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Digital Road for evolving Connected & Automated Driving

Review and Evaluation of NRAs

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Table of Contents

Introduction *6*

Overview of DiREC project **6**
Project Vision 6
Project Approach 6

Purpose of this report **6**

Overview of CRF framework **7**
Description of CAV Readiness Framework 7
How the CAV Readiness Framework Differentiates itself 8

How we use outcomes from this report **9**

1 Infrastructure Design and Operations *10*

1.1 Introduction **10**

1.2 Physical Infrastructure **10**
1.2.1 Roadway System 11
1.2.2 Carriageway Control 12
1.2.3 Ancillary 13
1.2.4 Road lighting 13

1.3 Digital Infrastructure **14**
1.3.1 Introduction to CAV systems 14
1.3.2 Digital infrastructure Components 14
1.3.3 Digital Twin and Naked Highway 16

1.4 Operation and Services **17**
1.4.1 Definitions 17
1.4.2 Operation Management 17

1.5 Roadmaps and Pilots **20**
1.5.1 Roadmaps 20
1.5.2 Pilots 22

1.6 Section Summary and Comment **23**
Road Financing 25
Infrastructure Classification Systems 25

2 Infrastructure Connectivity *29*

2.1 Understanding Connectivity **29**

2.1.1 Vehicle to Everything (V2X) and Vehicle-to-Infrastructure (V2I) **29**

2.1.2 WLAN: ITS-G5 .... **29**

2.1.3 Cellular: LTE-VTX / C-V2X and 5G **29**

2.2 ITS-G5 and C-V2X Technical Characteristics **32**

2.3 Connectivity requirements (ETSI standards) **36**

2.3.1 ETSI basic set of applications – Cooperative awareness service and decentralized environmental notification service **36**

2.3.2 ETSI Basic Set of Applications – Collective Perception Service **37**

2.3.3 V2X applications – road hazard signalling **38**

2.3.4 V2X applications – Intersection collision risk warning 39
2.3.5 V2X – Longitudinal Collision Risk Warning 40
2.4 Vulnerable road users (VRU) awareness service 41
2.4.1 LTE – V2X services 43
2.4.2 C-V2X (cellular vehicle to everything) 45
2.4.3 5G – enhanced V2X scenarios 47
2.5 Connectivity trials in Europe 48
2.5.1 5G-MOBIX – 5G for Cooperative, Connected and Automated Mobility 48
2.5.2 5G-DRIVE – 5G Harmonise Research and TrIals for service Evolution between EU and China 48
2.5.3 5G-LOGINNOV 48
2.5.4 5G-ROUTES 49
Conclusion 52
Bibliography Part 2 54
3 Data, Data Model and Exchange of Data 58
3.1 Overview of CAV data ecosystem 58
3.1.1 Categories of CAV data 58
3.1.2 Vehicle sensor data 58
3.1.3 Traffic safety data 59
3.1.4 Real-time traffic data 59
3.1.5 HD map data 59
3.2 The need for data exchange and communication in CAD environments 60
3.2.1 Types of data exchange 60
3.3 Data exchange standards within C-ITS 61
3.3.1 Traffic safety data exchange standards 62
3.3.2 Real-time traffic data exchange standards 63
3.3.3 HD map data exchange standards 65
3.3.4 Data exchange models and formats 67
3.4 Data exchange challenges 68
3.4.1 Traffic safety and real-time traffic data exchange challenges 68
3.4.2 HD map data challenges 69
Bibliography Part 3 71
4 Digital Twin 74
4.1 Why use a Digital Twin 75
4.2 Current Digital Twin activities 75

4.2.1 EU work to date 75
4.2.2 Industry activity 76
4.2.3 Construction 76
4.2.4 Rail Industry 76
4.2.5 Manufacturing 77
4.3 Digital Twins: Cities, NRAs and OEMS 78
4.3.1 German Ministry of Transport 78
4.3.2 DARS, Slovenia 78
4.3.3 National Highways (formerly Highways England) 78
4.4 Literature (Transport) on Digital Twins 79
4.4.1 OEMs 79
4.4.2 Open Data 80
4.4.3 Standards 81
4.5 NRA and the Digital Twin 85
4.5.1 End to End Capability 85
4.5.2 NRA Operations and Digital Twins 86
4.5.3 CAV Ready Framework: Digital Twin Expectations on Service Provision 88
Bibliography Part 4 90
5 Impact of Emerging Technologies 92
5.1 Introduction and overview of the regulatory landscape 92
5.1.1 Categories of rules that are fundamental to support CAV deployment on public roads 92
5.1.2 Branches of law that affect CAVs 93
5.2 UNECE international framework initiatives 94
5.2.1 UNECE Conventions 94
5.2.2 UNECE Working Parties 1 and 29 and their collaboration and common approaches on automated vehicles 95
5.2.3 Regulatory initiatives of WP.1 96
5.2.4 Regulatory initiatives of WP.29 96
5.3 Regulatory European Union and national initiatives on CAV – an overview 97
5.3.1 EU law – Main legal instruments 98
5.3.2 Germany 101
5.3.3 United Kingdom 102
5.4 Legal implications – Specific challenges related to CAV/CAD 103
5.4.1 Road signs' machine readability and Road marking reflectivity 103

5.4.2 Accuracy and currency of HD mapping 106

5.4.3 Timely information provision on incidents, events and crises 107

5.4.4 Cybersecurity for digital twins or I2V communications 107

5.5 Brief comments on stakeholder views, and conclusions on legal and regulatory aspects 108

Bibliography Part 5 110

6 Legal and Regulatory Aspects 112

6.1 Introduction.. 112

6.2 Connectivity.. 112

6.2.1 The connectivity deployment options 112

6.2.2 Current Status and future development of C-V2X and 5G-V2X 116

6.2.3 Plans for 6G... 118

6.2.4 Current status and future development of ITS-G5 119

6.2.5 The reliability of communications... 119

6.2.6 Connectivity options – Costs of providing connectivity and impact on road network coverage 120

6.3 Position technologies for CAD 121

6.4 Road-side infrastructure 124

6.5 Vehicular technologies that support CAD 125

6.5.1 Sensors and their limitations 125

6.5.2 Road infrastructure machine readability 126

6.5.3 Potential NRA involvement 127

Bibliography Part 6 129

7 Benefit and Costs 133

7.1 Introduction.. 133

7.2 General methodology for appraising CAD on Strategic Road Networks 133

7.2.1 The key steps in the CBA process... 133

7.2.2 Establishing and documenting the options and assumptions (step 2) 134

7.2.3 Identifying proposal impacts and quantifying direct impacts (step 3) 136

7.2.4 Construction of a systematic Cost Benefit model (step 4) 140

7.2.5 Communicating wider impacts (step 5) 141

Conclusion 143

Bibliography Part 7... 144

8 Vision and Mission 145

Appendix 1.1: SAE Levels ***146***
Appendix 1.2: ISAD Levels ***147***
Appendix 1.3: CAV Readiness Framework ***148***
Appendix 1.4: PIARC Special Project Smart Road Classification ***149***
Appendix 1.5: Infrastructure Support Level Classification ***150***
Appendix 1.6: Summary Table ***155***
Appendix 1.7: Autonomous Vehicles Readiness Index ***159***
Appendix 1.8: Classification of C-ITS services ***159***
SAE levels of cooperation 159
Other SAE C-ITS standardization documents 160
Day X classification (EC) 161
Other classifications and main use cases 161

Introduction

Overview of DiREC project

Project Vision

Connected and Automated Driving (CAD) is an important area of digital technology that will bring disruption to individuals, economies, and societies. Most forms of CAD require some level of infrastructure support for their safe operation. Additional infrastructure and services to support CAD have the potential to improve safety even further, and to bring other benefits such as increased efficiency or reduced congestion. However, the infrastructure requirements from Original Equipment Manufacturer (OEMs) are not always clear, and it is difficult for National Road Authorities (NRAs) to predict and plan for the future levels of support needed for CAD given rapidly evolving technology and uncertain projections of future CAD demand. In addition, there is also a need for better dialogue among NRAs, OEMs and service providers to articulate those requirements and to define a roadmap and responsibilities for achieving safe and smart roads through CAD.

Project Approach

The aim of DiREC is to establish a CAV Readiness Framework and a set of toolkits dedicated to CAVs (Connected and Autonomous Vehicles) that incorporates a wide range of components that affect CAD and the ability of highway infrastructure to support it. These components include machine readability of physical infrastructure, digital services, connectivity, in addition to aspects such as governance of the infrastructure and services, and legal and regulatory requirements. Together these components influence the ability of the NRA to become a digital road operator.

The DiREC project will thus provide a framework for NRAs, service providers and OEMs to support CAD. It will consolidate and combine standards, research, and recommendations from other projects and extend research into new areas such as creating a common vision for digital twins among NRAs, understanding connectivity and connectivity requirements to support digital services and analysing how these can be met, reviewing the quality management processes around digital data, and documenting existing legal and regulatory frameworks in all areas relating to CAD.

The framework will focus on four main aspects:

- **Needs** – the as-is situation of knowledge understanding about CAV impact and potential impact of CAV to road infrastructure and operators
- **Impact** – potential short-term and long-term impact that CAV would bring to infrastructure and road operators, which part would be affected
- **Risk and opportunity** – positive impact (e.g efficiency improvement) and negative impact (e.g., higher investment to infrastructure)
- **Recommendation** – any suggestions given to road operators for handling future challenges

The DiREC project will provide approaches that NRAs can adopt for supporting their pathway of CAV-ready transformation. It will arm NRAs with a future-proofing strategy to make better-informed decisions, leading to improved outcomes, aiming to place NRAs in a much stronger position to influence how traffic operates on the network and improve the efficiency in achieving the economic transformation.

Purpose of this report

For developing the framework and toolkits for CAD as described above, a list of tasks (WP2 – Review and Evaluation Task 2.1 to Task 2.8) have reviewed existing knowledge and experience, including:

- Task 2.1 Infrastructure Design and Operation
- Task 2.2 Infrastructure Connectivity
- Task 2.3 Data, Data Model and Exchange of Data
- Task 2.4 Digital Twins
- Task 2.5 Impact of Emerging Technologies
- Task 2.6 Legal and Regulatory Aspects
- Task 2.7 Benefits and Costs

- Task 2.8 Vision and Mission

This report covers main research outcomes from Task 2.1 – Infrastructure Design and Operation, contributing to Infrastructure Design and Operation section. It consolidates current research, knowledge, and experience in the infrastructure domain to feed into later activities under this project, as well as guiding a conversation with NRAs, OEMs, and other stakeholders. This review covers recent research materials and literature on physical infrastructure, digital infrastructure, operations, and service needs, and evaluates key outputs found from these reviews. It also discusses some existing pilots and roadmaps in Europe for implementation of automated driving. This report discuss further how these findings will feed into DiREC and help shape the CRF over the remainder of the project.

Overview of CRF framework

Description of CAV Readiness Framework

DiREC proposes to establish the CAV Readiness Framework (CRF) to address eight core subject areas that NRAs must consider in the delivery and management of connected infrastructure to support CAD. See

Appendix 1.3: CAV Readiness Framework. The CRF will incorporate eight subject areas Design and Operations, Digital Twin, Data, Data Models and Exchange of Data (Connectivity); Future Technologies; Legal and Regulatory; and Costs and Benefits, and Mission. These areas cover physical and digital infrastructure and connectivity aspects, whilst providing a flexible foundation to allow NRAs to consider the wider ranging needs of Connected Digital Infrastructure to support CAD. This will ensure that NRAs maintain influence in this area of their network operation. These subject areas will define the foundations of the DiREC approach.

How the CAV Readiness Framework Differentiates itself

When proposing this new framework, it is essential to discuss how this new framework will differentiate itself and complement existing work to support CAD. The DiREC project acknowledges some important contributions to the evolution of standards and definitions on the subject of autonomous driving and infrastructure to support it. In this domain, two main building blocks have been developed and widely adopted to assess the maturity of vehicle automation and the required infrastructure support.

The two building blocks are the Society of Automotive Engineers (SAE) Levels of Driving Automation and the Infrastructure Support Levels for Automated Driving (ISAD) as introduced below.

The SAE **Recommended Practice: Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles**, commonly referenced as the SAE Levels of Driving Automation, has been the industry's most-cited source for driving automation. SAE defines six levels of driving automation, from Level 0 (no driving automation) to Level 5 (full driving automation) in the context of motor vehicles and their operation on roadways. It focuses on what the human needs to do in the driver's seat (e.g. if drivers need to supervise the vehicle, and when support feature are engaged for drivers) and what kind of features will be required to support different level of automation (e.g. from low-level emergency braking, lane centring to high level traffic jam chauffeur and pedal and wheel steering). (SAE, 2014).

Another building block is the **Infrastructure Support Levels for Automated Driving (ISAD)**. The system was developed under the INFRAMIX project which aims to prepare the road infrastructure with specific affordable adaptations. In order to classify and harmonize the capabilities of road infrastructure to support and guide automated vehicles, we propose a simple classification scheme, similar to SAE levels for the automated vehicle capabilities. (INFRAMIX, 2020).

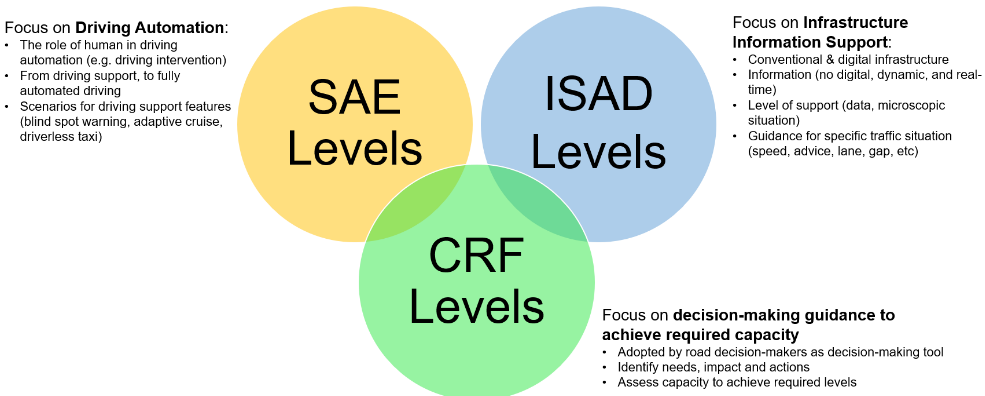

Figure 1 Building blocks of the CRF

The CRF will combine and build on these by developing a level of service approach covering machine readability of physical infrastructure, digital services, and connectivity, in addition to aspects such as governance of the infrastructure and services, and legal and regulatory requirements. See Figure 1. Some important differences of that focus is covered in

Table *1*.

Table 1 Outline Attributes of the CRF

Description	**SAE Levels**	**ISAD Levels**	**CAV Readiness Framework**
Main users	OEM	Road operator	Road operator
Classifications of driving automation	√	√	√
Driver's action for automation	√	√	√
Automation application feature	√	√	√
Classifications of Infrastructure support for CAV		√	√
Physical & digital infrastructure support		√	√
Impact identification of CAV to infrastructure and road operators			√
Cover both technical factors and non-technical factors (8 subject areas)			√
Knowledge and guidance for conducting adaptation			√
Organisational capacity for CAV			√
Examination tool for evaluating capacity and gap areas			√

How we use outcomes from this report

The outcomes from this report will feed into development of the CRF and help identify alternative measures and priorities for future CAD support. It will also be used to guide the selection and development of case studies under later work packages in this project.

1 Infrastructure Design and Operations

1.1 Introduction

This section reviews the implications of CAD for NRAs, including the potential needs to map, adapt or upgrade infrastructure. This includes understanding and defining the different levels of service required within the CRF. For example, different service levels could be defined in the standardisation of road signs, or through different operational policies and procedures for maintenance of road markings, to support CAD.

It includes review and evaluation of literature to establish a common definition for CAD requirements and service levels, and summarises NRA positions with respect to future design and operation.

Many elements need to be considered. For example, current highway design parameters such as line of sight (horizontal and vertical), road signs (size and placement) and road markings (luminosity) have been designed for ease of identification by humans. Automated vehicles may offer a very different perspective, either via the "naked highway" concept or using a reference digital twin. There is a need to understand the gaps between the expectations of NRAs and OEMs regarding the current and future needs of physical infrastructure.

1.2 Physical Infrastructure

The ISAD CAV Infrastructure Levels (see Appendix 1.2: ISAD Levels) are described in terms of conventional infrastructure and digital infrastructure support for automated driving. Conventional (or physical) infrastructure is depicted as supporting Levels E and D. Level E is described as, “*Conventional infrastructure without digital information. AVs need to recognise road geometry and road signs*”; Level D as, “*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 [variable messaging signs] need to be recognised by AVs*”.

