road design based on new standards during regular rehabilitation works.	Upgrade and amendment of general road design based on new standards during regular rehabilitation works.
Ramps and junctions	Use cases not to be expected on ramps already. Necessary provision for potentially lengthening and straightening ramps.	Ensuring visibility and long enough weaving sections for CAD.	Ensuring visibility and long enough weaving sections for CAD.
Road marking	Definition of standards for machine-readability. Pilot project sites with various types of road marking quality to increase knowledge. Enhanced maintenance on selected roads to ensure consistent and minimum quality of solid or dotted lines and symbols painted on the pavement	Mix of physical and digital information on road marking for which a clear rule set in case of discrepancies needs to be defined.	Mainly digital road guiding information, however road marking will still be required.

Action	2021-25	2026-30	2031-40
Road signs machine readability and digital twins	Implementation of TN-ITS standards to ensure digital replications of road signs. Permanent and temporary regulatory and traffic management signs in machine-readable quality to be implemented.	Ongoing deployment and maintenance of machine readable signs.	Potentially only temporary regulatory and traffic management signs in machine-readable quality, rest already provided digitally through V2I communication.
Road equipment	Additional gantries for VMS signs, lane control and other supporting digital infrastructure, and gates for separated lanes/areas to be installed on pilot project routes and crucial routes. Piloting of landmarks of different types on selected routes	Potentially slowly decreasing need for road equipment due to digital support. To be monitored on an ongoing basis. Coverage of selected routes with landmarks for positioning support	Potentially slowly decreasing need for road equipment due to digital support. To be monitored on an ongoing basis. Full coverage of main roads with landmarks

6.8 Enforcement

Technical consequences and recommendations

The whole area of enforcement will be heavily affected by digitization and connectivity in close relation with changes in traffic management. Besides the opportunities of improved cross-border and cross-entity cooperation provided by these developments some infrastructural amendments will also be necessary to support these opportunities. Enforcement is a broad field including enforcement of traffic regulations, weight/dimensions restrictions, environmental rules, road user charges, etc. The responsibility for the various types of enforcement are shared between NRAs, police and different public entities dependent on the road type (urban, motorway, etc.).

Focusing on infrastructure related consequences relevant for NRAs one particularly critical area identified in the expert workshop (Vienna, 10.09.2019) was the enforcement of allowed weights (and dimensions). With the potential of automated HCVs and truck platoons increasing loads on pavement and bridges an effective mean of weight enforcement becomes more critical than ever. The integration of weigh-in-motion (WIM) systems in the pavements and bridges with legally accurate measurements will allow for continuous measurements with less necessary infrastructural and personnel resources that are now required in designated weight control parking areas. Dimensions can be checked already now visually through toll cameras but legally those are not accurate enough as are the WIM systems.

The information exchange possible through V2I communication and connected traffic management would also provide for the potential of direct enforcement through the necessity of data provision from vehicles on their speed, weight, environmental category, etc. While this would potentially be desirable for NRAs and police, this subject is very sensitive in terms of privacy, data security and also market competitiveness. Trust building for safety critical traffic management will be more important than the outlook for an automated enforcement system in the near future.

The potential for forced vehicle stops or u-turns in case of violations through connectivity also provides new opportunities in the future which need to be integrated in digital and physical infrastructure standards.

Necessary changes of legal framework

The responsibility for the various types of enforcement (traffic regulations, weight, environmental, road user charges, etc.) are shared between NRAs, police and different public entities dependent on the road type (urban, motorway, etc.) and the enforcement type. Each EU country has their own slightly different split of responsibilities, so only general

Recommendations for implementation of changes

Table 50. Recommendations for enforcement

Action	2021-25	2026-30	2031-40
New infrastructure and regulations for traffic law enforcement	Connected speeding cameras providing necessary accuracy to be installed	Use	Use
Enforcement through weigh-in-motion systems	Tests of necessary accuracy of WIM systems and preparation of legal framework for enforcement	Direct V2I information of truck weights	Use
Environmental enforcement	Regulation of data exchange of environmental information of vehicles with infra for geofenced areas. Upgrade of CCTV for identification of environmental vehicle categories where necessary. Preparation of legal framework for enforcement.	Use	

6.9 ITS systems

This sub-chapter deals with the traditional ITS systems utilised by road authorities and operators, primarily systems deployed on the roads and in traffic management centres.

Technical consequences and recommendations

In an ecosystem of connected and highly-automated vehicles, the information and guidance currently provided via variable or static message signs can be replaced with data provided via cooperative ITS or other messages provided to the on-board systems in the vehicles. During the transition period, which can last to 2040 or even beyond, the human-operated, unconnected vehicles are also on the roads, and their drivers have to be considered. This means that at least all regulatory signs need to be maintained, while considerable number of human-operated unconnected vehicles use the roads. (RWS 2018)

The informative and route guidance signs, however, can gradually be abandoned. Likely this can be dealt with by not renewing the signs, when they had reached the end of their life-cycle.

In addition to variable and static message signs, the road operators have equipped their roads with roadside stations often in connection with monitoring systems (loop, radar and other traffic detectors, road weather sensors, cameras, etc.). The increasing penetration of connected vehicles will improve the possibilities of utilising the data from the connected vehicles and thereby obtaining monitoring data from the whole network instead of the cross-sections equipped with fixed monitoring systems. Despite this, the road operators should still maintain and install fixed monitoring stations. First, the fixed stations are needed for the use of forecasting and nowcasting the conditions on the road network. This has long been found important for road weather monitoring stations, but also for traffic monitoring stations (see e.g. Innamaa 2009). Second, it is not wise for the road operators to rely solely on other stakeholders to provide the data needed by road operators in their core business, but rather to also create and use their own data. (Sweatman 2019)

The future needs here are difficult to predict, and to mitigate impacts from this uncertainty, the road stations should not be rigid single-purpose components but should be adapted flexibly to meet the changing needs of the road operators. Hence, the traditional roadside stations at the end of their lifecycle should be replaced by flexible roadside stations that respond to current as well as future needs. (RWS 2018)

Highly automated driving makes the transport system increasingly reliant on digital and communication infrastructures, most of which require electric power to operate properly. Hence, solutions to mitigate the impacts of power black-outs need to be developed and deployed.

Changes in legal framework

No changes foreseen.

Recommendations for implementations of changes

Table 51. Recommendations for ITS systems

Action	2021-25	2026-30	2031-40
Removal of informative and route guidance road signs	Inventory of road signs to be potentially removed; Plan for removal in stages	Deployment of removal plan	Adaptation an deployment of removal plan
Flexible roadside stations	Piloting and specifications for flexible roadside stations	Replacement of existing limited purpose stations with flexible ones	Replacement of existing limited purpose stations with flexible ones

6.10 Digital infrastructure

The changes in traffic management and information systems including the provision of event and incident data and information as well as traffic rules and regulations have already been dealt with in previous parts of this chapter. Hence, this sub-chapter deals with the other parts of the digital infrastructure such as high-definition maps, satellite positioning, communication infrastructure, and fleet supervision centres.

Technical consequences and recommendations

The consequences for HD maps have been described in detail by the DIRIZON project (Malone, et al. 2019). The road operators are expected to provide data for the HD maps to road map and service providers directly or via national access points. The profiles, formats, structures and procedures needed to handle data streams are to be specified and tested in agreement with other stakeholders, and especially the HD map providers.

The road network data will need to be digitized including the any landmarks supporting accurate vehicle positioning. This will be carried out by HD map providers, but also road authorities and road operators may want to have it done for themselves as HD maps of the roads and their (sub-)structures can be regarded as a key asset of the road operators with regard to their core business. Outsourcing such a key asset to external service providers will carry considerable risks. By 2040, the feedback loops for maintaining data quality have been established, the digital traffic rules are included, the HD maps localization quality has been reached, most of the physical and digital infrastructure elements have been digitised and are available to HD maps, and HD digital map achieves the data quality levels required for the decision-making process in a CAV(Malone et al. 2019)

Specific attention needs to be given to including ODD attribute related data in the HD digital maps especially for physical infrastructure attributes, which may not be provided by the road operators throughout the road network due to their high costs. Examples of such are, for instance, wide shoulders, safe harbours and game fences. The availability and location of such attributes is essential for the highly automated vehicles in order to determine the existence of their ODD.

Highly automated vehicles utilise several independent positioning methods such as satellite positioning and inertial positioning, mobile phone network positioning as well as car sensors and HD map positioning (Koskinen et al. 2018). Satellite positioning is the basic positioning solution, and it has been shown to reach the desired 5 cm accuracy when supported by RTK (Real Time Kinetics) land stations. Such or similar stations should be provided especially in challenging environments such as northern latitudes and mountainous areas. They could also be integrated with the communication infrastructure.

Communication is developing fast and will likely do so during the next decades as well. The basic communication types will most likely still be vehicle to vehicle short range, vehicle to infrastructure short range, and vehicle to infrastructure medium/long range. The last mentioned will likely be provided via cellular networks, but the short range V2I communications will need communication beacons beside or over the road, connected to different servers (road operators, vehicle manufacturers, service providers, fleet managers, etc.) via trunk communications such as fibre optic cabling. Road authorities and operators benefiting from the connectivity can invest in the trunk communication and road side communication station investments in cases, where such investments are not made by other stakeholders due to their customer needs.

Remote operation centres to monitor and supervise fleets of automated vehicles are needed by several use cases of highly automated driving, if not all of them. As the fleets will mostly belong to other stakeholders, the implementation, operation and maintenance of such centres will be the responsibility of these other stakeholders. Some national road authorities and many road operators deal with the operational maintenance and winter maintenance of their road networks. Thereby, those road authorities and operations need to set up their fleet supervision centres.

Other elements than those mentioned above could be regarded as part of the digital infrastructure for automated vehicles or at least the management of the transport system for highly automated vehicles. Yeo (2019) has presented a concept of digital infrastructure, which contains the process for infrastructure management and diagnostics – prognostics – optimization. The Korean example presented by him includes the following components:

- data hub with Internet of Things
- AI based facility diagnostics
- big data based prognostics
- BIM/GIIS 3D virtual city
- urban simulation system
- optimal urban control

In Europe, most components would be regarded as part of traffic management and data analytics. Nevertheless, the concept of virtual transport system or a digital twin of the transport system as an element of the digital infrastructure could be very valuable. This would allow to use the digital twin in traffic management to simulate the impacts of various traffic management measures to identify the optimal measure in real time, or in fleet management to simulate the impacts of various route alternatives to specific vehicles or transports to choose the best ones, for instance. Hence, the realisation of virtual road networks and transport systems and the development and use of real-time simulation models for them would likely benefit the road operators and traffic managers.

Changes in legal framework

There is likely a need for a mandate for road operators to make their existing data available for HD road map purposes. There could also be a need for the OEMs and fleet managers to provide feedback about the anomalies in HD maps detected by their vehicle fleets. The increasing provision of digital infrastructures to ensure the ODD for automated vehicles will likely also result in increasing number and importance of product liability issues.

Recommendations for implementations of changes

Table 52. Recommendations for Digital infrastructure

Action	2021-25	2026-30	2031-40
HD map processes	Agreement of the processes; Specification and setting up of NAPs	Deployment and use of the processes	In use
Provision of data to HD maps	Data from existing digital road maps of the road operators made available to service providers including map providers	Digitalisation of the TEN-T road network in required content and quality, including landmarks for positioning support	Digitalisation of all public road networks
Maintenance of HD maps	Pilots on continuous update based on feedback from sensing systems in CAVs	Deployment of updating process	In use
RTK or corresponding land stations	Deployment along selected roads	Deployment along TEN-T core corridors	Deployment along TEN-T networks
Trunk communications for short range and longer range V2I	Deployment on selected corridors and all new main roads	Deployment along core TEN-T corridors	Deployment along TEN-T networks
Roadside stations for short range V2I	Deployment on selected corridors and hot spots	Deployment in hot spots and sections along core TEN-T	Deployment in hot spots and sections along TEN-T roads
Road operator fleet supervision centres	Research and limited pilots	Deployment and use for relevant vehicles	Deployment and use for relevant vehicles
Use of digital twins for the (road) transport system	Pilots of digital twins; Development and piloting of related real-time simulation models	Deployment and use	Adaptation and use
Mandate to provide existing data to HD Maps	Preparation and adoption	Deployment	In use
Mandate for fleet managers & OEMs to provide feedback on HD maps	Discussion and preparation	Adoption	Deployment and use
Product liability issues for digital infrastructure	Research, studies, preparation in pilot contexts	Solutions case by case by front runners	Solutions case by case, based on earlier ones

6.11 Road user charging

This sub-chapter deals with different aspects of road user charging services in relation to transport automation and specifically to automated vehicles.

General framework

In many countries privately financed and operated motorways form, based on long-term concessions, an essential part of the national highway network, while in other countries the networks are fully under control of the national road authorities. As automated vehicles may require additional investments in the tolling systems, legal measures may be needed regarding the concession agreements.