An early CATAPULT report ‘Future Proofing Infrastructure for Connected and Autonomous Vehicles’ for the Department for Transport (DfT) in UK and the Centre for Connected and Autonomous Vehicles (CCAV) (CATAPULT, 2017) identified several key policy areas for further consideration regarding the introduction of CAVs, including road markings and signage, safe harbour areas, traffic management measures, crossing and junctions, and bridge structures.

Several research projects have since identified comprehensive physical (or conventional) infrastructure elements that can impact, or be impacted by, automated driving.

A recent detailed and comprehensive report (European ITS Platform, 2021) sets out proposals for physical infrastructure requirements of automated vehicles on the road infrastructure to facilitate SAE Level 4. The report was compiled with information from two projects: the L3 Pilot project (L3 Pilot, 2021) provided insights from vehicle manufacturers, and the CEDR MANTRA project on the impacts of highly automated driving on national road authorities and operators. The work resulted in a list of ODD attributes relevant to road operators. This framework has been used in the DiREC project to consider the different opportunities for physical infrastructure to support CAVs (see

Appendix 1.6: Summary Table).

The following sections review how some of these attributes have been discussed and investigated in research literature and CAV-related implementation projects, and what the implications may be for planning and design of roads in future.

1.2.1 Roadway System

1.2.1.1 Road geometries and configurations

Roads and intersections could be designed differently depending on AV use cases. Intersection sight distance models are based on driver behaviour rather than the vehicle and roadway capacity. In the short-to-medium term it may be useful to simplify intersections in terms of interaction between vehicles. In the longer term, greater coordination between vehicles may allow intersections to become more compact (Austroads, 2017).

- Horizontal and vertical curvature. Current geometric standards or guidelines are largely based on the need of a human driver to maintain a good view of the road and other traffic. For self-driving vehicles functioning only with vehicle sensors, this requirement will continue to apply and current guidelines for infrastructure used by human drivers can be maintained. Connected vehicles, on the other hand, can obtain information on the route via digital systems. In those cases, the need for a good visual view of the road and the road environment becomes less important (Belgian Road Research Centre, 2020).
- Lane widths could be reduced, as Lane Keeping Systems will guarantee that the vehicle will maintain an optimal central position. A recommendation of a lane width of 2.72 m was found to have the same optimal probability of automatic and human lateral control, this therefore being the 'critical' lane width for safe operation. In addition, CAVs equipped with Lane Departure Warning (LDW) and Lane Keeping Aid (LKA) systems are highly dependent on roadway characteristics, such as lane markings (presence/clarity) and lane and shoulder width. (SLAIN, D7.2: Other initiatives to meet the needs of automated cars, 2020).

1.2.1.2 Pavement

Various research has identified areas of pavement design which may be impacted by the use of CAVs. Because CAVs will run consistently in the same lane positions there will be greater wear and tear in the wheel tracks, and that either the road area beneath the tracks will need to be strengthened, or maintenance repairs will need to be more frequent (Lamb, 2015).

CAVs can adjust vehicle speed through V2V and V2I communications to avoid sharp braking thus reducing the stopping distance design standard for pavements. The requirement for the coefficient of friction can be relaxed, so that less skid-resistant materials are possible for use in the surface course in the future (Dunford et al., 2014). However, the failure to estimate friction on the carriageway is identified as a significant cause of roadway departure crashes for CAVs, and so further research is recommended. It is also noted that reasonable levels of skid resistance are still required for other including motorcycles, bicycles, and pedestrians. (SLAIN, D7.2: Other initiatives to meet the needs of automated cars, 2020).

1.2.1.3 Bridge design

Current bridge design standards make assumptions about the number of vehicles likely to be on the bridge at any one time. Design standards need to be explored further to determine the impact of platooning (Austroads, 2017).

1.2.1.4 Tunnel design

Further research into detection and perception of tunnels under adverse weather and lighting conditions is needed, as well as investigation of sensor and GPS capabilities. (SLAIN, D7.2: Other initiatives to meet the needs of automated cars, 2020).

1.2.2 Carriageway Control

1.2.2.1 Road markings

Project SLAIN: Saving Lives Assessing and Improving TEN-T Road Network Safety (EuroRAP, 2020) identifies ways in which many different types of infrastructure support CAVS, or in which consideration should be given to adapting design for CAVs. It conducted consultations with road authority representatives on relevant standard-setting bodies, the European Union Road Federation and the International Road Federation.

A number of AV manufacturers note problems with recognising existing signs and lines, so that greater consideration of machine readability is required when designing signs and lines (Austroads, 2017).

With regards to road markings, project SLAIN conducted desk-based research review on CAVs camera systems and image processing to identify issues with recognition of overlapping and inconsistent road markings, quality of markings, and recognition during adverse weather conditions and at different times of day.

1.2.2.2 Road signs

Project SLAIN (SLAIN, D7.1: Quality of horizontal and vertical signs, 2020) concluded that the width of lines was not as important as their condition; also proximity of the line to materials such as concrete shoulder and concrete safety barriers which have similar properties to lines from a machine learning perspective made these harder for CAV systems to identify them. Other early research also showed that road marking improvement gives a positive benefit-to-cost ratio (BCR) with respect to crash/casualty cost savings, but more trials are needed to test CAV crash patterns in relation to road marking deterioration. Researchers commonly agree that improving maintenance and design standards can generate significant network-wide safety and performance gains.

Project SLAIN also concluded that the issues identified with regards to CAV readability of traffic signs could be addressed by the adoption of harmonised regulation and standardisation of sign types, symbols used, shapes, heights, locations, and orientations. To ensure consistency in signing, a comprehensive and systematic traffic signs asset inventory system is essential. This would enable a road authority to better understand the location and form of the assets on their network and help to reduce the costs for their maintenance.

As long as there is a mix of vehicles with different SAE levels, however, it will remain important to meet minimum standards of signs and road markings, and to maintain these accordingly.

1.2.2.3 Kerbs and shoulders

Many studies have identified that shoulders provide opportunities for CAVs, for example using them as safe harbour areas, or to increase capacity of the network for example for platooning, or more generally to increase capacity for all vehicles. Dynamic hard shoulder running is already being implemented in many countries including Netherlands, Belgium, Germany, Denmark, Austria and UK. However, some stakeholders have concerns in terms of traffic and road safety from the point of view of access and response times by emergency services in the event of incidents. (CEDR Working Group Traffic and Network Management, 2018).

Shoulder widths and bearing capacity typically need to be increased to allow hard shoulder running. The Study of Infrastructure Support and Classification for Automated Driving on Finnish Motorways proposes that shoulder widths be increased, and that shoulder bearing capacity be upgraded to be sufficient for platoons of 3 trucks moving slowly with a gap of 15 m between trucks (Finnish Transport Infrastructure Agency, 2021).

1.2.2.4 Entry and exit ramps

On motorways with dedicated high-speed lanes for CAVs, reserved exit ramps should be considered (SLAIN, D7.2: Other initiatives to meet the needs of automated cars, 2020).

Project MANTRA concluded that increased automation gave benefits to all vehicles in terms of reduced delays. However, modeling on entry ramps indicated long delays for both automated and non-automated cars on entry to the motorway (MANTRA, Impacts of automation functions on NRA

policy targets, 2020).
Therefore consideration needs to be given to design of entry and exit ramps in mixed vehicle scenarios.

1.2.2.5 Safe harbour areas

The SAE J3016 standard (SAE, 2014) outlines the need for highly automated vehicles to have the capability to bring themselves to a "minimal risk condition", which could be a complete stop. This could result in the need for laybys in tunnels and at the end of AV routes (e.g. at off-ramps) (Austroads, 2017). The provision of safe harbour areas is also a key safety issue for all road users on traditional infrastructure.

1.2.3 Ancillary

1.2.3.1 Rumble strips

Rumble strips are also relevant for CAVs. Shoulder and centreline rumble strips can significantly reduce severe collisions and specific collision types in off-road right, off-road left, and head-on collisions combined. Project SLAIN has called for research to focus on the effects of centreline rumble strips in different types of in-vehicle systems and different types of road environments under different weather conditions, taking into consideration noise and their relationships with road markings (SLAIN, D7.2: Other initiatives to meet the needs of automated cars, 2020).

1.2.3.2 Median and side guard rails

Median barriers and side guard rails mitigate the negative consequences of lane and road departure. However, where the road is undivided, rumble strips or in-vehicle lane support systems such as LDW, LKA and Emergency Lane Keeping (ELK), can play an important role in reducing unintentional lane drifting and reduce crashes. Installation of cable median barriers may present challenges since CAV systems may have greater difficulty detecting smaller objects. (SLAIN, D7.2: Other initiatives to meet the needs of automated cars, 2020).

1.2.4 Road lighting

There are various opportunities and constraints related to road lighting, from the point of view of CAV systems and NRAs. CAV systems may require support of external lighting in order to recognise road markings, signs, or pedestrians. That support may be in the form of more closely spaced signs or better illumination (Shaldover & Bishop, 2015). CAVs and road-side lighting may also communicate to support and enhance CAV's vehicle vision. Lighting poles can operate as landmarks for positioning, and are a feature for potential inclusion in HD maps. (Finnish Transport Infrastructure Agency, 2021). Improved street lighting will be generally beneficial to road safety through reductions in crashes and injuries. (SLAIN, D7.2: Other initiatives to meet the needs of automated cars, 2020).
Some ODD-related requirements for highway autopilot (L4) require lighting during darkness (Traficom, 2019).

DiREC Summary and Conclusions on Physical Infrastructure

This review has highlighted many ways in which physical infrastructure might be improved to support CAV. These are summarised in
Appendix 1.6: Summary Table.
The physical infrastructure requirements of roads will differ for different AVs, and for different use cases.
Most research concludes that it is not practical to implement changes to physical road design on roads with a mix of vehicles of different SAE levels. Where there are sections, carriageways or lanes dedicated to a particular SAE level of vehicle, then certain physical design changes might be considered. On those roads where there is a mix of traffic, then improvements such as to road signs or markings could provide support to CAVs in addition to helping improve safety for non-connected or automated vehicles, but further research is needed to demonstrate the benefits of those.
In almost every area, there are different schools of thought and approaches as to how, or whether,

changes should be made to the design of physical infrastructure to support CAVs. This is discussed further in section 1.6.

1.3 Digital Infrastructure

Digital road infrastructure is defined here as "the digital representation of road environment required by Automated Driving Systems, C-ITS and Advanced Road/Traffic Management System".

1.3.1 Introduction to CAV systems

Connected and Autonomous Vehicles (CAVs) syndicate connectivity and automated technologies to assist or replace humans while they drive. They combine the use of advanced sensor technology, on-board and remote processing, GPS and telecommunications to accomplish this.

Connected Vehicle (CV) systems enable a car to access the Internet, communicate with smart devices, as well as with other cars and road infrastructures, and collect real-time data from multiple sources (Coppola & Morisio, 2016). There are typically three types of CV systems identified: V2V (vehicle to vehicle); V2I (vehicle-to-infrastructure or vice versa, I2V); and V2D (vehicle-to-device or vice versa, D2V). Or on a general level, described as V2X (vehicle to anything).

Automated Vehicle (AV) systems enable a car to safely complete journeys without the need for a driver in all normally encountered traffic, road and weather conditions (Department for Transport, 2015). There are six levels of AV systems widely adopted by industry, ranging from zero to five (SAE, 2014).

Despite the fact that CV and AV are very different, these two concepts are often confused with each other. CV is the enabler of the AV, and CV has a significant influence on the AV. It is widely accepted by the industry that the combination of connected and automated technologies will create a safe and reliable vehicle (Shladover, 2018).

For most of today's conventional infrastructure, there are no digital infrastructure data available that denotes Class E in the ISAD classification. In the absence of redundant second sources of information, the vehicle is exclusively reliant on its onboard sensor systems to recognise road geometry and road signs independently. This can be through utilising many advanced technologies, for example:

- Lidar has an array of laser beams, which can create 3D images of objects helping the car 'see' hazards along the way. This device calculates how far an object is from the moving vehicle based on the time it takes for the laser beams to hit the object and come back. These high intensity lasers can calculate distance and create images for objects in an impressive 200m range.
- Cameras help the car to 'see' objects around it. These include the road features (e.g. traffic signs, safety barriers, road markings, etc.) and other road users. The videos captured by the camera are intelligently interpreted by the car's inbuilt software, to discern information like road signs and traffic lights.
- Bumper Mounted Radar can enable the car to be aware of vehicles in front of it and behind it. This technology has been used in adaptive cruise control systems.
- An aerial receives information about the precise location of the car. The car's GPS inertial navigation unit works with the sensors to help the car localise itself.
- Ultrasonic sensors on rear wheels can keep track of the movement of the car and will alert the car about the obstacles in the rear. These sensors are already used in 'Reverse Park Assist' technology.
- Altimeters, gyroscopes, and tachymeters can measure various parameters, that can offer highly accurate positional data for the car to operate safely.
- Software/algorithms help the car to analyse the data gathered by sensors to make safe and intelligent decisions on roads.

1.3.2 Digital infrastructure Components

1.3.2.1 Sensors, connectivity and cloud

Convectional infrastructure sensors: Some existing sensors on the road infrastructure could potentially improve the safety and efficiency of autonomous vehicles. For example, Rebsamen et al. (Rebsamen, et al., pp. 1-5) investigated the feasibility of using traffic camera to provide crucial information about the surrounding environment of a vehicle when on-board sensors cannot detect it.

Road Marking Units (RMUs): These intelligent electronic devices are integrated into the next generation of road markings. Two types of sensors are used in RMUs: a magnetic sensor and a high-performance accelerometer. These sensors can be used to measure and estimate properties of road surfaces, vehicles, and traffic situations. These devices facilitate safe and efficient interaction between drivers and the road infrastructure. These devices can notify the driver of three important safety issues: the end of the queue, the wrong way to drive on the highway, and the overtaking danger (Birk, Osipov, & Eliasson, 2009).

Road Side Units (RSUs): speed limit beacons can be used to control speed and regulate traffic flow and magnetic nails/reflective strips can be used for lane keeping and infrastructure-assisted merging and lane changing (Zhang, 2013).

Internet of Vehicles: Gerla et al. (Lee, Gerla, Pau, Lee, & Lim, 2016)discussed with the help of vehicular cloud, the communication, storage, intelligence, and learning capabilities will allow the vehicles to anticipate the customers' intentions. Eltoweissy, Olariu and Younis (Eltoweissy, Olariu, & Younis, 2010) proposed the concept of Autonomous Vehicular Clouds (AVCs). AVCs provide on-demand solutions to events that cannot be mitigated effectively in a proactive way or with pre-assigned assets and offer autonomous cooperation among vehicular resources and seamless integration and decentralized management of cyber-physical resources. Hayeri, Hendrickson, and Biehler (Hayeri, Hendrickson, & Biehler, 2015) argued that in a fully connected world, information will be transmitted directly to onboard units in vehicles via V2I and V2X. The current ITS message signs and radio advisories will be obsolete.

1.3.2.2 Digital maps & road database

Automated vehicles require digital maps to help with navigation, planning, localisation, and comfort. These digital maps are highly detailed (e.g. 3D lane geometry), highly accurate (e.g. sub-meter absolute, decimetre-level relative), and richly attributed (e.g. lane-level attributes, position landmark, road DNA (a robust and scalable positioning content)) (TomTom, 2016).

Noh, An and Han (Noh, An, & Han, 2015)present and test a cooperative system by V2I communications for highly automated driving. The data fusion integrates road infrastructure with a high-precision road map to produce the V2I augmented map. It can enhance the capability of situation awareness as well as expand the range of environmental perceptions.

Detailed digital maps are considered as the most fundamental infrastructure for automated vehicles (Hu, et al., 2013). They can be used to develop a Velocity Profile Planning Module that adapts vehicle speed based on the road design characteristics (Bauer & Mayr, 2003); can improve road users' safety in major dangerous situations based on five set applications (hazard and incident warning, speed alert, road departure prevention, cooperative intersection collision prevention, and safety margin for assistance and emergency vehicle) on the road side.

Costs have been estimated for the Finnish Transport Agency for ODD features. Unit cost estimates are provided for deployment of HD Maps of roads and structures, including LiDAR data; signs and/or barriers for access control; satellite positioning enhancement with land stations; positioning enhancement with land stations; low-latency wireless broadband; provision of safe harbours; and VMS/C-ITS warnings at road works and automated road works and maintenance vehicles. They also estimate annual maintenance costs for each of the ODD features deployed (Traficom, 2019).