Road user charges on the European road network, urban and interurban motorways, major and minor roads, and various structures, such as tunnels or bridges, and ferries, are ruled by the EU Directive 2019/520 (European Parliament 2019b) on the interoperability of electronic road toll systems (EETS – European Electronic Toll Service). The Directive, and the Implementing and Delegated Acts based on the Directive, also rules concerning the allowed technologies of the tolling systems. Electronic road toll systems, which require the installation or use of on-board equipment shall, for carrying out electronic toll transactions, use one or more of the following technologies: a) satellite positioning (GNSS), b) mobile communications or c) 5,8 GHz microwave technology (DSRC). The Directive does not apply to a) road toll systems which are not electronic or b) small, strictly local road toll systems.

Most of the tolling systems are still based on DSRC, but there are already some extensive GNSS based systems and there is a clear trend towards those. Furthermore, some automatic licence number recognition based toll systems exist and this technology is frequently used for enforcement of road user charges both in DSRC- and GNSS-based systems.

The Directive also provides for an open tolling market in the sense that the toll charger role and the payment service provider role are separated. On the European level, EETS Service Providers (ESPs) can be accredited and may then provide tolling payment services all over Europe. This is already emerging.

Technical consequences and recommendations

In GNSS based systems there exist only virtual toll plazas, if any. Consequently, properly equipped automated vehicles can behave as traditional vehicles in these systems (e.g. German and Belgian HGV charging systems).

Modern DSRC tolling systems are based the “multi-lane free-flow” principle. In these systems properly equipped automated vehicles can also behave as traditional ones.

However, there are still quite many older toll systems in Europe that are based on large toll plazas with barriers providing the enforcement. These systems often provide for many payment options such as cash, card or DSRC, often on separate lanes. At these toll plazas physical rearrangements may be required to provide for smooth tolling of automated vehicles. In some cases, free flow lanes might already have been added for DSRC users, to which automated vehicles can be guided.

As driverless freight vehicles hardly can pay tolls manually at toll plazas, they require an automatic payment lane. In very many cases such lanes exist. They may be channelized 1-lane passages or often even so called “free flow multilane” solutions within the standard road cross-section. Commercial driverless vehicles performing taxi services often drive empty and require as well an automatic payment lane.

Driverless maintenance vehicles are considered a) not to do maintenance on toll plazas b) not to pay tolls.

In the case of narrow single lane toll passages with manual or card payment, some investments are required to enable the toll plaza to be included in the ODD. These investments may in the case of concession road networks require complicated negotiations regarding the stipulations in the concession agreement.

Hence, changes in the physical infrastructure are only required on roads with traditional toll plazas. At the toll plaza area approaches, gates and exits, standardised markings should be used to indicate to mark the routes and lanes to be used by highly automated vehicles. Automatic payment lanes need to be included in the toll plaza setup.

Concerning the digital infrastructure, the road charge information needs to be a part of the dynamic layer of the HD map, for instance in the rules and regulations part.

Changes in legal framework

In cases, where changes are to be made to the toll plazas and their approaches or exits, contractual negotiations between the concessionaires and national road operators are likely necessary. These might result also in tariff changes.

Recommendations for implementations of changes

Table 53. Recommendations for road user charging

Action	2021-25	2026-30	2031-40
Marking of toll plazas for highly automated vehicles	Development and agreement of standardised markings and guidance	Deployment of standardised markings and guidance	Use
Inclusion of road use charges into HD maps	Specifications: development and agreement concerning dynamic charging	Deployment and use	Use

6.12 New core businesses

CAD has enormous change potential. Significant cornerstones in the road transport ecosystem will be blending with a broader IOT and AI ecosystems. Obviously this also means potentially new core businesses for NRAs. MANTRA's results form some of the building blocks and starting points for discussion and agreement of new NRA roles and views related to automation of road vehicles and network operation, especially with regard to the core business of NRAs. The results concerning the changing and new core business and roles of NRAs and road operators in general are dealt with in the final deliverable of work-package 5.

In general new core businesses will not so much relate to infrastructure provision but rather shift the focus to an even more service provider oriented business model for NRAs. Furthermore, the service ecosystem will extend and grow with much more interaction between market players and higher investments. In order to secure the investments, a licence based business model might be an option at least for some period of time as has been done in the tolling and telecommunications businesses.

The following is an initial non exhaustive list of candidate options:

- Service provider for some elements in a broader mobility-as-a-service ecosystem, when mobility and quality of life are kind of blended in a technology (hands free) where travel time or road based transport is not seen as mainly unproductive time between two destinations. Proactively managing customer expectations and societal expectations in road transport might add to this new core role
- Service provider integrating (and potentially mitigating) a potentially increasing number of services and non-traditional vehicle concepts and services
- Service provider to mitigate issues of a highly fragmented communication network reality in Europe (e.g. mitigate end of network / end of high quality communication infrastructure impacts, including expectation management)
- Service provider in terms of validating quality of service in communication infrastructure and map infrastructure
- Entire new roles in a freight automation context with entirely new forms of vehicles in terms of length and behaviour – also taken up proactively to mitigate risks of alternative service providers impacting road operators' core processes.
- Service provider for populations that even in 2040 prefer driving manually with specific vehicles
- Service provider for a more dynamic parking management

7 Conclusion

This report compiles recommendations for NRAs on the expected impact of highly automated driving and the respective necessary changes to physical and digital infrastructure that can support cooperative, connected and automated road traffic. The work was carried out as part of the CEDR project MANTRA, which set out to provide a guideline to NRAs how their core business will be affected by connectivity and automation.

Introducing connected and automated mobility on public roads is expected to effectively address several traffic safety, efficiency and environmental problems. While the expected impacts to infrastructure are manifold those resulting from the need to provide the required Operational Design Domain (ODD to ensure safe deployment for those automated functions considered as potentially soon available were identified as most pressing. The identified impacts obviously only reflect the recommended actions in order to enlarge the automated vehicle's ODD coverage as far as economically feasible.

Most of the changes in the road infrastructures are motivated by the proactive need to ensure the ODD for highly automated vehicles contributes positively to transport policy goals of the national road authorities and road operators. There are some inherent difficulties in supporting the ODDs as they depend on the capabilities of the sensors and software including AI of the automated vehicles, and these capabilities are improving quite quickly with the evolution of related technologies.