1.3.2.3 Exact positioning of vehicles

According to Böhm and Scheider (Böhm & Scheider, 2007), the most important challenges when it comes to cooperative systems between vehicles and infrastructure are the accurate geo-positioning of the vehicles, matching events with the in-car map database, and presenting the data to the driver.

1.3.2.4 Digital traffic rules and regulations

Traffic regulations describe the constraints under which a vehicle is allowed to move on a road, covering aspects like speed, allowed vehicle characteristics such as width, height, weight and permissible movements like lane change, right/left turn, overtaking, etc. Traffic regulations apply independently of the automation level.

Traffic regulations are implemented traditionally in the ISAD level E world via road signs or markings placed on, above or near the road. Vehicles detect traffic regulations via sensors (e.g. cameras), but the detection may be difficult in certain environments (adverse weather conditions, sign "forest" in urban scenarios), hence digital regulations become important at higher levels of ISAD.

Dynamic traffic regulations become possible – e.g. access regulations based on certain vehicle criteria that only apply if certain conditions are met.

Digitalisation of traffic rules and regulations is a priority recommended action in the project MANTRA roadmap (MANTRA, Road map for developing road operator core business utilising connectivty and automation, 2020). It notes that METR (Management for Electronic Traffic Regulations) studies and pilots are ongoing, managed under CEN/TC 278 Intelligent Transport Systems. It also recommends development and standardisation of Trusted Electronic Access Points for wider deployment.

1.3.2.5 Fleet monitoring and supervision

Many organisations will operate remote centres to monitor and manage their CAV fleets. Where NRAs manage fleets for operational and winter maintenance, then they will need to set up fleet supervision centres. This will require regulations for remote supervision and control of vehicles; also a legal framework for a remote driving license for operators at these centres; there needs to be secure communications channels for such remote supervision; and NRAs need to determine which parts of their networks that their remote fleets can operate on. (MANTRA, Road map for developing road operator core business utilising connectivty and automation, 2020).

1.3.3 Digital Twin and Naked Highway

The term 'naked highway' refers to roads without physical roadside signs, such as speed limit signs, smart motorway gantries, and stop signs. Instead, all traffic signs will be digitized and transmitted to vehicles.

Also, in future, physically separated lanes may become superfluous and the available road width can be divided into lanes in a flexible and dynamic way as a function of the time of day, weather conditions and the actual traffic (so-called target group lanes), possibly even with different speed regimes. Lane allocation can be done via I2V communication. If self-driving trucks are excluded from one or more lanes via automation, lanes on road sections with no or very limited interaction may be narrowed. However, in places where there is a lot of exchange (entrances and exits) narrowing may not be appropriate. (Belgian Road Research Centre, 2020).

DiREC Summary and Conclusions on Digital Infrastructure

This section, summarised in

Appendix 1.6: Summary Table, has highlighted many ways in which digital infrastructure components can support CAVs.

Satellite positioning support is key to automation functions. High accuracy positioning needs infrastructure support such as land stations, and special research is envisaged for positioning performance in challenging environments, particularly tunnels. Static digital information is relevant to low level of ISAD, while dynamic digital information is important to higher levels of automation. HD Mapping is seen as important to provide both static and dynamic information in a high-precision environment.

The report on Assessment of Key Road Operator Actions to Support Automated Vehicles (Austroads, 2017) concluded that "there will be greater focus on digital mapping and data exchange as part of core operating capabilities into the future. Road operators will need to consider how best to support these elements, which data it should make available, and what it should be the authoritative source for. The fact that the private sector is currently collecting and supporting AVs with data, may mean that the balance of the roles of public and private sectors may shift over time. Ensuring that data is available to ensure the best operational outcomes on the network will be a key challenge for road operators. The need to consider and protect the privacy of road users will continue to be a significant issue."

As with physical infrastructure, there are different schools of thought and approaches as to how, or whether, NRAs should involve themselves in the provision and maintenance of data and digital infrastructure to support CAVs. There does appear to be appetite among NRAs to identify and prioritise gaps in physical infrastructure that may be closed by digital infrastructure. These include advance notice of roadworks, real-time traffic signals particularly where traffic lights may be blocked by other vehciles or barriers, coverage of blackspots or AV/HD maps for locations with insufficient lighting such as tunnels. (Austroads, Minimum Physical Infrastructure Standard for the Operation of Automated Driving, 2022).

However, from the results of stakeholder interviews under DiREC, many NRAs feel that they are under-researched with regard to current technologies and future technology direction. It is clear that there will be different requirements and different priorities within the strategic road network of a country, and many NRAs are only now beginning to understand, define and plan for what those levels of support might be. Better engagement with OEMs is necessary to achieve this.

1.4 Operation and Services

1.4.1 Definitions

Operations and services comprise the following for conventional infrastructure: incident and event management; crisis management; traffic management and control; road maintenance; winter maintenance; traffic information services; enforcement; road user charging. (MANTRA, Road map for developing road operator core business utilising connectivty and automation, 2020).

1.4.2 Operation Management

1.4.2.1 Incident and event management

The CEDR project PRIMA proposed a concept of pro-active incident management and incident prevention, in which connected vehicles plays a key role in detecting and reporting incidents (Weekley, Cornwell, & Nitsche, 2017). Fully automated incident warnings and rerouting services are possible. The incident management services will be improved by the advanced environment perception of CAVs. The sensors of CAVS can detect the information of the finalisation of incident clearance and report to other road users (Kulmala, et al., 2020).

Project MANTRA examined the impacts of two different types of automated maintenance: a safety trailer in front of a slow moving work zone (15 km/h), and a winter maintenance truck for snow ploughing (45 km/h) and preventative salting (60 km/h). In its simulation testing, the position of the automated maintenance vehicle was communicated to other automated vehicles only, combined with advice to move to the other lane. It showed that communication leads to delays for all types of vehicles, mainly caused by hindering non-automated vehicles not always being able to merge into a lane due to large speed differences. No communication (i.e. only using sensors to detect that the speed of the vehicle(s) in front is low) results in the smoothest traffic flow. It concluded that communication should be available to either both automated and non-automated vehicles or neither, rather than being given to automated vehicles only. (MANTRA, Impacts of automation functions on NRA policy targets, 2020).

Project MANTRA also proposed several actions in relation to incident and event management, including: standardisation and marking and provision of data at incident sites at an EU level; standardised CAV response to emergency vehicles; and legal harmonisation to enable sharing of safety critical data.

1.4.2.2 Crisis management

Crisis or emergency management generally includes law enforcement, fire rescue, emergency medical service, vehicle breakdown and recovery teams, and the road authority's maintenance teams, mobile safety patrols and traffic management or control centres. Depending on the severity of the event, local, regional and national agencies may also be involved.

Driverless and self-driving vehicles could have a major role in evacuation and rescue operations, although some crises may be outside the ODD of the automated vehicle.

The crisis may also relate to essential communications infrastructure for CAVs. Also, the communications networks might not function at all due to a disaster, such as a terrorist attack of a natural catastrophe. (MANTRA, Road map for developing road operator core business utilising connectivty and automation, 2020).

1.4.2.3 Traffic management and control

Traffic management is concerned with safe and efficient operation of road networks. Cooperative traffic management has evolved with the development of connected vehicles, and will continue to evolve as the building blocks develop. These building blocks include classification of roads according to a network hierarchy, geo-fencing, establishment of network performance levels of service specifications, triggering conditions, and an overall picture of the traffic situation. There will be an ability to optimise traffic management operations, which will require cooperation among road users, public traffic management centres, and private service providers. (MANTRA, Road map for developing road operator core business utilising connectivty and automation, 2020).

Speed is one of the most crucial road attributes for CAVs and is an important component of traffic management and control. Intelligent Speed Assistance (ISA) is included in all new vehicles as part of the EU General Safety Regulation (GSR) Directive (European Commission, Revision of the EU General Safety Regulation and Pedestrian Safety Regulation, 2018), to give feedback to the driver and them keep within the speed limit. ISA uses speed sign-recognition video camera and/or GPS-linked speed limit data to advise drivers of current speed limit and automatically limit the speed of the vehicle as needed.

Automated driving systems can also adapt the speed of the vehicle based on the road design characteristics. (Austroads, 2017).

1.4.2.4 Road maintenance

NRAs are usually hesitant to ensure certain condition levels for road marking or cleanliness of road signs because of potential liability. There are many reasons why it may not be possible for roads agencies to implement strict higher maintenance levels, for example because of bad weather or damage by vehicles. It is also important to consider removal of old road markings to reduce potential confusion to CAVs.

Maintenance costs would increase with increased levels of inspection and cleaning. A harmonized definition of machine readability at a European level would provide NRAs with some legal certainty, however NRAs still do not want to be held liable. (MANTRA, Road map for developing road operator core business utilising connectivty and automation, 2020).

New vehicle use cases, particularly heavy vehicle platooning, will also require a different consideration of maintenance regimes for structures and pavements.

The UK RAC Foundation (RAC Foundation, 2017) notes that experience in other transport sectors, such as aviation, suggests that the approach to maintenance has to change as automation increases. Also, maintenance costs typically increase – partly because the infrastructure has to be better maintained for safety reasons, and partly because it becomes more sophisticated, meaning that the maintenance workforce has to be more skilled and, therefore, charges more for its services.

Roadworks are of particular concern to AV manufacturers and system suppliers. It is necessary to ensure that roadworks become well planned events and real time information is provided to AVs. This information should include physical changes to the road layout, which may be more complex for an AV to negotiate. There are currently significantly different approaches between projects and across different jurisdictions and there is a need for consistency in treatment of these environments. (Austroads, 2017). However, there are opportunities through implementation of work zone protection in CAVs.

1.4.2.5 Winter maintenance

As a part of road maintenance, CAD may impact on requirements and service levels, but the objectives and mission of winter maintenance will remain the same.

A highly automated winter maintenance vehicle fleet could significantly reduce the workload of winter maintenance staff, and result in a smoother traffic flow with faster operation speed.

The possibility for vehicles to provide road condition data through V2I communications to the road operator could provide major improvements to predictive maintenance. (MANTRA, Impacts of automation functions on NRA policy targets, 2020). Mercedes Benz is testing the provision of data on snowy or icy road conditions through electronic stability control (ESC) and anti-lock braking systems (ABS) to enable more efficient winter maintenance planning, although such data may only be obtained where vehicles tend to accelerate or decelerate e.g. on ramps or at exits or approaches.

1.4.2.6 Traffic Information Services

With the growth of autonomous vehicles, the role of traffic information is changing. Policy in the past has been to provide information about traffic conditions and incidents on the road network to drivers, then let them make their own decisions. The traffic manager needs to decide on behalf of individual drivers and automated vehicles so that the transport system can perform at its peak while reducing emissions, congestion, and fatalities on the road.

Highly automated driving will be less reliant on “traditional” traffic information than human drivers or travellers. Highly automated vehicles can collect and transmit data related to traffic and road conditions to traffic management centres and share with other road users.

1.4.2.7 Traffic Enforcement

The aim of traffic enforcement is to support safe and efficient road transport. Enforcement policies are determined by government, roads authorities and police. NRAs typically set speed limits following the polices agreed, and decide locations of speed cameras and stations.

Digitalisation, connectivity, automated driving and cooperative traffic management will allow evolution of new enforcement systems. By utilising V2I communication and connected traffic management, direct enforcement is possible via information exchange with vehicles providing data on speed, weight, environmental category, etc. (MANTRA, Impacts of automation functions on NRA policy targets, 2020).

1.4.2.8 Road user charging

Road use charges can be used as a tool for promoting the introduction and use of highly automated vehicles, although it is felt that such a tool would only be used to a limited extent and for a limited period of time. (MANTRA, Road map for developing road operator core business utilising connectivty and automation, 2020).

There are various potential impacts on operations and use of technologies, including GNSS-based payment systems with virtual toll plazas, automatic number plate recognition, and charging based on number of occupants of vehicles.

Some physical impacts could include dedication of a physical lane for automatic tolling and guidance to that lane for highly automated vehicles, and update of HD maps with tolling information.

DiREC Summary and Conclusions on Operations and Services

A separate CEDR project TM4CAD (Traffic Management for Connected and Autonomous Driving) is exploring the role of infrastructure in creating awareness of Operational Design Domains (ODDs) for CAD systems, hence DiREC is not exploring TM in detail.

It is clear that NRAs need to be invovled in the discussions around Traffic Management and the various operations and services (incident and event management, road maintenance, traffic enforcement etc). Introduction and uptake of CAVs will have implications for traffic volumes and speeds on the network, and NRAs should have a clear position on how to respond via traffic management. The various digitial infrastructure components described in the previous section (sensors, HD Mapping, digital traffic rules and regulations etc.) all have a part to play in traffic management, and NRAs must be fully involved in discussions around the design and provision of such services.
Consideration will also need to be given by road operators in the next decade to operations and services for digital and communications infrastructure, including data centre maintenance; software updates; cloud security; and data privacy. These aspects should be considered under the CRF being developed under the DiREC project.

1.5 Roadmaps and Pilots

1.5.1 Roadmaps

A number of roadmaps are available at EU and national levels, including internationally. These documents show the way to achieve a transport system fully connected (V2X), meaning cooperative driving in specific time horizons. At EU level the documents attempt to harmonize across member states common approaches, definitions, and frameworks; while at national levels, focus is on scenario/project based specific activities to enable automated, connected, and cooperative mobility. A list of roadmaps identified, with a short synopsis, is included below.

- The project MANTRA roadmap (MANTRA, Road map for developing road operator core business utilising connectivty and automation, 2020)consists of tables describing actions in different areas of the national road authority core business areas up to 2040. The 92 actions of the roadmap tables were prioritized by NRA and other experts on automated driving resulting in 22 priority actions. The actions were categorized according to business area, the content and timeframe of the action, the automated driving task and stakeholders affected, the legal prerequisites, the responsible stakeholders and their responsibilities, the roles of CEDR and NRAs, and the possible risks. Key priority areas include provision of additional emergency bays, wide shoulders and safe harbour areas for CAVS; provision of road markings of sufficient retro-reflectivity in different visibility and weather conditions; and machine readability of road signs.

- European Automobile Manufacturers Association Roadmap for the deployment of automated driving in the European Union (ACEA, 2019). It defines three levels of automated driving (i.e., assisted, automated, and autonomous driving) and how to get there by naming four key focus areas such as security, user adoption, AI, and testing. For the deployment across member states, it is important the introduction of automated lane keeping systems (ALKS), standardisation, dynamic traffic management systems, event data recorder (EDR), revision of EU type approval regulation, harmonisation of traffic laws, liability regime, adaption of physical and digital infrastructure, and perform large scale cross-border testing on open roads.

- According to Zenzic's UK Connected and Automated Mobility Roadmap to 2030 (Zenzic, 2020), digital signage should be sufficiently evolved enough by 2027 to enable local authorities to be able to reduce their investment in road-side infrastructure and potentially start to remove some pieces of infrastructure. Trials are underway across the UK to develop the technologies which will underpin digital signage, but in terms of a fully 'naked' highway, it is more realistic to think of this as something that will happen in 2047 or 2057.

- The European Road Transport Research Advisory Council (ERTRAC) has published its Connected Automated Driving Roadmap (ERTRAC, 2019). That roadmap defines the challenges for implementation of higher levels of automated driving functions. It also provides development paths for three different categories of vehicle: passenger cars, freight vehicles, and urban mobility vehicles. Each roadmap identifies automation functions from SAE (such as adaptive cruise control, stop and go, traffic jam chauffeur, highway chauffeur etc.) and estimates timelines at when these different levels of automation will penetrate road networks.