Kulmala et al. (2018a) produced a list of ODD attributes relevant to the road operators and this was used by MANTRA. This report indicates that the list should be complemented with three new items of traffic management, infrastructure maintenance, and fleet supervision (centres). All three are elements, which affect the management and realisation of the ODDs but are not direct ODD requirements. We also consider the adding of virtual road network or the network's digital twin as a candidate for an ODD attribute, which supports the management and supervision of highly automated vehicles as a basic element for real-time simulation to assist in the choices of the traffic and fleet managers of the automated vehicles. All of the four new attributes relate to digital infrastructure and are dynamic in nature. The updated ODD list proposed is presented in

Table 54.

Table 54. Road operator related ODD attributes

ODD attribute	Physical / Digital infra-structure	Static / Dynamic
Road	Physical	Static
Speed range	Physical	Static
Shoulder or kerb	Physical	Static
Road markings	Physical	Static
Traffic signs	Physical	Static
Road equipment	Physical	Static
Traffic	-	Dynamic
Time incl. light conditions	-	Dynamic
Weather conditions	-	Dynamic
HD map	Digital	Static/Dynamic
Satellite positioning	Digital	Static
Communication	Digital	Static
Information system	Digital	Static
Traffic management	Digital	Dynamic
Infrastructure maintenance	Physical/Digital	Dynamic
Fleet supervision	Digital	Dynamic
Digital twin of road network	Digital	Dynamic

As this report looked specifically at consequences to infrastructure, ______________________

Table 55 and Table 56 detail the attributes of the physical and digital infrastructure related to connected and highly automated vehicles.

Table 55. List of physical infrastructure attributes relevant for CAD

Physical infrastructure attributes		
Infrastructure attribute	**Sub-attributes**	**Comment**
Road	Road type	Basic road types such as motorway, highway, street, private road indicate separation of carriageways, intersection arrangements, types of road users etc.
	Special road sections	Additional requirements for critical road sections such as tunnels, bridges, toll plazas etc.
	Separation of automated vehicles	Dedicated lanes or areas; permanent or temporary such as night time only
	Pavement of road	Ease of detection of the roadway
Speed range	Speed limit or recommendation	The speeds in which the automated driving system has been designed to function. Either static or dynamic speed limits/recommendations. Dynamic ones relate to traffic management
Shoulder or kerb	Wide shoulder	possibility to use as “safe harbour” if ODD ends
	Lay-bys or parking areas	as above
	Passenger pick-up/drop off areas	necessary for automated shuttles and robotaxis
Road markings	Existence of lane markings	lateral positioning
	Visibility, machine-readability	visibility to vehicle sensors
	Markings indicating use by automated vehicles	indicating of right to use or prohibition of use by highly automated vehicles
Traffic signs	Visibility, machine-readability	visibility to vehicle sensors
	Signs indicating use by automated vehicles	indicating of right to use or prohibition of use by highly automated vehicles
Road equipment	Landmarks	Static physical landmarks possible equipped by sensor reflectors or radio beacons or similar to support accurate positioning
	Gantries for road signs	indicating of right to use or prohibition of use by highly automated vehicles
	Gates and barriers	Access to dedicated lanes, roads or areas
	Road lighting	Support to automated vehicle’s vision system
Infrastructure maintenance	Winter maintenance (snow removal, de-icing)	Visibility of road markings and traffic signs in adverse weather conditions
	Road maintenance incl. road marking painting, clearing of vegetation	Quality and visibility of road markings and traffic signs
	Inspections of infrastructure	Inspections according to standardised test/inspection protocols for both physical and digital infrastructure

Table 56. List of digital infrastructure attributes relevant for CAD

Digital infrastructure attributes		
Infrastructure attribute	**Sub-attributes**	**Comment**
Communication	Short-range V2I	Communication at hot spots and road sections
	Medium and long-range V2I	Communications over road networks and corridors
	Medium and long-range V2I with low latency and wide bandwidth	Communications facilitating remote supervision of vehicles
Satellite positioning	Land stations	Improving accuracy of positioning in challenging areas
	Positioning support in tunnels	GPS repeaters or other solutions to provide accurate positioning also in tunnels
HD map	Maps of road environment including landmarks for camera, radar, and ultrasound sensors	Accurate positioning of the vehicle in the transport system, road and lane
	Maps of road environment including landmarks for LIDAR sensors	Accurate positioning of the vehicle in the transport system, road and lane
Information system (digital layer of the HD map)	Real-time event, roadworks, incident & other disturbances	Providing extended horizon beyond sensor range
	Digital traffic rules and regulations	Proving permanent and temporary rules of operation
	Geofencing information	Informing of access to specific roads, networks, and areas and/or right of use of specific automated driving use case
	Availability of physical infrastructure	Real-time information of the availability and usability of the physical infrastructure required for ODD
Traffic performance status on road network	Traffic status on network	Provides the transport system real-time traffic status information to the HD map
	Real time digital twin of the network managed including traffic flows	Enables simulation, modelling and testing of different traffic management measures in order to select optimal measure for vehicle flows including also CAVs
Traffic management	Road works management	Standardised markings and processes to maintain ODD
	Incident management	Standardised markings and processes to maintain ODD
	ODD management	Management of factors affecting the ODDs of vehicles using the roads
	Traffic management centre and processes	Adaptation of the centres and processes to consider special requirements from automated vehicles and mixed fleets
Fleet supervision	Fleet monitoring and supervision centres	Remote monitoring and supervision of fleets, likely necessary for shuttles, robotaxis, roadwork trailers, maintenance vehicles

The physical and digital infrastructure are closely connected. For instance in the case of road markings and traffic signs the automated vehicles benefit from a ”hybrid” combination of both the physical markings and signs as well as their digital twins in HD maps.

Looking at the unit costs of the various infrastructure changes proposed, the largest costs per road km are due to

- provision of safe harbours (in case of ODD termination)
- signs and barriers for access control (in the special cases where needed)
- adaptation of traffic centres and systems
- up-to-date HD maps
- trunk communications with fibre optics cabling
- game fences alongside roads

The biggest changes will, however, take place in the digital infrastructure required by highly automated vehicles. Many of the changes are related to digitalisation in general and would happen due to the requirements of also other road operator core activities. For instance, the communication infrastructure is needed just for connectivity purposes even without automation to facilitate C-ITS, OEM servicing, and infotainment services. Yet, connectivity also makes highly automated vehicles much better in terms of safety, efficiency and cleanness.

Finally, it should be noted that the results reflect the knowledge of the likely function and ODDs of highly automated vehicles at the time of writing at the end of 2019. It is likely that technology, market and policy developments will change the importance, benefits and costs of the individual changes in the physical and digital road infrastructure considerably until 2040.

8 Sources

Abe, Katsuya (2019): The role of government for deploying connected and automated vehicle in Japan. Session AP04 - Automated driving of snowplows. 26th ITS World Conference 23.10.2019. Ministry of Land, Infrastructure, Transport and Tourism, Japan. Singapore, 2019.

ACEA (2019): High Capacity Transport. Smart policies for smart transport solutions. Available online at https://www.acea.be/uploads/publications/ACEA_Paper-High_Capacity_Transport.pdf, accessed on 1/17/2020.

Aigner, Walter; Kulmala, Risto; Ulrich, Sandra (2019): Vehicle fleet penetrations and ODD coverage of NRA-relevant automation functions up to 2040. MANTRA: Making full use of Automation for National Transport and Road Authorities – NRA Core Business, Deliverable 2.1.

Alonso Raposo, Maria; Ciuffo, Biagio; Makridis, Michalis; Thiel, Christian (2017): The r-evolution of driving: from Connected Vehicles to Coordinated Automated Road Transport (C-ART), Part I: Framework for a safe & efficient Coordinated Automated Road Transport (C-ART) system, EUR 28575 EN, doi:10.2760/225671. Available online at https://publications.jrc.ec.europa.eu/repository/bitstream/JRC106565/art_science_for_policy_report_1-soa_final_tobepublished_online.pdf, accessed on 1/17/2020.

Arabzadeh, Ali; Notani, Mohammad Ali; Zadeh, Ayoub Kazemian; Nahvi, Ali; Sassani, Alireza; Ceylan, Halil (2019): Electrically conductive asphalt concrete: An alternative for automating the winter maintenance operations of transportation infrastructure. In *Composites Part B: Engineering*, p. 106985. DOI: 10.1016/j.compositesb.2019.106985.

Avenue21 (2019): Avenue21 Project. future.lab, TU Wien. Edited by Daimler und Benz Stiftung. Available online at http://avenue21.city/, accessed on 1/17/2020.

Bergenheim, Carl; Shladover, Steven; Coelingh, Eric (2012): Overview of platooning systems. Proceedings of the 19th ITS World Congress, Oct 22-26, Vienna, Austria 2012.

Bladescanner (2019): RISKMON Anlageninspektion und Risk-Monitoring mit Hochleistungsdrohnen und Sensorik. Mobilität der Zukunft 2016. Available online at https://www2.ffg.at/verkehr/projekte.php?id=1538&lang=de&browse=programm, accessed on 1/17/2020.

Brandt, Andrea; Jentzsch, Gregor; Pradka, Alexander (2019): EDDI - Electronic Drawbar - Digital Innovation. Project report - presentation of the results. Available online at https://www.deutschebahn.com/resource/blob/4136372/d08df4c3b97b7f8794f91e47e86b71a3/Platooning_EDDI_Project-report_10052019-data.pdf, accessed on 1/17/2020.

Brockfeld, Elmar; Lorkowski, Stefan; Mieth, Peter; Wagner, Peter (2007): Benefits and limits of recent floating car data technology - an evaluation study. 11th World Conference on Transport Research. C2-830. Available online at https://www.researchgate.net/publication/224987136_Benefits_and_limits_of_recent_floating_car_data_technology_-_an_evaluation_study, accessed on 1/17/2020.

Carlson, Paul & Brown, Les (2019): Impacts of Automated Vehicles (AVs) on Highway Infrastructure. Slides for the Session at Automated Vehicles Symposium, 18.07.2019. Orlando, Florida, 2019.

CARMERA (2019): CARMERA Autonomous Map. Available online at www.carmera.com, accessed on 1/17/2020.

Carreras, Anna; Daura, Xavier; Erhart, Jacqueline; Ruehrup, Stefan (2018): Road infrastructure support levels for automated driving. Session EU-TP1488, 17-21 September 2018. 25th ITS World Congress, Copenhagen, Denmark, 2018.

CEDR (Ed.) (2018): National Road Authority CAD strategy 2018-28. Connected and Automated Driving Working Group. Available online at http://www.cedr.eu/download/Publications/2018/NRA-CAD-strategy-2018-final-v2.doc, accessed on 1/17/2020.

C-Roads (Ed.) (2019): Harmonised C-ITS Specifications for Europe - Release 1.4. Available online at https://www.c-roads.eu/fileadmin/user_upload/media/Dokumente/Harmonised_specs_text.pdf, accessed on 1/17/2020.

Czarnecki, Krzysztof (2018): Operational Design Domain for Automated Driving Systems - Taxonomy of Basic Terms.

Dreher, Stephane (2019): Roles and implementations of content standards and data exchange for AV on the Public Sector side in EU. Presentation made at the “Automated Vehicle (AV) DATA – Show has it? Who wants it? What format?”. Session at Automated Vehicles Symposium 2019, Orlando, Florida. 16 July 2019.

DTF (Ed.) (2019): Data for Road Safety. European Data Task Force. Available online at https://www.dataforroadsafety.eu/, accessed on 1/17/2020.

Dutch Ministry of Infrastructure and the Environment (Ed.) (2016): European Truck Platooning Challenge 2016. Available online at https://eutruckplatooning.com/Support/Booklet+Lessons+Learnt/handlerdownloadfiles.ashx?idnv=529927, accessed on 1/17/2020.

EC (2013): Commission Delegated Regulation (EU) No 886/2013 supplementing Directive 2010/40/EU of the European Parliament and of the Council with regard to data and procedures for the provision, where possible, of road safety-related minimum universal traffic information free of charge to users. No 886/2013. In *Official Journal of the European Union L 247/6-10,*. Available online at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32013R0886&from=EN, accessed on 1/17/2020.

EC (2015): Commission Delegated Regulation (EU) No 2015/962 supplementing Directive 2010/40/EU of the European Parliament and of the Council with regard to the provision of EU-wide real-time traffic information services. No 962/2015. In *Official Journal of the European Union L 157/21-31,*. Available online at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32015R0962&from=EN, accessed on 1/17/2020.

EC (2016): Commission Communication (2016) A European strategy on Cooperative Intelligent Transport Systems, a milestone towards cooperative, connected and automated mobility. Available online at https://ec.europa.eu/energy/sites/ener/files/documents/1_en_act_part1_v5.pdf, accessed on 1/17/2020.

EC (2017): C-ITS Platform Final report Phase II. Cooperative Intelligent Transport Systems Towards Cooperative, Connected and Automated Mobility. Available online at https://ec.europa.eu/transport/sites/transport/files/2017-09-c-its-platform-final-report.pdf, accessed on 1/17/2020.