- In Sweden, the National Road Administration (Trafikverket, 2019) has produced a roadmap for a connected and automated transport system. It highlights the pathways to achieve accessibility and sustainability goals of the Swedish society for 2030. The roadmap identifies six dimensions to focus on such as user behavior and acceptance, physical and digital road infrastructure, data management, IT and communication infrastructure, vehicle developments, regulations and legal framework, and business models. Each dimension is described briefly pointing out challenges and most importantly, questions that need to be answered. For the physical infrastructure, the challenge is that its development is not as fast as the digital infrastructure, because it takes time to adapt the physical infrastructure.
- The Australian Road Research Board (Austroads, Minimum Physical Infrastructure Standard for the Operation of Automated Driving, 2022) produced a number of reports on support for automated driving. These reports acknowledge that the needs for safe and efficient operation of CAVs may differ in some respect from the needs of human road users. They provide guidance to road agencies in Australia and New Zealand on appropriate investments in the road network to support automated driving, based on projected market share of CAVs in specific CAV markets under different uptake scenarios. In the immediate to short term (next 5 years), the reports recommend that road agencies focus on implementing changes to signs and traffic signals, to increase their interpretability to both current and emerging CAVs; and to focus on improving visibility of line markings. Beyond 2025, they recommend shifting to supporting partial automation to supporting full automation. This might include ensuring availability of suitable safe stopping zones on motorways, supporting remote parking facilities, and mobility hubs. They also identify several potential infrastructure improvements that might be valuable to support CAV uptake but which have challenging economic investment cases. One example is the use of intelligent equipment and signs at temporary work zones, whose economic feasibility might improve if they could be implemented at lower cost, or if they were used in targeted deployments in higher traffic areas. Other digital infrastructure and/or vehicle intelligence might provide alternative methods to make these economically viable in the longer term. Finally, they make the point that rapid development in sensor and processing technology means that the costs and benefits can change rapidly, and there should be regular review of any recommendations.
- Transport Scotland has published a roadmap for the adoption of CAV technologies where it explored where and how CAV could be used, where and how benefits could come from, and what initiatives might be required. Key themes identified from stakeholder consultation were the need for clarity of investment (infrastructure), accessibility and inclusivity (rural areas, low income groups), data (privacy, cybersecurity), collaboration (public-private close partnerships), and information (communicating the benefits of CAVs). The document further outlines 13 initiatives on how CAV technology will be adopted in Scotland. Important aspects are the provision of real-time data and simulation studies to allow testing in virtual environments. Project 'CAV Forth' is highlighted, which is a 14-mile route of autonomous bus capability. (Transport Scotland, 2020).

- The Finnish government has published a strategy to uptake digital infrastructure to support CAV technologies (Ministry of Transport and Communications, Finland, 2018). The broadband network is well-developed and the government is encouraging optical fibre connections for high-speed wireless connections. Vehicles are expected to be terminals requiring real-time information as well as floating 'sensors' collecting and communicating huge amounts of information. Important aspects to secure the foundations for autonomous transport are reliable and high-quality networks with enough data transfer capacity. Other important aspects are privacy (cybersecurity) and digitalisation in rural areas. The strategies to achieve the above goals include promoting the construction of 5G network allocated to high frequency band (26 GHz) and low frequency bands of 3400 – 3800 MHz, in parallel with optical fibre network construction.

1.5.2 Pilots

There have been many pilots completed or ongoing. Some are summarised and listed below.

There is a need for a common EU approach for implementing, operating, recording, analyzing, comparing, data processing, and reporting of pilots, scenarios, and use cases to enable the benchmarking of project results and speed-up learning from experience. Pilots should be very specific with goals and key performance indicators (KPI) to be able to measure their impact on safety, efficiency, costs, etc.

Also, NRAs should focus on demonstrating the benefits that CAVs can bring into the transport system, setting up clear visions, plans, strategies as well as defining roles, responsibilities, tasks, and creating a sound ecosystem based on cooperation and trust, very likely prioritizing public transport systems.

- NordicWay was an EU project to test and demonstrate the interoperability of cellular C-ITS (cooperative ITS) services both for passenger and freight traffic, piloting continuous services offering a similar user experience in the whole NordicWay network in Denmark, Finland, Norway and Sweden. NordicWay was a real-life deployment pilot, aiming to facilitate a wider deployment in the Nordic countries and in Europe in the next phase. The common key services were: 1. cooperative weather and slippery warning. 2. cooperative hazardous location warning. 3. cooperative road works warning. 4. probe vehicle data. (Scholliers, 2017).

- InterCor. The Interoperable Corridors project is a European project which aims to connect the C-ITS corridor initiatives of the Netherlands C-ITS Corridor (Netherlands-Germany-Austria), the French corridor defined in the SCOOP@F project, and the United Kingdom and Belgian C-ITS initiatives. The InterCor project plans to achieve a sustainable network of C-ITS corridors providing continuity and serving as a Test Bed for Day-One C-ITS service development and beyond. (InterCor, 2021).

- L3 Pilot. The European research project **L3Pilot** tests the viability of automated driving as a safe and efficient means of transportation on public roads. It focuses on large-scale piloting of SAE Level 3 functions, with additional assessment of some Level 4 functions. The functionality of the systems will be exposed to variable conditions with **1,000 drivers and 100 cars across ten European countries,** including cross-border routes. (L3 Pilot, 2021).

- Project SLAIN conducted CAV Readiness pilots in Croatia, Spain, Greece, Turkey.

- The C-Roads project [1] includes many pilot projects focusing on connectivity for supporting automated driving. These included projects in Austria, Belgium/Flanders, Belgium/Wallonia, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Netherlands, Norway, Portugal, Slovenia, Spain, Sweden and UK. The focus was on the interoperability and testing of Day 1 and Day 1.5 C-ITS hybrid (short-long range) communication services.

[1] https://www.c-roads.eu/platform.html

DiREC Summary and Conclusions on Roadmaps and Pilots

It is clear from these roadmaps and from stakeholder engagement that there is significant uncertainty over the timelines for uptake or deployment of CAVs, which will underpin the need for investment in physical and digital infrastructure and operations. Some experts think that fully automated vehicles will not be available until after 2070, with market penetration of SAE Level 4 vehicles expected to be ~ 15% by 2030 (Belgian Road Research Centre, 2020). Current surveys on acceptance of self-driving or driverless vehicles indicate reservations of many people towards such vehicles, which may be different in different countries.

There is also significant uncertainty as to whether automated driving will lead to an increase in traffic, and what that increase might mean in terms of the capacity of existing road networks.

The RAC Foundation highlighted that the road infrastructure adoption of CAVs will be driven by two important aspects: (i) what level of automation Governments decide to support and (ii) how Governments will implement the required changes. The speed of these changes will rely on the desire and ability of the Governments to support CAVs technologies. (RAC Foundation, 2017).

From the sample of roadmaps reviewed here (which is by no means exhaustive), and from interviews with NRAs, some key messages/questions can be drawn for NRAs to support CAV technologies. Firstly, it is the decision of the Governments to what level of CAV to support/aim for. This decision will heavily affect all other components of the transport system, therefore, the benefits of CAVs need to be clearly stated and need to be aligned with wider societal goals.

For both physical and digital infrastructure some aspects that need to be further developed are:

- Standardisation (e.g., of line widths, reflectivity, sign placements)
- Definitions (e.g., ODD, driver)
- Roles and responsibilities (e.g., stakeholders, engagement, financing)
- Data exchange/refinement (e.g., interfaces, formats, fusion, security, privacy)
- Facilitate new business models (e.g., in-house, outsourced, public-private, fair competition)
- New type approvals (e.g., new services, new operations)
- Interoperability (e.g., 5G, cloud services, HD maps, digital transportation infrastructure)
- Repositories of digital roads

1.6 Section Summary and Comment

Physical Infrastructure

In almost every area of design, there are different schools of thought and approaches as to how, or whether, changes should be made to the design of infrastructure to support CAVs.

To pick one example, platooning on bridges, several research projects note that current bridge design standards make assumptions about the number of vehicles likely to be on the bridge at any one time. Yet a valid approach advocated by some roads authorities would be, rather than increase the design standards for bridges, to use C-ITS technology to instruct the platoon to increase the gap between trucks.

Another example is in relation to issues around identification and visibility of road signs or road markings. One approach might be to invest heavily in standardisation and maintenance of physical road signs (as recommended by project SLAIN), another approach might be to leave it up to the vehicle OEMs to recognise existing signages through extra vehicle intelligence, while yet another approach would be to invest in making digital sign information available to CAVs.

None of these approaches is wrong. But these examples do serve to emphasize that NRA support to CAVs needs to be aligned with wider government policy on sustainable transport.

Digital Infrastructure
There is also debate over how much effort roads authorities should put into digital infrastructure for AVs. Level 4 AVs, which are restricted to operating in certain ODDs, will be limited to areas with adequate digital infrastructure. Level 5 AVs should not need to rely on external digital infrastructure to operate, however a number of studies suggest that AVs will drive more defensively than humans, suggesting slower speeds and more congestion. CAVs will likely have significant implications for usage and speeds, especially in mixed vehicle environments, and NRAs should have a clear position on how to respond via traffic management. Digital infrastructure, allowing V2I communications, is a potential solution to this through centralized traffic management. However, it potentially means different AV operating scenarios within a country. In cities and major highways between cities, it will be more important for governments to invest in digital infrastructure and require AVs to interface with the systems they establish. While in rural areas, for example, AVs may have to rely more on their own systems.

Operations and Services
NRAs need to be involved in the discussions around Traffic Management and the various operations and services (incident and event management, road maintenance, traffic enforcement etc). Introduction and uptake of CAVs will have implications for traffic volumes and speeds on the network, and NRAs should have a clear position on how to respond via traffic management. The various digitial infrastructure components described in the previous section (sensors, HD Mapping, digital traffic rules and regulations etc.) all have a part to play in traffic management, and NRAs must be fully involved in discussions around the design and provision of such services.

Future Uptake of CAVs

There is a lot of uncertainty about future uptake of CAVs and future travel demand. This impacts budgeting and planning, and in general causes uncertainty about whether NRAs should support CAD, and the type of support that they should consider. Uptake of CAVs is likely to be driven by legislation. Once the legislation is in place, then people's perceptions and behaviours will likely change quickly. Future projections of CAVs on the network, and usage of those CAVs, will impact the business case for NRA support to CAVs. It is also important to understand that NRAs are funded by the taxpayer, and in general investment should be inclusive, and should be seen to benefit all road users.

In the NRA stakeholder interviews, some NRAs highlighted a need for a collective international NRA approach to say, *"These are the levels of service we can provide, and this is how much it is going to cost, and this is how long it will take us to implement on our networks".* However, to date, there has been insufficient engagement between NRAs, OEMs and telecoms providers on the capabilities and future technologies of vehicle systems. Early engagement and understanding is necessary for NRAs to articulate their strategies, identify roles and responsibilities, and to plan and budget to support CAVs. Roles and responsibilities of NRAs in the areas of physical and digital infrastructure and services are still evolving. There will also be different requirements and different priorities within the strategic road network of a country, and many NRAs are only now beginning to define and plan for what those levels of support might be.

Road Safety
The literature and the NRA stakeholder interviews identified a significant recent focus on road safety in Europe. The EU Road Safety Policy Framework (2021 – 2030) (European Commission, Next Steps towards 'Vision Zero', 2020) describes the EU's approach to meeting its long-term goals to close to zero deaths by 2030 ("Vision Zero"). It recognizes new trends in connectivity and automation and their ability to help achieve the Vision Zero goals.

The EU has mandated new EU infrastructure safety rules [2] which include risk mapping and safety rating for roads of the strategic Trans-European Transport Network (TEN-T), motorways and primary roads, although without prescribing a specific methodology. These revised rules prepare the way for higher levels of automation in vehicles, by launching work towards specifications for the performance of road signs and markings, including their placing, visibility and retro-reflectivity. This is already important for the functioning of driver assistance systems like Intelligent Speed Assistance and Lane Keeping Assistance and will become more important as the level of automation increases.

The SLAIN project (SLAIN, D7.2: Other initiatives to meet the needs of automated cars, 2020) has a heavy focus on road safety. It identifies that there is still much research needed in relation to physical road attributes and crash types, rates and patterns. It calls for research into the effectiveness of individual countermeasures (rumble strips, striping, adjustments to lane widths) with increases in penetration of CAVs, as well as trials to test other relevant road attribute requirements and performance under different configurations (retroreflectivity, weather conditions etc.). It also recommends research into the effects of different speed profiles in mixed operating environments. Speed differences are problematic for road safety, and CAVs provide the ability to reduce speed differences among vehicles. Headway is also an important issue in road safety delay (Oakes-Ash et al, 2018) which should be researched further.

Road Financing

All of the uncertainties regarding future uptake and technology options, and the impacts on road safety, will affect road financing too. Choices to upgrade or innovate in existing road sections can follow different criteria than investing in new roads or road sections. The path forward for physical, digital, and operational road infrastructure in support of CAD requires evidence-based research and strong partnerships between stakeholders. Road owners and operators need full appreciation of the investment business case and need to have confidence that the interventions will deliver results.

Infrastructure Classification Systems

The CAD RoadMap (ERTRAC, 2019) recommends that the categorisation of infrastructure support needs to be standardised based on the ISAD levels, which provide additional information for on-board decisions of CAVs and enable a better end-user acceptance. Literature review identified several proposed infrastructure classification systems based around ISAD.

The PIARC Special Project Smart Road Classification System (Garcia et al, 2021) builds upon different layers and interactions with other classification systems including ISAD, road typology and expanded classifications of users. It recognises that connectivity and automation create new kinds of user interactions. See Appendix 1.4: PIARC Special Project Smart Road Classification.

The Finnish Transport Infrastructure Agency also proposed a classification of physical and digital infrastructure components, environmental conditions and traffic management services for different ISAD levels (Finnish Transport Infrastructure Agency, 2021). This classification was proposed for the Finnish motorway network, but may be considered as a framework for other motorway networks. See Appendix 1.5: Infrastructure Support Level Classification.

A related idea commonly discussed is the possibility of 'certifying' road sections as being able to support specific AV use cases. Road operators could have responsibly for applying certificate classifications. This could also include for example by ruling out certain types of vehicles (or certain use cases) on specific road sections – so rather than certifying for particular types of vehicles, road owners could rule out certain types of vehicles. Requirements for certification could include any combination of physical, digital and connectivity services. However, such a scheme could mean liability issues for road authorities. (Austroads, 2017).

[2] https://www.eumonitor.eu/9353000/1/j4nvk6yhcbpeywk_j9vvik7m1c3gyxp/vl3xhlfcyhzo

We also identified indices which address some of the core areas of the proposed CRF. The Autonomous Vehicle Readiness Index (KPMG, 2020) for example is based on 28 different measures under 4 pillars - policy and legislation, technology and innovation, infrastructure and consumer acceptance. Its measures include assessments of the governance in a country, of innovation in general as well as in AVs and digital infrastructure, coverage and extent of EV charging stations and broadband; and adoption and use of technology including ride-sharing market penetration. The list of 28 Autonomous Vehicle Readiness Index indicators is given in

Appendix 1.7: Autonomous Vehicles Readiness Index.

The CRF is intended to be more focused on the physical and digital infrastructure and services to support CAV, nevertheless there are some concepts and indicators in the above proposals and studies that are worth investigating as the CRF develops. Areas for consideration should include 4G coverage, mobile connection speeds, cybersecurity, and cloud computing infrastructure.

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2 Infrastructure Connectivity

This section investigates what is meant by infrastructure connectivity, namely vehicle-to-everything (V2X) and vehicle-to-infrastructure (V2I). It also examines the current state of communications technologies to enable infrastructure connectivity, and the challenges for those technologies, namely, ITS-G5 and LTE-V2X / Cellular-V2X. The section also reviews how the most recent developments with their specifications will impact infrastructure connectivity for CAVs, as well as what the current standards are for both technologies under various C-ITS scenarios.

2.1 Understanding Connectivity

2.1.1 Vehicle to Everything (V2X) and Vehicle-to-Infrastructure (V2I)

In C-ITS, the term vehicle-to-everything (V2X) refers to low latency, high-bandwidth, and highly reliable communication between a broad range of traffic and transport-related sensors and developments. The main purpose of V2X technology is to improve road safety, energy savings, and traffic efficiency on the roads. This can be accomplished through the sharing of data between vehicles and other surrounding entities such as infrastructure (V2I), pedestrians (V2P), devices (V2D) and other vehicles on the road (V2V).

This section focuses on V2I and the communication technologies that allow vehicles to share data with road system devices and visa verse. These devices consist of RFID readers, signage, cameras, lane markers, streetlights, and parking meters among others. Currently there are two main communication technologies that exist on the 5.9 GHz band designated for V2X communication relating to C-ITS. These are ITS-G5/DSRC, based on WLAN and Status Vehicle Ad-hoc Network (VANET) and 5G/LTE-V2X/C-V2X, based on Cellular and Status IP.

2.1.2 WLAN: ITS-G5

WLAN (local beacon-based) technologies, often referred to as ITS-G5 [or simply 'G5'], DSRC, WAVE (US) and based on 802.11p, were used as the original V2X communication to transmit data between vehicles (V2V) and infrastructure (V2I) using special frequencies and protocols designed purely for transport. Because of the specialist and short-range nature of the link, many automotive manufacturers consider ITS-G5 as the most mature short-range communication technology for C-ITS. (Karoui, Freitas and Chalhoub, 2019) They are more reliable, more secure, and more rapid than existing cellular communications.