EC (2018): Commission Communication (2018) On the road to automated mobility: An EU strategy for mobility of the future. Available online at https://ec.europa.eu/transport/sites/transport/files/3rd-mobility-pack/com20180283_en.pdf, accessed on 1/17/2020.

EC (2019): Delegated Act on C-ITS, intended to supplementing Directive 2010/40/EU of the European Parliament and of the Council with regard to the deployment and operational use of cooperative intelligent transport systems. Available online at http://www.europarl.europa.eu/cmsdata/161226/Delegated%20Regulation%20C-ITS.pdf, accessed on 1/17/2020.

ERTRAC (Ed.) (2017): Automated Driving Roadmap. Version 7.0. Working Group "Connectivity and Automated Driving". Available online at https://www.ertrac.org/index.php?page=ertrac-roadmap, accessed on 1/24/2020.

ERTRAC (Ed.) (2019): Connected Automated Driving Roadmap. ERTRAC Working Group "Connectivity and Automated Driving". Available online at https://www.ertrac.org/uploads/documentsearch/id57/ERTRAC-CAD-Roadmap-2019.pdf, accessed on 1/17/2019.

EU EIP (2017): Workshop report (15–16 March 2017, Utrecht): Facilitating Connected & Automated Driving – a Road Operator's Perspective. Version: 1.0 30.6. 2017, EU EIP.

European Parliament (1996): Directive 96/53/EC of 25 July 1996 laying down for certain road vehicles circulating within the Community the maximum authorized dimensions in national and international traffic and the maximum authorized weights in international traffic. Directive 96/53/EC, accessed on 8/17/2019.

European Parliament (2004): Directive (EU) 2004/54/EC on minimum safety requirements for tunnels in the Trans-European Road Network, accessed on 7/26/2019.

European Parliament (2015): Directive 2015/758 of the European Parliament and of the council of 29 April 2015 concerning type-approval requirements for the deployment of the eCall in-vehicle system based on the 112 service and amending Directive 2007/ 46/ EC, accessed on 11/28/2019.

European Parliament (2019a): Directive (EU) 2019/1936 of the European Parliament and of the Council of 23 October 2019 amending Directive 2008/96/EC on road infrastructure safety management, accessed on 2/20/2020.

European Parliament (2019b): Directive (EU) 2019/520 of the European Parliament and of the council of 19 March 2019 on the interoperability of electronic road toll systems and facilitating cross-border exchange of information on the failure to pay road fees in the Union. EU Directive 2019/520, accessed on 8/17/2019.

Eurostat, European Comission (Ed.) (2007): Illustrated Glossary for Transport Statistics, 4th edition.

Finnra (Ed.) (2007): Aitojen suunnittelu [Planning of Fences]. Tiehallinto [Finnish National Road Adminsitration]. 9.1.2007. [In Finnish].

Haspel, Ulrich (2019): C2SBA und C2NBA. Aktueller Stand und Planungen. Bayerische Staatsbauverwaltung, Zentralstelle Verkehrsmanagement.

HERE (2019): HERE HD Live Map. Available online at https://www.here.com/products/automotive/hd-maps, accessed on 1/17/2020.

Highways England (Ed.) (2018): Annual Report and Accounts 2017-2018. Available online at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/727819/GFD17_0045_Annual_report_V15-3_-_web_.pdf, accessed on 1/17/2020.

House of Commons, Transport Committee, UK (Ed.) (2016): All lane running, Second report of session 2016-17.

Innamaa, Satu (2009): Short-Term Prediction of Traffic Flow Status for Online Driver Information. Espoo 2009. VTT Publications 708. Available online at http://lib.tkk.fi/Diss/2009/isbn9789513873417/isbn9789513873417.pdf, accessed on 1/17/2020.

Irzik, Marco; Kranz, Thomas; et al. (2016): Feldversuch mit Lang-LKW . Edited by Bundesanstalt für Straßenwesen. Available online at https://www.bast.de/BASt_2017/DE/Verkehrstechnik/Fachthemen/v1-lang-lkw/v-lang-lkw-abschluss.pdf;jsessionid=6834392FBA85215F777156CB29D8EDE4.live11293?__blob=publicationFile&v=3, accessed on 1/17/2020.

Kamalski, Theo; Rytkönen, Mika (2015): iMobility Forum SafeAPP WG. Presentation at the iMobility Forum Steering Group Meeting. ERTICO, 19/11/2015. 13 p.

Karjalainen, Matti (2011): Tien parantamistoimenpiteiden kustannukset [Costs of road improvement actions]. Oulun seudun ammattikorkeakoulu, Rakennustekniikka, Insinöörityö.

Kawashima, Hironao (2019): ODD management and integrated communication systems. Presentation at the Workshop on Constructs of the Operational Design Domain (ODD) of Automated Vehicles held at Nanyang Technical University 22 October 2019.

Kolisoja, Pauli (2019): Impact of heavy trucks and truck platooning on road pavement Presentation at CEDR MANTRA workshop on 10 September 2019 in Vienna.

Koopman, Philip; Fratrik, Frank (2019): How Many Operational Design Domains, Objects, and Events? Preprint: Safe AI 2019: AAAI Workshop on Artificial Intelligence Safety, Jan 27, 2019.

Koskela, Alina (2018): Aurora Borealis automated driving & intelligent infrastructure testing area – 1st results. Presentation given at NEXT-ITS3 A4 ICT Infrastructures meeting, Helsinki 22-23 August 2018.

Koskinen, Jarkko; Kuusniemi, Heidi; Hyyppä, Juha; Thombre, Sarang; Kirkko-Jaakkola, Martti (2018): Positioning, location data and GNSS as solution for autonomous driving. Presentation made at I Aurora Summit, Olos 16-17 January 2018. Available online at https://vayla.fi/documents/20485/421308/Koskinen_Aurora_Summit.pdf/bf11703e-fc5a-4377-98ef-d784469e5be0, accessed on 1/17/2020.

Kulmala, Risto; Jääskeläinen, Juhani; Pakarinen, Seppo (2018a): The Impact of Automated Transport on the Role, Operations and Costs of Road Operators and Authorities in Finland. EU-EIP Activity 4.2 Facilitating automated driving. Available online at https://www.traficom.fi/sites/default/files/media/publication/EU_EIP_Impact_of_Automated_Transport_Finland_Traficom_6_2019.pdf, accessed on 1/17/2020.