Additionally, due to the direct nature of the vehicular ad-hoc network provided by vehicle installed DSRC units, the WLAN technology does not require any communication infrastructure for V2V, making it particularly well-suited for vehicles to communicate where safety is critical in remote or underdeveloped areas. It transmits messages such as Cooperative Awareness Messages (CAM) or Basic Safety Message (BSM), and Decentralised Environmental Notification Messages (DENM). Other roadside infrastructure related messages are Signal Phase and Timing Messages (SPAT), In-Vehicle Information Message (IVI), and Service Request Message (SRM). The data volume of these messages is very low. For V2I communication, roadside units (RSUs) are required to be installed – which would mean high deployment costs in the short term for the NRAs.

2.1.3 Cellular: LTE-VTX / C-V2X and 5G

Cellular technologies, (often referred to as 3G, 4G, LTE and 5G) are based on mobile phone and data services. The key advantage is that it is widely used already: the networks are continuously improving and sustained by an external business case. Because of this, they can be used in any vehicle, old or new, or indeed by pedestrians, cyclists etc. (V2P, V2D). Existing user devices (smartphones) are easily complemented by systems (apps), and the investment needed on the infrastructure side is made by industry. It is important to differentiate between the various technologies, as well as each version, within the cellular family. 5G refers to next generation mobile communications run over a cellular network and is the next standard for cellular communications. When running, it will offer connectivity not just for road transport but for many IoT applications. It is already part of the national investment plan for telecommunications. While ITS-G5 is a specific approach tailored to road user applications,

5G, in the general sense, is not. In fact, the technology developed specifically to compete with ITS-G5 to deliver short range road safety-critical services is Cellular-V2X (C-V2X). Initially defined by 3GPP as LTE-V2X in Release 14, C-V2X can operate in several different modes: V2I, V2V and V2N. (Castañeda Garcia *et al.*, 2021) Release 15 of C-V2X was then specified to expand on V2X functionalities to support 5G. Though C-V2X provides a migration path to 5G based systems and services, it does suggest incompatibility and higher costs compared to 4G based solutions. As for Release 16, 3GPP has already discussed multi-RAT (Radio Access Technology) scenarios.(Castañeda Garcia *et al.*, 2021) In this specification, it is described that LTE-V2X will operate with New Radio-V2X (NR-V2X) in order to ensure interoperability. 3GPP is developing cellular standards for V2X communications aiming to offer better QoS support, larger coverage, high reliability and low latency. In addition to direct mode communication (V2I, V2V, I2V), this specification proposed a support for wide area communication over a cellular network (V2N) in which different elements that support V2N functionalities communicate with each other using Evolved Packet Switching (EPS). (Karoui, Freitas and Chalhoub, 2019) As with ITS-G5, investment for short-rang safety critical services to be provided by current LTE-V2X specifications also require deployment of localized road-side units. (Majeed, 2018b)
Summary table of what technology OEMs are leaning towards.

OEMs		
Organisation	**5G/LTE-V2X**	**ITS-G5**
Toyota	ü	ü
GM	ü	ü
Volkswagen		ü
Ford	ü	
BMW	ü	
Daimler	ü	
Audi	ü	
Volvo	ü	ü
Groupe PSA	ü	ü
Jaguar Land Rover	ü	
Lexus (Australia)	ü	
Renault		ü
Honda	ü	ü
Hyunda	ü	ü
Nissan	ü	
GSMA	ü	
Bosch	ü	ü
Waymo		ü

2.1.4 ITS-G5 and LTE-V2X Interoperability Challenges

The full benefits of V2X systems will take time to be realized because, for a vehicle to communicate with an entity, that entity must be equipped with V2X technology. Most entities like parking spaces, traffic lights, and traditional vehicles do not have the V2X systems, which means that they cannot communicate with the vehicles already using the system. As the market for V2X expands, vehicles will be able to communicate with other vehicles, traffic systems, and other road users like cyclists or pedestrians and their smartphones equipped with V2X systems. This is an important aspect of V2X technology that the NRA's can start putting into place. To establish effective and reliable short-range communication among CAVs, two conditions must be in place regardless of which technology is used. The first is for a common standard for direct V2V to be in place while the second is for a critical mass of cars to be equipped with compatible short-range communication technologies to achieve the required network effects. (Majeed, 2018a) Both standards for DSRC and ITS-G5 use similar hardware and have evolved over the past 20 years to work over medium-range distance (300m to 1km). They enable communication among fast-moving objects and allow for data rates of up to 25Mbps at minimal latencies. (Majeed, 2018a) As C-V2X technology is much younger, the lack of an agreed-upon standard for the technology is much slower in its progress in establishing short-range communication among vehicles. Automotive OEMs will need to equip vehicles with these communication capabilities as soon as possible and configure them to send messages, such as the intention to change lanes, even though there is no one to receive the messages yet. Only by doing so can a critical mass be achieved to enable CAVs to react to these messages and overcome any penetration issues. However, any extra cost from adding components to the car's bill of material with no immediate benefit is not a compelling case for the OEMs. Therefore, even agreeing on a common standard might not be enough, and the industry might have to agree, linked to suitable policy and legislation direction, that all cars are to be equipped with short-range communication.

With regard to putting a common standard for direct V2V in place, there are current concerns over interoperability challenges between ITS-G5 and LTE-V2X and unfair channel access opportunities presented by LTE-V2X dominance over the designated 5.9GHz spectrum. (Cziczatka and Ziegelwanger, 2019) The European C-ITS Deployment Group recognizes that in its current state, C-V2X is not backwards compatible with release 14, 15 and 16. The members have stated that C-V2X cellular VANET technologies do not comply to their functional needs, is not "inter-system interoperable", and does not provide solutions to not interfere with any other system in the 5.9 GHz band or the adjacent 5.8 GHz band. Furthermore, the C-ITS Deployment Group has also noted that there is a lack of business model or operator interest foreseen to date.

In relation to the issues of interoperability between C-V2X and ITS-G5, the main problems lie with C-V2X's long-term duty cycle fulfilling the limit of 1% per hour as set out by the ECC Report 228 (Electronic Communications Committee, 2015) a claim which is also supported by ECC Report 290 (CEPT ECC, 2019). While both technologies can operate on the 5875-5905 MHz spectrum, LTE-V2X demands a much higher proportion. While ECC Report 228 sets out a duty long-term duty cycle limit of 1% per hour and short term of 3% per second, C-V2X has a duty cycle ranging the full 1% (peak rate of 2% in worst case scenario*). (CEPT ECC, 2019) This dominance over the spectrum could lead to unfair transmit opportunities in the form of:

- "Cut-off problems" – C-V2X accesses the channel after reservation, while ITS-G5 is already using it. The ongoing ITS-G5 transmission is cut-off. This collision in transmissions could impair the channel used for safety messages
- "Trap problems" – C-V2X transmissions using subsequent timeslots would leave only 71µs space at the end of each subframe. This will "trap" or collide with high priority ITS-G5 transmissions who have a wait time shorter or equal to the 71µs gap
- "Blockade problems" – Aligning with the trap problem, C-V2X transmissions are scheduled subsequently. ITS-G5 Priority 2 messages such as CAM always have wait times longer than the 71µs gap. As they don't start transmissions until after the channel becomes idle, CAMs will be delayed if C-V2X occupies the channel

Through RSCOM19-34, Austria suggested that the European Commission enforce a duty cycle limit as well as polite spectrum access to reduce the risk of interference and delays and ensure fair channel accessibility. (Cziczatka and Ziegelwanger, 2019) Long-range cellular communication networks are not suited for low-latency road safety use-cases, but they do, however, play a key role in transmitting larger volumes as well as non-time critical data to vehicles. ITS-G5 is the only mature technology for safety critical low-latency V2X applications. In effect, the main bulk of investment for ITS-G5 technology would be equipping vehicles (96%), whilst investment in roadside equipment is expected to be low (4%). Due to a different business model, both, C-V2X long- and short-range communication services would very likely come along with license fees for chipsets, which would need to be paid to non-European companies. To date, early C-V2X chipset samples, whose readiness for mass production remains unclear, are only offered by a small group of American and Chinese vendors. Moreover, 3GPP Releases 14, 15 and 16 suggest that future C-V2X will very likely require significantly different equipment from the regular and already available non-V2X LTE modems. This is also true for the base stations. Currently available LTE base stations would need to be upgraded to cater for C-V2X. (Filippi *et al.*, 2020)

2.2 ITS-G5 and C-V2X Technical Characteristics

Direct communication uses the PC5 interface based on Proximity Services Communications (Prose). This interface has enhancements to accommodate high speeds/high Doppler, high vehicle density, improved synchronization and decreased message transfer latency. This mode is suitable for proximate direct communications (hundreds of meters) and for V2V safety applications that require low latency (e.g., ADAS (Advanced Driver Assistance Systems), awareness). For LTE-PC5 interface, release 14 3GPP specifications define two communications modes specifically designed for vehicular communications: (i) Mode 3, and (ii) Mode 4. Mode 3 is base station-scheduled and cellular-assisted, for scenarios where vehicles are in areas of coverage; while Mode 4 is pure ad-hoc V2V and is autonomously-scheduled for vehicles that are out of coverage. (Karoui, Freitas and Chalhoub, 2019) This means that C-V2X can work both in and out of network coverage. However, network-based communication that uses LTE-Uu interface is supported only when UEs are inside network coverage where UEs can receive V2X messages via downlink unicast or uplink broadcast. It also uses the existing LTE Wide Area Network (WAN) and it is suitable for more latency-tolerant use cases (e.g. situational awareness, mobility services).

Table 2 below lists a set of commonly discussed Day 1 Co Operative Intelligent Transport Systems (C-ITS) services and comments on the applicability of cellular or local communications. It shows few areas where one method or the other is incapable, and in many cases a need for both where both local and wider afield impact is needed. (Transport Technology Forum, 2017)

When examining Table 2, it is important to consider that:

- "Cellular" can encompass a wide range of technologies - from 2G through to 5G. It is assumed here that the most appropriate technology is available (often, but not always 4G or 5G) in line with the "System of systems" view
- The contents of what is sent by data communications and the way it is sent are often confused. The contents of the messages (e.g., a CAM or DENM is not touched on here) this table focusses on how the message is sent, not the content
- In some areas it is not known if customer expectation for an "always on" service rapidly updated will drive vehicle makers to a particular rapid communications solution, or if customers using other technologies they may not have paid for regard it as "good enough" (or both). The various solutions for satellite navigation show this, from premium in vehicle system to free apps.
- Some solutions may only be needed most when communications networks are also busy – e.g., traffic congestion, but some like Green Light Optimal Speed Advice (GLOSA) might only work well in off peak traffic networks when communications loads are also lighter.
- Some solutions e.g., emergency vehicle approaching, are linked to local policy and legislative requirements

Table 2 - The applicability of cellular or local communications to Day 1 C-ITS Services (Transport Technology Forum, 2017)

Day 1 Service	Cellular	Local
Slow or stationary vehicle(s) & Traffic Ahead warning	Timing may be an issue for local warning services but dependent on use case, as road ahead warnings are already done by sat nav using cellular (but immediate road ahead is	High level of performance needed for immediate hazard warning

	not)	
Road works warning	Timing may be an issue for local services but dependent on use case as warnings are already done by Sat Nav using cellular (but immediate road ahead is not). Potential use of data to monitor signal performance	High level of performance for immediate hazard
Weather conditions	Apps available already using cellular but not necessarily immediate road ahead (e.g., icy patch)	Local Comms will provide immediate road ahead warnings (e.g., 'icy patch 100m ahead') but broadcast will be needed for wider messaging ('Snow on Snake Pass — don't leave/work from home')
Emergency electronic brake light	Must be local	Local communications essential for timing
Emergency vehicle approaching	Suitable for vehicles which are further away in the network	Better suited to critical elements such as road crossings
Other hazardous notifications	Suitable for longer-distance warnings, e.g., road works or flooding a mile ahead	Suitable for immediately adjacent hazards (e.g., pothole, debris, animals in road)
In-vehicle signage (fixed signs)	Already done with cellular sat nav for non-time dependent.	Unlikely to be necessary or beneficial for most signs
In-vehicle speed limits	Done by sat nav and OEM device — National Highways and Transport for London (TfL) have shown cellular app — but may be latency issues for smart motorways	May be useful for immediate warnings or enforcement action
Signal violation / Intersection safety	Latency likely to be too high	Needs local comms
Traffic signal priority request by designated vehicles	Most UK bus priority works satisfactorily over cellular using fixed time plans through bus scheduling information	Possible beneficial for emergency services or public transport where the need for dynamic requests is necessary
Green Light Optimal Speed Advisory (GLOSA)	May or may not work well enough for customers and OEM performance needs and depends on if adaptive or fixed time signals. More research is needed on users' needs and performance in peak times	Local communications assure timing of messages
Probe vehicle data	Proven for most applications; signal strategies, journey time, asset management, emissions	Useful as probe data input to signal control algorithms — local data needed for some approaches. But not for wider point-to-point across network information
Shockwave Damping	Driver advice can be provided	Local comms needed for

	over cellular (smart motorways)	automated vehicles, driver support, platooning
Smart parking	Suitable for navigation and payment	Suitable for automated parking (i.e., not under driver control) but not wider zones
Tolling	Suitable for spots, cordons and zones, including payment	Suitable for cordons and zones (nonintegrated payment) but not wider distance charging
Infotainment	Well suited, using mainstream entertainment applications	Unlikely to be suitable because of coverage

In July 2020, 3GPP completed 5G NR Release 16, this is the second phase of 5G where all the system enhancements are listed in Figure 2 - Release 16 Stage 3 Specifications (3GPP, 2020)Figure 2.The first phase being the addition of the 5G NR specifications for standalone (SA) mode to complete the 5G NR non-standalone (NSA) mode, launched in 2019, which leverages the LTE core network. The new set of specifications from the first phase allows 5G NR to be deployed with 5G core network, enabling new end to end features, from network slicing to better quality of service. (3GPP, 2020) Network Slicing is one of the most important technologies in 5G Method of creating multiple unique, logical, and virtualized networks over common multi-domain infrastructure. Release 17 is the 3rd phase of 5G and is set to reach stage 3 maturity in 2022 Q2 with even more enhancements show in Figure 3. (3GPP, 2019) Congruently, Release 18 is set to reach maturity in Q2 2024 with system enhancements as shown in Figure 4. (3GPP, 2021)

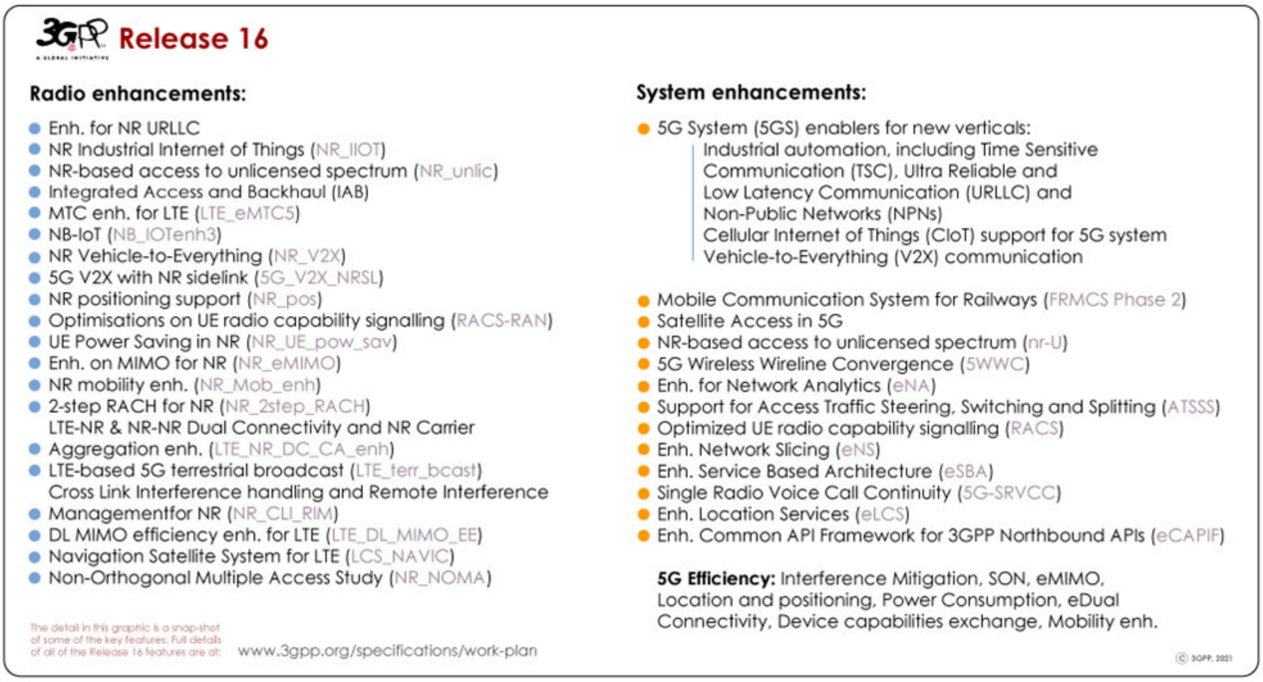

Figure 2 - Release 16 Stage 3 Specifications (3GPP, 2020)

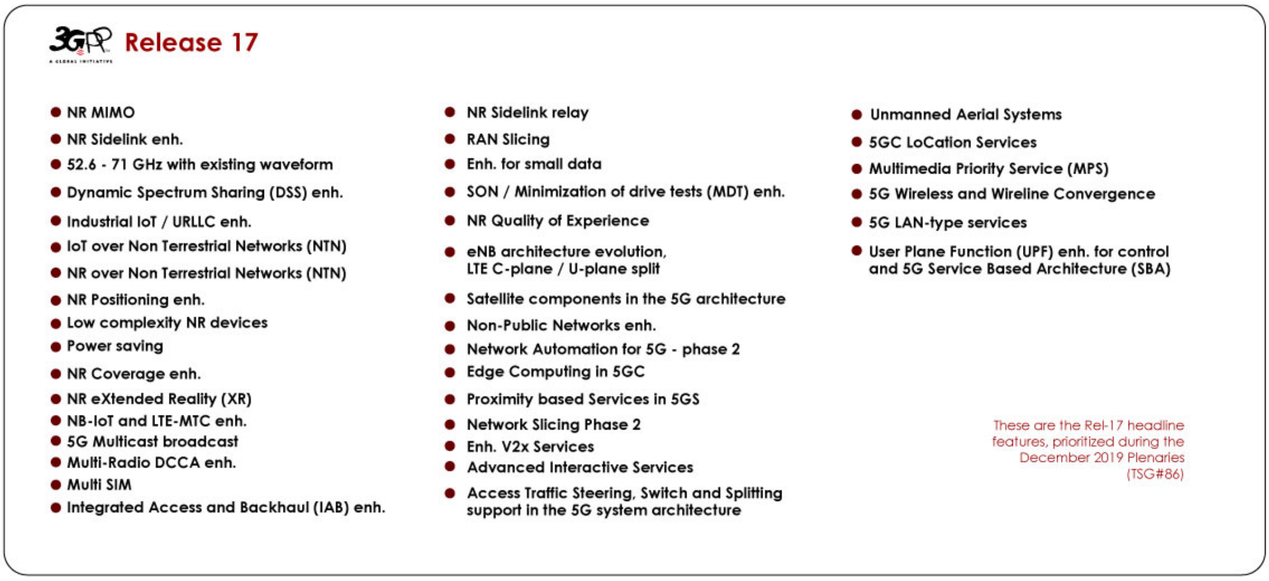

Figure 3 - Release 17 Specifications (3GPP, 2019)

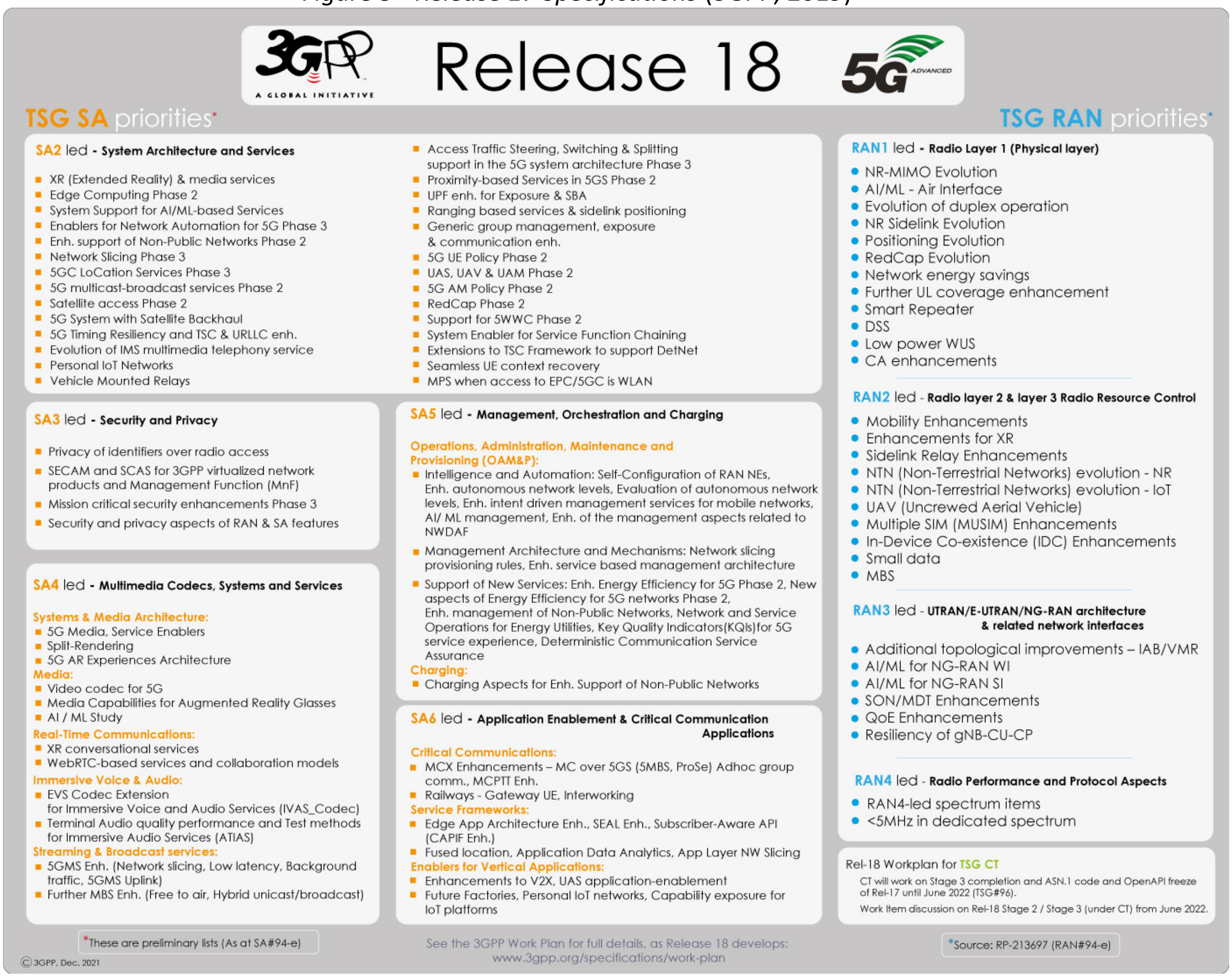

Figure 4 - 3GPP Release 18 Specifications (3GPP, 2021)

C-V2X is expected to perform the transition path to 5G. But, it still requires further examinations especially that in some vehicular use cases, it is needed to fulfill required latency and reliability in order to guarantee the efficiency of targeted C-ITS services. One of the actual challenges for telecommunication firms is to ensure an adequate choice between both technologies as well as distinguishing scenarios in which a technology can be more suitable compared to another (Filippi *et al.*, 2019)

2.3 Connectivity requirements (ETSI standards)

ETSI standards define a number of services which are directly related to connected and automated driving or can be used to support it. These include the ETSI Basic Set of Applications such as Cooperative Awareness Basic Service (ETSI, 2019a) and Decentralized Environmental Notification Basic Service (ETSI, 2019b). In the scope of ETSI Basic Set of Applications, a description has been provided also for Collective Perception Service (ETSI, 2019c). In addition to the Basic Set of Applications, ETSI has provided specifications for a number of other services such as Intersection Collision Risk Warning (ETSI, 2018a) and Vulnerable Road User Awareness Service (ETSI, 2021a). LTE also provides support for a number of V2X (vehicle to everything) use cases (3GPP, 2015). Requirements of V2X applications have also been taken into account in the specification for service requirements of 5G (ETSI, 2022).

In addition to service specifications, connectivity requirements have been provided for many of the services and use cases. This chapter summarises the connectivity requirements described in ETSI standards. The main focus is on performance and quality of service requirements for data transmission and the access layer technologies required, not providing complete descriptions of the protocol stack required for operation of the services.

2.3.1 ETSI basic set of applications – Cooperative awareness service and decentralized environmental notification service

In addition to other services, ETSI basic set of applications includes cooperative awareness basic service and decentralized environmental notification service based on dissemination of cooperative awareness messages (CAMs) and decentralized environmental notification messages (DENMs) between ITS stations. Early on in the development of ETSI basic set of applications, the use cases intended to be supported with CAM and DENM messages were defined in a specification providing the functional requirements for ETSI basic set of applications (ETSI, 2010)

Cooperative awareness basic service in the ITS facilities layer. The specifications of the services do not explicitly define connectivity or quality of service requirements, but it assumes that other layers of C-ITS protocol stack are available (e.g. network and transport layer and ITS access technologies located under the ITS facilities layer) (Figure 5). Cooperative awareness messages (CAMs) are one-hop messages broadcast by ITS stations.

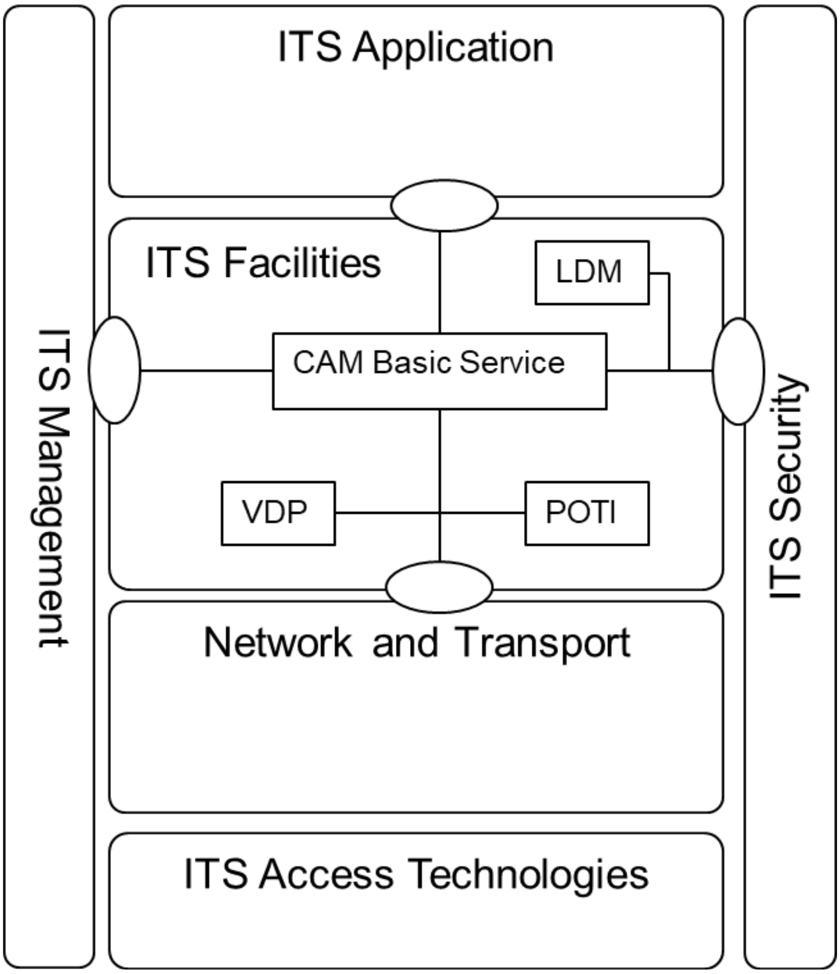

Figure 5. C-ITS protocol stack (according to ETSI EN 302 637-2, V1.3.2, Figure 1)

The CA basic service determines the frequency of CAM messages (ETSI, 2019a). In practice, CAM messages are generated with intervals of 100–1000 milliseconds. Especially high-density situations, the number and volumes of CAM messages may exceed the data transfer capacity provided by the ITS access layer such as ITS-G5 or C-V2X. In case of ITS-G5, functionalities required for congestion control are performed at different layers of the C-ITS protocol stack by the decentralized congestion control (DCC) mechanism (ETSI, 2018b). In congested channel conditions, the frequency of CAM generation is reduced based on the measured channel busy ratio. In case of C-V2X, congestion control of CAM messages is performed by the C-V2X congestion control function for the PC5 interface of C-V2X (ETSI, 2018c). Congestion control mechanisms for vehicular communication are an active research topic. The limitations of the DCC defined by ETSI for ITS-G5 include issues with oscillation between states and fairness between ITS stations (Balador, et al., 2022).

Table 2. ETSI Basic Set of Applications – connectivity requirements

Requirement	Description	Availability
ITS-G5 or C-V2X access technology	ETSI ITS-G5 or C-V2X access technology is available	yes/no

2.3.2 ETSI Basic Set of Applications – Collective Perception Service

In addition, collective perception service (CPS) is being developed as a part of the ETSI basic set of applications. An analysis of the service has been provided in ETSI TR 103 562 (ETSI, 2019c) while the full specification of the service is under drafting by ETSI (work item: DTS/ITS-00167 (ETSI, 2015), expected publication of the specification: December 2022 (ETSI, 2022). Collective perception service allows an ITS station to share information about objects it has detected in the surrounding environment with radar, camera or other sensors. The objects to be detected may be e.g. non-connected road users or safety-critical objects on the road. The service is also intended for sharing information about connected road users detected by the ITS station (with aggregation of CAM messages).

Collective perception messages are generated periodically, with intervals of 100–1000 ms (ETSI, 2019c). In the study describing the Collective perception service, ITS-G5 or C-V2X access layers are expected to be available, but no detailed information is provided on connectivity requirements. Point-to-multihop communication defined in ETSI specification for Geonetworking is suggested for communication of Collective perception messages. In addition, decentralized congestion control mechanisms are used with the Collective perception service to prevent the saturation of the radio channel, including the congestion control defined as cross-layer function for ITS-G5 (ETSI, 2018b) and the congestion control mechanism defined for PC5 interface of LTE (ETSI, 2018c).

2.3.3 V2X applications – road hazard signalling

Road hazard signalling application (RHS) allows an ITS station share information on hazards detected in road environment. The specification for the application requirements for RHS considers 10 use cases (ETSI, 2013a):

- Emergency vehicle approaching
- Slow vehicle
- Stationary vehicle
- Emergency electronic brake lights
- Wrong way driving
- Adverse weather condition
- Hazardous location
- Traffic condition
- Roadwork
- Human presence on the road.

These use cases are mainly based on communication of DENM messages between ITS stations, and many of them correspond to the Day-1 C-ITS applications defined by the C-ITS Platform. The application requirements specification for RHS does not prescribe any ITS access layer technology but provides requirements for connectivity (for a summary , see Table 3).

Table 3. Road Hazard Signalling – connectivity requirements

Requirement	Description and notes	Value
packet loss	Class A systems, ITS-G5, in line-of-sight conditions	≤5%
intended communication range	may be reduced in certain situations, e.g. when the radio channel is congested, please see OR6 and OR8 in (ETSI, 2018a)	≥300 m
message volume	capability of the receiving ITS station to process messages	≥5000 messages/second
use of congestion control mechanisms	for high priority messages (priority 1 or 0), the originating ITS station should not reduce transmission power or increase message time interval	On/Off (Yes/No)

interval for CAM and DENM messages, for class B systems	for class B systems	100 ms – 1000 ms
latency (originating vehicle ITS-S), for class B systems	(from T0 to T2, from obtaining raw data from sensors to transmitting a message over network)	<1.5 s (incl. the message interval of 1 s)
latency (receiving vehicle ITS-S), for class B systems	(from T3 to T6, from receiving a data packet to communicating a decision on automatic action to vehicle systems or communicating a required action to the driver)	<500 ms

Regarding the end-to-end latency for collision avoidance and pre-crash applications, the application requirement document (ETSI, 2013a) provides a guideline:
"For critical road safety application (collision avoidance) and for pre-crash application an estimated 300 ms end to end latency time seems to be required to avoid false decisions based on old data."

2.3.4 V2X applications – Intersection collision risk warning

The use cases supported by Intersection Collision Warning application are described in ETSI TS 101 539-2 (ETSI, 2018a). The use cases have been divided in two groups (crossing collision warning and traffic sign violation warning. The connectivity requirements for intersection collision risk warning are summarized in Table 4, based on (ETSI, 2018a).