Kulmala, Risto; Öörni, Risto; Laine, Tomi; Lubrich, Peter; Schirokoff, Anna; Hendriks, Teun; Ryström, Leif (2018b): Quality of Safety-Related and Real-Time Traffic Information Services. Quality package. EU EIP SA 4.1 Determining Quality of European ITS Services, Deliverabble version 1.1. 26 February 2018. Available online at https://www.its-platform.eu/filedepot/folder/1077?fid=6305, accessed on 1/17/2020.

Liao, Chen-Fu; Donath, Max; et al. (2018): Development of Driver Assistance Systems to Support Snowplow Operations. Test and Demonstration of Connected Vehicles Applications to Maintenance Operations. CTS18-14. With assistance of University of Minnesota.

Ludovic, Simon (2019): Standardisation activities, presentation EU EIP 4.2 Meeting.

Malmivuo, Mikko (2010): Maanteiden talvihoidon kokonaisedullisuus Suomessa [Cost-efficiency of winter maintenance on public roads in Finland]. Liikenne- ja viestintäministeriön julkaisuja 34/2010.

Malone, Kerry; Schreuder, Max; Berkers, Frank; Helfert, Katharina; Radics, Lena; Boehm, Martin et al. (2019): Digitalisation and Automation. Implications for use cases, Identification of Stakeholders and Data Needs and Requirements. DIRIZON Deliverable Nr 3.1. Draft 0.7, October 2019.

next mobility news (2019): C2X-Kommunikation für einen effizienteren Winterdienst. Available online at https://www.next-mobility.news/c2x-kommunikation-fuer-einen-effizienteren-winterdienst-a-872528/?cmp=nl-392&uuid=2A64A51F-61C9-46CA-A09B-4EAF0263493C, accessed on 1/17/2020.

Nicodeme, Christophe; Diamandouros, Konstantinos; Diez, Jose; Durso, Concetta; Arampidou, Kyriaki; Nuri, Ari Kemal (2017): Road Statistics Yearbook 2017. Edited by ERF European Union Road Federation. Available online at http://www.erf.be/wp-content/uploads/2018/01/Road_statistics_2017.pdf, accessed on 1/17/2020.

Nitsche, Philippe; Aleksa, Michael; Piribauer, Thomas (2018): via-Autonom, Verkehrsinfrastruktur und Anforderungen für autonomen Straßenverkehr. Mobilität der Zukunft, 6. Ausschreibung (2015).

Novak, Thomas; Aigner, Walter; Kuhn, Andreas; Pollhammer, Klaus (2018): Making Infrastructure Fit for Automated Driving. In AustriaTech – Gesellschaft des Bundes für technologiepolitische Maßnahmen GmbH (Ed.): Proceedings of 7th Transport Research Arena TRA 2018, April 16 - 19, 2018, Vienna, Austria.

NVIDIA (Ed.) (2019): End-to-end Hd Mapping for Self-driving Cars. Available online at https://www.nvidia.com/en-us/self-driving-cars/hd-mapping/, accessed on 1/17/2020.

Park, David Jung Hoon (2019): Road Classification and in situ ADS Tests for Coevolution between Our Community and CAVs. Presentation at the 26th ITS World Congress in Singapore, 21-25 October 2019.

Pettersson, Jan; Resch, Stefan; Straten, Eric thor; Miettinen, Hanna-Mari; Limbach, Roman; Romaidou, Katerina et al. (2018): Trans-European Road Network, TEN-T (Roads) 2017 Performance Report. Edited by Conference of European Directors uf Roads (CEDR). Available online at https://www.cedr.eu/download/Publications/2018/TEN-T-Performance-report-2017.pdf, accessed on 1/17/2020.

Rintamäki, Jaakko; Setälä, Niko; Pöllänen, Laura; Ansio, Virpi (2013): Pohjanmaan ja Keski-Pohjanmaan joukkoliikenteen palvelutasomääritys. Palvelutasosuunnitelma vuosille 2014-2018. [Regional public transport level of service specification. Service level plan for years 2014-2018.] Elinkeino-, liikenne- ja ympäristökeskus, raportteja 91/2013. Available online at https://www.obotnia.fi/assets/1/Planlaggningsenheten/Trafik/joukkoliikenteen-palvelutaso.pdf, accessed on 1/17/2020.

Russ, Martin (2019): Comment made at Special Interest Session 01 Highly connected and automated multimodal urban system, 26th ITS World Congress in Singapore, 21-25 October 2019.

RWS (Ed.) (2018): Traffic Management Roadmap 2022. Improving the nextwork services. Renewal based on Smart Mobility. Rijkswaterstaat, Ministry of Infrastructure and Water Management, October 2018.

SAE (Ed.) (2018): J3016 - Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles. SAE.

Schildorfer, Wolfgang; Kuhn, Andreas; Aigner, Walter (2019): Connecting Austria - First results of C-ITS focused level 1 truck platooning deployment. Presentation at 13th ITS European Congress, Brainport Einhoven, The Netherlands, 3.-6.6.2019.

Scholliers, Johann; Kulmala, Risto; Sörensen, Anders Bak; Sundberg, Jonas; Kotilainen, Ilkka; Svedlund, JOhnny et al. (2018): Nordic Way, Final report, accessed on 8/6/2019.

Schöneburg, Rodolfo (2019): Die Auswirkungen Des Hochautomatisierten Fahrens Auf Die Fahrzeugsicherheit Der Zukunft – Gedanken zu neuen Schutzsystemen, Interieurkonzepten und Fahrzeugarchitekturen. Public presentation Vienna ÖVK, Haus der Industrie, January 22, 2019. Mercedes-Benz Cars / Development Safety, Durability, Corrosion Protection, Daimler AG.

Schulz, Susanne; Reusswig, Achim; Lülfing, Ralph-Carsten; Thiel, Julian van; Wulf, Oliver; Rief, Christian et al. (2019): aFAS Automatisch fahrerlos fahrendes Absicherungsfahrzeug für Arbeitsstellen auf Bundesautobahnen. Gemeinsamer Schlussbericht. Version 01-00-00.

Shladover, Steve (2018b): Comments made to EU EIP report (Kulmala et al. 2018) draft on 20 December 2018.

Shladover, Steve (2018a): Practical Challenges to Deploying Highly Automated Vehicles. Presentation for Drive Sweden, Gothenburg, 14 May 2018.

SOCRATES 2.0 (Ed.) (2018): Proposed cooperation framework & bottlenecks. Activity 2 – deliverable, June 2018. Available online at https://socrates2.org/application/files/3515/5488/4491/SOCRATES2.0_report_Act2_Cooperation_Framework.pdf, accessed on 1/17/2020.