Table 4. Intersection collision risk warning – connectivity requirements [summarized from ETSI (2018a)]

Requirement	Description	Value
communication coverage	in line of sight conditions, in conditions of light channel load	≥300 m
transmission power (ITS-G5)	measured at antenna level, in non-congested conditions of G5A channel	18 dBm
performance class	required for intersection collision warning to achieve low enough end-to-end latency	performance class A
latency (may be required)	from T4 to T6 (from reception of the message by the application layer at the receiving ITS station to communicating required action to vehicle systems or communicating recommended action to the driver)	≤ 80 ms

end-to-end latency (example value, typically required)	from T0 to T6 (from availability of sensor data at originating ITS station to communicating required action to vehicle systems or communicating recommended action to the driver at the receiving ITS station)	≤300 ms
DENM update frequency	when a collision risk or violation exists, and the DENM has been triggered by the IRCW applications	10 Hz
message rate	capability of a conforming ITS station to process CAM and DENM messages	≥ 1000 messages/s
communication range, for a roadside ITS station or traffic light controller		"sufficient to ensure collision risk detection with a vehicle driving at its maximum design speed" (ETSI, 2018a)
message frequency , SPATEM/MAPEM/IVIM messages	please see OR15 in (ETSI, 2018a)	≥ 1 Hz
latency, SPATEM/MAPEM/IVIM messages	please see OR16 in (ETSI, 2018a), latency between T2-T0, between message transmission at the receiving ITS station and availability of information from the sensors of the originating ITS station	< 800 ms

2.3.5 V2X – Longitudinal Collision Risk Warning

Longitudinal collision risk warning is based on CAM and DENM messages sent by ITS stations. Application requirements for longitudinal collision risk warning are provided in ETSI TS 101 539-3 (ETSI, 2013b). The application includes two operational modes, the originating mode and the receiving mode and the following use cases, divided in two groups (ETSI, 2013b):

forward and forward / side collision risk warning:

- safety relevant lane change
- emergency electronic brake light/traffic conditionsn
- roadworks
- stationary vehicle
- stability problem
- collision risk warning from a third party
- frontal collision risk warning
- wrong way vehicle driving
- safety relevant vehicle overtaking.
- collision risk warning from a third party

Table 5. Longitudinal collision risk warning – connectivity requirements [summarized from ETSI (2013b)]

Requirement	Description and other comments	Value
communication range, target vehicle	in line of sight situations and with light channel load, may be reduced in certain conditions such as in slow traffic or congested radio channel, please see OR008 and OR009 in ETSI (2013b)	≥ 300 m
transmitting power	for ITS-G5, when the ITS-G5A channels are not congested, please see OR009 in ETSI (2013b)	18 dBm
performance class	please see OR010 in ETSI (2013b)	A
latency, receiving ITS station	T4-T6, between message reception by the application layer at the receiving ITS station and communicating required action to vehicle systems or communicating recommended action to the driver	≤ 80 ms
latency, end to end	from T0 to T6, from data acquisition by sensors in the originating vehicle to provision of information on required action or automatic action in the receiving vehicle, the provided value is an example of latency which may be required, please see ETSI (2013b)	≤300 ms
message rate	capability of a conforming ITS station to process CAM and DENM messages	≥ 1000 messages/s

2.4 Vulnerable road users (VRU) awareness service

Vulnerable road users (VRU) awareness service aims to increase the awareness for VRUs and awareness of VRUs in traffic environment. The service covers a number of use cases which are expected to be relevant in three types of traffic situations: (1) situations in which a conflict between a VRU and another road user is imminent, and there is an immediate safety risk for the VRU, (2) situations in which the safety of VRU can be improved by increasing awareness of the VRU to avoid a conflict situation (3) situations supporting VRUs with special needs by improving their mobility (ETSI, 2021b). The specification of the service describes several use cases and proposes a classification for use cases (ETSI, 2021b):

- Category A: Direct VRU communication, VRUs are equipped
- Category B: Direco communication from VRU to vehicle, both VRU and vehicle are equipped
- Category C: A vehicle detects a hidden VRU and provides information to other vehicles, vehicles are equipped, but the VRU may be or not be equipped
- Category D: Roadside equipment detects a hidden VRU and provides information to vehicles. Roadside equipment and vehicles are equipped, the VRU may be or not be equipped.

- Category E: A control centre or cloud service monitors the status of the VRU. Roadside equipment and vehicles are equipped, the VRU may be equipped.
- Category F: Roadside equipment monitors the VRU, the VRU may be equipped with an ITS station capable of detecting risks of collision and capable of acting to avoid a collision with monitored vehicles (e.g. by sending an alarm), roadside equipment and vehicles are equipped

Connectivity requirements of the service are summarized in Table 6.

Table 6. Vulnerable road users (VRU) awareness service – connectivity requirements [summarized from ETSI (2021a)]

Requirement	Description and other comments	Value
Density of users	Number of users (e.g. VRUs), inside a circle with radius of no less than 300 m, please see FCOM01 in ETSI (2021a)	5000 users
congestion control	The system shall support a suitable congestion control mechanism, please see FCOM02 and FCOM03 in ETSI (2021a)	yes
latency, end-to-end	Latency has to be low enough to ensure that the data is relevant for collision avoidance purposes, the provided value is an example, please see OSYS05 in ETSI (2021a)	< 300 ms
data update rate	the provided value is an example, please see OSYS05 in ETSI (2021a)	10 Hz
transmission range, VRU ITS station supporting communication with infrastructure ITS station	supports an use case in which a VRU ITS station is detected by infrastructure ITS station, and the infrastructure ITS station transmits information on the VRU as collective perception message (CPM) or forwards the original VRU awareness message (VAM), please see OCOM01.1 in ETSI (2021a)	≥ 25 m
transmission range, VRU ITS station supporting communication with vehicle ITS station for collision avoidance purposes	When determining this requirement, a vehicle moving at 45 km/h, a stationary pedestrian and 5 s time to collision have been assumed, please see OCOM01.2 in ETSI (2021a)	≥ 70 m

transmission range, VRU ITS station supporting communication with vehicle ITS station for cyclist collision avoidance purposes	When determining this requirement, 5 s time to collision, a cyclist moving at 30 km/h and vehicle speed of 90 km/h have been assumed, please see OCOM01.3 in ETSI (2021a)	≥ 150 m
transmission range, VRU ITS station supporting communication with vehicle ITS station for motorcycle collision avoidance purposes	comparable to communication range in V2V collision avoidance applications, please see OCOM01.4 in ETSI (2021a)	≥ 300 m
communication latency	from start of the request to transmit data (access layer level) to reception of data (access layer level) at the receiving end, in open sky conditions and line of sight from sender to receiver, please see OCOM02 in ETSI (2021a)	< 5 ms

2.4.1 LTE – V2X services

Development of support for V2X (vehicle to everything) services in LTE started as a part of release 14 (3GPP, 2015). The study on LTE support for V2X services published in 2015 described 27 V2X use cases for LTE (3GPP, 2015):

- forward collision warning
- control loss warning
- V2V use case for emergency vehicle warning
- V2V emergency stop use case
- cooperative adaptive cruise control
- V2I emergency stop use case
- queue warning
- road safety services
- automated parking system
- wrong way driving warning
- V2X message transfer under MNO control
- pre-crash sensing warning
- V2X in areas outside network coverage
- V2X road safety service via infrastructure
- V2N traffic flow optimization
- curve speed warning
- warning to pedestrian against pedestrian collision
- vulnerable road user (VRU) safety
- V2X by UE-type RSU [vehicle to everything by user equipment type roadside unit]
- V2X Minimum QoS [vehicle to everything minimum quality of service]
- Use case for V2X access when roaming
- Pedestrian road safety via V2P [vehicle to pedestrian] awareness messages
- mixed use traffic management
- enhancing positional precision for traffic participants

- privacy in the V2V communication environment
- V2N [vehicle to network] use case to provide overview to road traffic participants and interested parties
- Remote diagnosis and just in time repair notification.

In 2020, a specification describing the service requirements for V2X services to be supported by LTE was published (ETSI, 2020a). The specification covers use cases in the following categories: vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-network (V2N) and vehicle-to-pedestrian (V2P).

Table 7. LTE – V2X services – connectivity requirements [summarized from ETSI (2020a)]

Requirement	Description and other comments	Value
availability of LTE transport		yes
density of user equipment	capability of the network to support high density of user equipment, please see R-5.1-012 in ETSI (2020a)	high
latency, for message transfer between two UEs supporting V2V/P application	data transfer directly or via RSU, requirement for E-UTRA(N), please see R-5.2.1-001 in ETSI (2020a)	≤ 100 ms
latency, for message transfer between two UEs supporting V2V application	requirement for E-UTRA(N), please see R-5.2.1-002 in ETSI (2020a)	≤ 20 ms
latency, for message transfer between EU supporting V2I application and RSU	requirement for E-UTRAN(N), please see R-5.2.1-003 in ETSI (2020a)	≤ 100 ms
end-to-end delay, for message transfer via 3GPP network elements between UE and application server supporting V2N application	requirement for E-UTRAN, please see R-5.2.1-004 in ETSI (2020a)	≤ 1000 ms
reliability of message transfer without need for application layer retransmissions	requirement for E-UTRA(N), please see R-5.2.1-005 in ETSI (2020a)	high
message payload, periodic broadcast messages between two UEs	security related message part not included, requirement for E-UTRA(N), please see [R-5.2. 2-001] in ETSI (2020a)	50–300 bytes
message payload, event-triggered messages	requirement for E-UTRA(N), please see [R-5.2. 2-002] in ETSI (2020a), not including security related message part	≤ 1200 bytes
message frequency	requirement for E-UTRA(N), please see [R-5.2.3-001] in ETSI (2020a)	≤ 10 messages/second
communication range	requirement for E-UTRAN, please see [R-5.2.4-001] in ETSI (2020a) The E-UTRAN shall be capable of supporting a communication range sufficient to give the driver(s) ample response time (e.g. 4 seconds).	"sufficient to give the driver(s) ample response time (e.g. 4 seconds)"
speed, for V2V application	relative velocity between UEs, please see [R-5.2.5-001] in ETSI (2020a)	≤ 500 km/h

speed, for communication between UEs supporting V2V and V2P applications	relative velocity between UEs, please see [R-5.2.5-002] in ETSI (2020a)	≤ 250 km/h
speed, communication between UE and RSU supporting V2I application	absolute velocity of the UE, please see [R-5.2.5-003] in ETSI (2020a)	≤ 250 km/h

2.4.2 C-V2X (cellular vehicle to everything)

C-V2X (cellular vehicle to everything) is based on the technology of LTE and 5G networks. The use cases defined for C-V2X are described in two white papers [18, 19] published by 5GAA (5G Automotive Association). The first of the white papers provides a classification for use cases (5G Automotive Association, 2019):

- Safety
- Vehicle Operations Management
- Convenience
- Autonomous driving
- Platooning
- Traffic Efficiency and Environmental friendliness
- Society and Community.

The white paper (5G Automotive Association, 2019) also defines the following C-V2X service level requirements:

- Range
- Information requested/generated
- Service level latency
- Service level reliability
- Velocity
- Vehicle density
- Interoperability/regulatory/standardization required.

The latter of the white papers (5G Automotive Association, 2020) provides descriptions and service level requirements for 19 use cases related to automated driving:

- Automated Intersection crossing
- Autonomous Vehicle Disengagement Report
- Cooperative Lane Merge
- Cooperative Manoeuvres of Autonomous Vehicles for Emergency Situations
- Coordinated, Cooperative Driving Manoeuvre
- HD Map Collecting and Sharing
- Infrastructure Assisted Environment Perception
- Infrastructure-Based Tele-Operated Driving
- Remote Automated Driving Cancellation (RADC)
- Tele-Operated Driving (ToD)
- Tele-Operated Driving Support
- Tele-Operated Driving for Automated Parking
- Vehicle Collects Hazard and Road Event for AV
- and one use case related to platooning:
- Vehicles Platoon in Steady State.

Examples of service level requirements defined for three use cases related to automated driving and platooning are provided in Table 8.

Table 8. Examples of service level requirements in three C-V2X use cases related to automated driving and platooning (5G Automotive Association, 2020).

Service level requirement	**Vehicle Platooning in Steady State**	**Vehicle Collects Hazard and Road Event for automated vehicle**	**Tele-Operated Driving Support (user story: Remote Steering)**
Range	member of a platoon – member of a platoon: 5–15 m head of a platoon – member of a platoon: > 175 m head of platoon – coordination with cloud: long	Scenario 1: 300 m (information received by automated vehicle) Scenario 2: not applicable (information received by application server)	10,000 m
Information Requested/Generated	member of a platoon – member of a platoon: 100 bytes head of a platoon – member of a platoon: 300 bytes (20 Hz) head of platoon – coordination with cloud: 1000 bytes (event based)	300 bytes/message	from host vehicle to remote driver: 32 Mbit/s (video streaming) Or from host vehicle to remote driver: Optional: 36 Mbps (if video streaming and object information is sent) from remote driver to host vehicle: up to 1000 bytes per message (up to 400 kbit/s) (Commands from remote driver)
Service Level Latency	member of a platoon – member of a platoon: 50 ms head of a platoon – member of a platoon: 100 ms head of platoon – coordination with cloud: >1000 ms	20 ms	from host vehicle to remote driver: 100 ms from remote driver to host vehicle: 20 ms
Service Level Reliability	member of a platoon – member of a platoon: 99.9% head of a platoon – member of a platoon: 99.9% head of platoon – coordination with cloud: 99%	99.9%	from host vehicle to remote driver: 99% from remote driver to host vehicle: 99.999% (Very high)
Velocity	227.8 m/s	City: 19.4 m/s Highway: 69.4 m/s	2.78 m/s
Vehicle Density	highway: 4500 vehicle/km^2	12,000 vehicles/km^2	10 vehicles/km^2

	rural: 9000 vehicle/km^2 urban: 12000 vehicle/km^2		
Positioning	0.5 m (3σ)	1.5 m (3σ)	0.1 m (3σ)
Interoperability / Regulatory / Standardisation Required	Yes/Yes/Yes	Yes/Yes/Yes	No/Yes/No

2.4.3 5G – enhanced V2X scenarios

ETSI has defined service requirements for V2X scenarios in 5G in the following areas (ETSI, 2020b):

- General aspects
- Vehicles platooning
- Advanced driving
- Extended sensors
- Remote driving
- Vehicle quality of service support.

The document provides service requirements for different levels of vehicle automation. Service requirements for high level or higher levels of automation in selected scenarios are summarized in Table 9.

Table 9. 5G – examples of connectivity requirements in selected V2X scenarios supported in 5G, high level or high levels of automation

Scenario	**Cooperative driving for vehicle platooning, intra-group exchange of information**	**Advanced driving: Information sharing for automated driving between UE supporting V2X application and RSU**	**Remote driving: Information exchange between UE and a V2X Application Server**
degree	**highest level of automation**	**higher degree of automation**	**-**
Payload [bytes]	50–1200	-	-
Transmission rate [messages/s]	30	-	-
End-to-end latency [ms]	≤ 10	≤ 100	≤ 5
Reliability [%]	99.99	-	99.999
Data rate [Mbit/s]	-	50 (note: includes both cooperative manoeuvers and cooperative perception data that could be exchanged using two separate	uplink: 25 downlink: 1

		messages within the same period of time)	
Communication range [m]	≥ 80	≥ 360	-

2.5 Connectivity trials in Europe

2.5.1 5G-MOBIX – 5G for Cooperative, Connected and Automated Mobility

The aim of 5G-MOBIX project (5G for Cooperative, Connected and Automated Mobility) is to test the use of 5G technology to implement services for cooperative, connected and automated mobility [21, 22]. The work plan of 5G-MOBIX includes trial sites in Finland, France, Germany, The Netherlands, China and Korea and two cross-border corridors (Spain-Portugal and Greece-Turkey) (Plestan & Soua, 2021). The use cases included in 5G-MOBIX have been classified in a way similar to ETSI/3GPP. The use cases related to cooperative, connected and automated driving supported by 5G-MOBIX have been classified in the following categories (Martín & Vélez, 2019):

- Advanced Driving
- Platooning
- Extended Sensors
- Remote Driving
- Vehicle quality of service Support.

The evaluation approach used in the project covers technical evaluation, impact assessment and evaluation of user acceptance (Katsaros, 2020). The evaluation results of the trial sites and corridors were not available at the time of writing. The technical evaluation planned to be carried out includes data collection on multiple layers of the protocol stack and a number of key performance indicators (KPIs): TE-KPI1.1: User Experienced Data rate, TE-KPI 1.2: Throughput, TE-KPI 1.3: End-to-end latency, TE-KPI 1.4: Control plane latency, TE-KPI 1.5: User plane Latency, TE-KPI 1.6: Reliability, TE-KPI 1.7: Position accuracy, TE-KPI1.8: Network Capacity, TE-KPI 1.9: Mean Time To Repair, TE-KPI 2.1: NG-RAN Handover Success Rate, TE-KPI 2.2: Application Level Handover Success Rate, TE-2.3: Mobility interruption time, TE-KPI 2.4: International Roaming Latency, TE-KPI 2.5: National Roaming Latency (Katsaros, 2020).