Stolte, Torben; Reschka, Andreas; Bagschik, Gerrit; Maurer, Markus: Towards Automated Driving: Unmanned Protective Vehicle for Highway Hard Shoulder Road Works. IEEE International Conference on Intelligent Transportation Systems, ITSC 2015 – 2015 IEEE 18th International Conference. Available online at http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.715.6821&rep=rep1&type=pdf, accessed on 1/17/2020.

Sweatman, Peter (2019): Presentation at Special Interest Session 01 Highly connected and automated multimodal urban system, 26th ITS World Congress in Singapore, 21-25 October 2019.

TM2.0 (Ed.) (2018): Platform web site. Available online at http://tm20.org/, accessed on 1/17/2020.

TN-ITS (Ed.) (2019): TN-ITS Map Update Exchange. Available online at https://tn-its.eu/, accessed on 1/17/2020.

TomTom (Ed.) (2019): HD Map with RoadDNA. Available online at http://download.tomtom.com/open/banners/HD_Map_with_Road_DNA_Product_Info_Sheet.pdf, accessed on 1/17/2020.

Transport for London (Ed.) (2012): Bus stop/shelter replacement costs. Response to Freedom of Information request by Mr A Earle. Available online at https://www.whatdotheyknow.com/request/bus_stopshelter_replacement_cost, accessed on 1/17/2020.

Transport Systems Catapult (Ed.) (2017): Future Proofing Infrastructure for Connected and Automated Vehicles. Technical Report. Available online at https://s3-eu-west-1.amazonaws.com/media.ts.catapult/wp-content/uploads/2017/04/25115313/ATS40-Future-Proofing-Infrastructure-for-CAVs.pdf, accessed on 1/17/2020.

U.S. DOT (Ed.) (2018a): ITS Cost Elements. United States of America, Department of Transportation, Intellogent Transport Systems, Joint Program Office. Available online at https://www.itsknowledgeresources.its.dot.gov/ITS/benecost.nsf/Images/Reports/$File/CostElements%202015-02-11.xls, accessed on 1/17/2020.

U.S. DOT (Ed.) (2018b): Preparing for the Future of Transportation. Automated Vehicles 3.0. Available online at https://www.transportation.gov/sites/dot.gov/files/docs/policy-initiatives/automated-vehicles/320711/preparing-future-transportation-automated-vehicle-30.pdf, accessed on 1/17/2020.

Ulrich, Sandra; Reisenbichler, David; Schildorfer, Wolfgang (2019): Auswirkungen von Truck Platooning auf den Straßenoberbau. Spurvariation, Deliverable D4.1, VIF 2018.

van der Tuin, Marieke; Farah, Haneen; Penttinen, Merja; Ulrich, Sandra; Carsten, Oliver; Kulmala Risto (2020): Impacts of connected and automated vehicles. MANTRA: Making full use of Automation for National Transport and Road Authorities - NRA Core Business, Deliverable 3.1 and 3.2.

Vantomme, Joost (2019): Connectivity and automated driving. Perspectives from the vehicle manufacturers. Presentation given at CCAM Single Platform WG3 Physical and Digital Road Infrastructure meeting 3 December 2019.

Vardhan, Harsha (2017): HD Maps: New age maps powering autonomous vehicles. Geospatial World 09/22/2017. Available online at https://www.geospatialworld.net/article/hd-maps-autonomous-vehicles/, accessed on 1/17/2020.

Vermaat, Peter; Reed, Nick; Kievit, Martijn de; Wilmink, Isabel; Zlocki, Adrian; Shladover, Steven (2017): DRAGON: Driving automated vehicle growth on national roads. WP 4: Findings report. Available online at http://www.cedr-dragon.eu/images/reports/DRAGON_Final_Report.pdf, accessed on 1/17/2020.

Vreeswijk, Jaap (2019): Workshop report: constructs of the Operational Design Domain (ODD) of Automated Vehicles. ITS World Congress Singapore, 22.10.2019.

Waymo (Ed.) (2017): On the road to fully self-driving. Waymo Safety Report. Available online at https://www.mtfchallenge.org/wp-content/uploads/2017/02/waymo-safety-report-2017-10.pdf, accessed on 1/17/2020.

Wisely, David; Wang, Ning; Tafazolli, Rahim (2018): Capacity and Costs for 5G Networks in Dense Urban Areas. IET Communications, vol. 12, no. 19, pp. 2502-2510, 4 11 2018. doi: 10.1049/iet-com.2018.5505.

Yeo, Hwasoo (2019): Digital infrastructure for multi-modal autonomous transit service. Presentation at Special Interest Session 01 Highly connected and automated multimodal urban system, 26th ITS World Congress in Singapore, 21-25 October 2019.

Zencic (Ed.) (2019): UK Connected and Automated Mobility Roadmap to 2030. Available online at https://zenzic.io/roadmap/, accessed on 1/17/2020.

Workshops and international discussions

Workshop PEB and CEDR CAD WG, Vienna, 31.08.2018

22nd annual meeting international task force on vehicle-highway automation, Copenhagen, 16.09.2018

ITS world conference 2018, interactive panel discussion within the special interest session on “Systemic impacts from infrastructure-based management of connected and automated driving (SIS69)”, Copenhagen, 20.09.2018

Workshop CEDR CAD WG, Oslo, 06./07.11.2018

Workshop together with ARCADE/ERTRAC, Brussels, 02.2019

Workshop CEDR CAD WG, Tallinn, 06./07.03.2019

EU-CAD Conference 2019, Brussels, 02./03.04.2019

Workshop with project ARCADE Brussels 04.2019

ITS Europe conference 2019 interactive panel discussion within the special interest session on “Touching the real infrastructure and embracing the unknown (SIS13)”, Eindhoven, 04.06.2019

Workshop with Asfinags team for ITS, automated and connected driving, Vienna, 06.05.2019

Kolloquium Future Mobility, Esslingen, 02.07.2019

Workshop CEDR CAD WG on truck platooning, Stockholm, 12.06.2019

Workshop in cooperation with Austrian projects on truck platooning Connecting Austria and Spurvariation, Vienna, 08.07.2019

Workshop with ASECAP, COPER III, Vienna, 24.07.2019

Expert Workshop, Vienna, 10.09.2019

Participation/presentation in EU EIP, Action 4.2, Multi-stakeholder workshop on ODD, cost and benefits of automated driving, Turin, 01.-02.10.2019

Participation/presentation in break-out session on constructs of the ODD of Automated Vehicles, ITS World Congress, Singapore, 22.10.2019