2.5.2 5G-DRIVE – 5G Harmonise Research and TrIals for service Evolution between EU and China

5G-DRIVE (5G Harmonize Research and Trials for service Evolution between EU and China) (5G-DRIVE, n.d.) validated and tested the interoperability between European and Chinese 5G networks. The main focus of the technical evaluation was on the interoperability of European and Chinese 5G networks in V2X applications (Kutila, et al., 2021). In addition to 5G, the project tested the functioning of C-V2X, including the PC5 interface used for vehicle to vehicle (V2V) communication, and studied the co-existence of ITS-G5 and C-V2X on a shared frequency band.

The project included two V2X communication testbeds (testbed at European Commission Joint Research Centre in Ispra, Italy and testbed at University of Luxembourg) and V2X trials in Europe (Tampere, Finland and Ispra, Italy) and in China (Shanghai) (Kutila, et al., 2021). The trials carried out in the project focused on two main V2I (vehicle to infrastructure) use cases: green light optimum speed advisory (GLOSA) and intersection safety (intelligent intersection with functionality for vulnerable road users The project was active during 2018–2021, and it was carried out in collaboration with its twin project in China (5G Large-scale trials).

2.5.3 5G-LOGINNOV

The aim of 5G-LOGINNOV (5G creating opportunities for Logistics supply chain Innovation (5G-LOGINNOW) (5G-LOGINNOV , n.d.) is to study the application of 5G in logistics. The project has started in September 2020, and it is expected to be completed in August 2023 (5G-LOGINNOV , n.d.). The project includes three living labs (Athens, Hamburg and Koper) (Gorini, et al., 2021). The living labs address the following logistics use cases enabled by 5G (Basaras, et al., 2021):

Athens

- UC2: Device Management Platform Ecosystem
- UC3: Optimal Yard Truck selection
- UC4: Optimal surveillance cameras and video analytics
- UC5: Automation for ports: port control, logistics and remote automation
- UC7: Predictive Maintenance

Hamburg

- UC8/9: Floating Truck & Emission Data (FTED)
- UC10: 5G GLOSA & Automated Truck Platooning (ATP)-under 5G-LOGINNOV Green initiative
- UC 11: Dynamic Control Loop for Environment Sensitive Traffic Management Actions (DCET)

Koper

- UC1: 5G-LOGINNOV Management and Network Orchestration platform (MANO)
- UC5: The 5G-LOGINNOV automation for ports: port control, logistics and remote automation
- UC6: The 5G-LOGINNOV 5G mission critical communications in ports.

2.5.4 5G-ROUTES

The objective of 5G-ROUTES (5th Generation connected and automated mobility cross-border EU trials) is to validate the latest 3GPP specifications connected and automated mobility (5G-ROUTES, n.d.). The project focuses on 5G technology and related solutions for connected and automated mobility defined in 3GPP releases 16 and 17. The project covers four groups of use cases of which two are related to automated driving (Automated Cooperative Driving and Sensing Driving) (Durkin, et al., 2020). The plan for validation of 5G features involves the following network-level performance indicators: data rate, mobility, latency, jitter, connection density, reliability, positioning accuracy, coverage and availability (Krupp, 2021). The project started in September 2020, and it is expected to be completed in August 2023.

InterCor

The INTERCOR project (Interoperable Corridors linking the C-ITS corridor initiatives of the Netherlands C-ITS Corridor NL-DE-AT and the French SCOOP@F and extending to United Kingdom and Belgium C-ITS initiatives to achieve a sustainable network of corridors providing continuity of C-ITS services and offering a TestBed for beyond Day-One C-ITS service development) focused on connecting the corridors where Day-1 C-ITS services are provided or piloted (Intercor, n.d.). The technical evaluation carried out in the project involved three topical areas: interoperability, communication performance and applications and services (Crockford, et al., 2020). The trials carried out in the project involved service implementations of Day-1 C-ITS services based on ITS-G5, cellular communication and a hybrid communication solution.

NordicWay2

NordicWay2 piloted Day-1 and Day1½ C-ITS services in the Nordic environment in Finland, Sweden, Norway and Denmark [36, 37]. The C-ITS pilots implemented in the project used ITS-G5, cellular communication and a hybrid communication solution (Innamaa, et al., 2020). The evaluation of the C-ITS pilots included seven evaluation areas of the C-ROADS project: user acceptance, safety, traffic efficiency, environment, organisational aspects, socio-economic aspects and quality of service. The quality of service evaluation area included KPIs related to connectivity such as physical coverage, number of C-ITS messages distributed per service and node, location accuracy, latency (end-to-end), latency (between federated interchange nodes), message success rate, cross-border continuity of services and cross-organisational/cross-brands data sharing.

NordicWay3

Currently underway and building on the NordicWay and the NordicWay 2 activities under the C-Roads Platform, to extend joint pilot activities, including also urban areas. The pilots focus on safety and efficiency of the TEN-T Scandinavian-Mediterranean Core Network Corridor. It is envisaged that the actions will support the long-term development of a safe, secure and efficient road transport system allowing for management of cross border traffic, ensuring that implemented C- ITS services are interoperable and continuous across borders.

SOD5G

The Finnish Meteorological Institute (FMI) has developed a hybrid vehicular network infrastructure using ITS-G5 with a cellular-based 5G Test Network (5GTN). (Tahir, Sukuvaara and Katz, 2020) The hybrid vehicular network infrastructure provides an advanced, intelligent network containing heterogeneous networking capabilities for road traffic safety between vehicles and Roadside Units (RSU)/Road weather sensors (RWS). The data from vehicle sensors as well as the weather observation information from the RWS are used to develop a service architecture for VANETs that supports real-time intelligent traffic services. It is mainly commercial equipment, e.g., Sunnit briefcase and Cohda MK5 radio transceivers that are used to test the pilot system and to conduct field measurements in vehicular networking. The idea is to develop the most recent road traffic safety service architecture with the best services in terms of location-based road weather data, forecast and accident alerts. It would also provide a platform for a real-time two-way communication with tailored pilot scenarios for vehicular networking. Pilot measurements were conducted using the Sod5G test-track in Sodankylä, Finland. The Sod5G test-track is funded by the European Regional Development Fund (ERDF). The test-track has a length of 1.7 km and is equipped with two road weather stations supporting an ITS-G5 protocol and a 5G test network base station together with different Internet of Things (IoT) sensors. This test-track offers the opportunity to design, develop, and test road weather services even in severe weather situations. (Tahir, Sukuvaara and Katz, 2020)

C-Roads

The C-Roads Platform is a joint initiative of European Member States and road operators for testing and implementing C-ITS services in light of cross-border harmonisation and interoperability. It is lead by Austria and was established in 2016 with 8 Member States (Austria, Belgium, the Czech Republic, France, Germany, Netherlands, Slovenia and the UK). Currently 26 Member States take part of this Platform (19 Core and 7 Associated members) and 19 pilots are being developed and deployed in Europe. In terms of pilots in the urban environment, 37 37 European cities have joined the C-Roads Platform, at least 29 of which will implement C-ITS services.

Several milestones of C-Roads comprehend: 20,000 kms covered by ITS-5G; 100,000 km equiped with cellular/long range; 2,300 operational RSUs and 3,000 hours invested in cross-tests.

Through the C-Roads Platform, authorities and road operators join together to harmonise the deployment activities of cooperative intelligent transport systems (C-ITS) across Europe. The goal is to achieve:

i) the deployment of interoperable cross-border C-ITS services for road users;
ii) the development, sharing and publication of common technical specifications (including the common communication profiles);
iii) verify to verify interoperability through cross-site testing;
iv) develop system tests based on the common communication profiles by focusing on hybrid communication mix, which is a combination of ETSI ITS-G5 and existing cellular networks

The starting point for pilot deployments is the short-range communication technology ETSI ITS-G5 (basically WiFi boxes) and existing cellular networks. In accordance with the European C-ITS strategy, the C-Roads Platform also supports the combination of both technologies in a hybrid communication mix.

The implementation of C-ITS services of the project compreheends 5 different stages: Stage 1 - Begin C-ITS Implementation; Stage 2 - High Level Service Specific Definitions; Stage 3 - System Specification; Stage 4 - Architecture & Technology Definition (including ITS-G5 and IP-based technology) and Stage 5 - Test & Pilot.

Stage 5 deliverables (Test & Pilot) provide the basis for validating the interoperability of C-ITS implementation and provide a guide through all aspects of interoperability testing for C-ITS services.

These documents contain a common procedure for generating and naming data packets (PCAP files) for cross-border exchange between C-Roads project partners. This procedure enables interoperability testing by using a range of equipment before the actual road tests take place. During the various test cycles, the pilots evaluate the impacts of Day 1 and Day 1.5 C-ITS services and use cases implemented in the following impact areas: i) User Acceptance; ii) Functional evaluation; iii) Socio-economic aspects; iv) Road safety; v) Traffic efficiency and vi) Environmental effects.

5G-CroCo

The aim of 5G-CroCo project (Fifth Generation Cross-Border Control) is to define a successful path towards the provision of CCAM services along cross-border scenarios and reduce the uncertainties of a real 5G cross-border deployment.

This project started in 2018 (36 Months trials – 5G and CV2X), and 24 partners from 7 Member States are involved in 5G technology trials in the cross-border corridor connecting the cities of Metz-Merzig-Luxembourg, traversing the borders between France, Germany and Luxembourg (Germany-Luxemburg and France-Germany).

It will work with 3 use cases along these two cross-border corridors: i) Tele-operated driving; ii) HD Mapping and iii) Antecipated Cooperative Collision Avoidance.

Five small scale test sites are also part of this project:

- **Montlhéry (France)** – deployment of TECHMO project, a new Technology Center for automated and connected mobility, with 12 km of closed testing tracks and associated facilities;
- **Motorway A9 5G-ConnectedMobility (Germany)** – approximately 30km long segment of the German Motorway A9, which is part of the larger Digital Test Field Motorway supported by the German Federal Ministry of Transport & Digital Infrastructure and the Bavarian Road Construction Administration;
- **Munich (Germany)** – tests done in the vicinity of Huawei Munich Research Center (North of Munich), comprehending public roads and a private parking area;
- **AstaZero (Sweden)** - features highway and country roads and has testing capabilities for different environments, including rural road, city area, high speed area, and multi-lane road. In addition, two communication networks are available: 1) A cellular test network that controls different objects during the tests, e.g., a balloon vehicle, a moose, and a pedestrian. 2) A second network with high flexibility, e.g., coverage, network load, and handover setups, including emulation of country;
- **Barcelona (Spain)** - test site composed of a 5G neutral hosting platform and a cross-border Internet Exchange Point (IXP) platform. The small-scale site is integrated within the 5GBarcelona end-to-end infrastructure and the test site will emulate a cross-border scenario, with different virtual MNOs which operate MECs and the LTE small cells, and an IXP and public cloud for cross-border applications.

5G-CARMEN

5G-CARMEN (5G for Connected and Automated Road Mobility in the European UnioN) is funded by HORIZON2020 and started in 2018 (duration: 36 months).

Focusing on the Bologna-Munich corridor (600 km, over three countries) the objective of 5G-CARMEN (26 partners) is to leverage on the most recent 5G advances to provide a multi-tenant platform that can support the automotive sector delivering safer, greener, and more intelligent transportation with the ultimate goal of enabling self-driving cars.

The key 5G-CARMEN innovations are centred around developing an autonomously managed hybrid network, combining direct short range V2V (vehicle to vehicle) and V2I (vehicle to infrastructure) communications with long-range V2N (vehicle to network) communications. The 5G-CARMEN platform employs different enabling technologies such as 5G New Radio, C-V2X (Cellular vehicle to everything), and secure, multi-domain, and cross-border service orchestration system to provide end- to-end 5G enabled CARMEN services.

Cross-border trials of 5G technologies in 5 major use cases: cooperative manoeuvring, situation awareness, video streaming, green diving, and Cooperative and automated lane-change maneuvers.
The project main tasks is task T5.1, which takes input mainly from T2.2 “Use case definition and requirements analysis”, from T4.4 “Use cases Integration and Testing” and from T3.6 “Services and applications for CCAM” and collaborate with T5.4 for exemption procedures and safety issues, to deliver a viable plan for T5.2 “Test execution” and T5.3 “Test validation and use case benchmarking”.
The pilot plan set-up performed in T5.1 has required the following steps: i) Definition of technical KPIs; ii) Design and plan of the experimentations; iii) Define data and meta-data recording methodologies, procedures and management and iv) Design and plan of the subsequent evaluation.

5G-PPP

The 5G Infrastructure Public Private Partnership (5G PPP) is a joint initiative between the European Commission and European ICT industry (ICT manufacturers, telecommunications operators, service providers, SMEs and researcher Institutions), that was launched in 2013.
In 2017, 5G PPP was signed with EU under Horizon2020, using the a new approah of HORIZON2020 which now offers a new instruments called Contractual PPP (cPPP) (2014-2020 funding period):

- Advanced 5G Network Infrastructure for the Future Internet Public Private Partnership in Horizon 2020: "Creating a Smart Ubiquitous Network for the Future Internet".

The 5G PPP has been designed in a structured way to start with innovative concepts (Phase 1), move through the development of key technical breakthroughs (Phase 2), and follow up with trials and pilots (Phase 3). This programme has 91 projcts and currently is in Phase 3 (started in 2018).
The project will deliver solutions, architectures, technologies and standards for the ubiquitous next generation communication infrastructures of the coming decade. The challenge for the 5G Public Private Partnership (5G PPP) is to secure Europe’s leadership in the particular areas where Europe is strong or where there is potential for creating new markets such as smart cities, e-health, intelligent transport, education or entertainment & media.
The key challenges for the 5G Infrastructure PPP (KPIs) are:

- Providing 1000 times higher wireless area capacity and more varied service capabilities compared to 2010
- Saving up to 90% of energy per service provided. The main focus will be in mobile communication networks where the dominating energy consumption comes from the radio access network
- Reducing the average service creation time cycle from 90 hours to 90 minutes
- Creating a secure, reliable and dependable Internet with a “zero perceived” downtime for services provision
- Facilitating very dense deployments of wireless communication links to connect over 7 trillion wireless devices serving over 7 billion people
- Ensuring for everyone and everywhere the access to a wider panel of services and applications at lower cost

Since 2019, the 5G PPP Initiative has released another ten white papers disseminating key findings (https://5g-ppp.eu/white-papers/) .

Conclusion

There is no common agreement on the technologies of choice for delivery of CV/AV/C-ITS. That is underpinned by the lack of clarity on the business cases to be addressed with the emergence of these communication technologies. To further complicate matters, in a muti-party ecosystem, the business case and the cost v’s award across different actors is not sufficiently clear.
However, progress is being made, Large scale ITS deployments have taken place, albeit in limited areas and further activity is planned through C-Roads and other organisations.
The choice of technology installation for a National Road Authority is linked to addressing the following questions:

1. Is the technology aligned to the Car Manufacturing Industry?

2. Is the technology mature enough to start procurement ?
3. Does it need to be for the services of interest to the NRA?
4. Is there a timeline of ROI linked to investment in new technologies?
5. Is there a definitive business case that allows migration away from current approaches and methods to date?
6. What extra business insight will connected vehicles bring to NRAs and how is that used in the organisation?
7. Will penetration levels be sufficienct, considering the significant number of current vehicles that will not have this technology?
8. Is there a Target Operating Model to support the new technology and is this part of wider stakeholder engagement within the digital ecosystem?
9. How is performance of these approaches mesaured and what is the impact for NRAs, both in yealry capital budgets but also in terms of structure and skill sets?
10. For a Data to Vehicle (and vice-versa) data exchange, will the NRA be subjected to new operating models?

What is clear is that the Technologies themselves can provide capability in the deliver of a range of services. The choice of the technology can be related to the time requirements of the service and the coverage area required to deliver these services.

Whilst there is no immediate direction on the 'technology of choice' between 5G and ITSG5, it is clear that in the interim a mixture of technologies is required to ensure adequate timeliness and coverage of the services desired. A discussion across NRAs is needed to identify the applications and services they are looking to address and engagement with the various key actors, OEMS, NRAs, Telcos, is needed to underpin a delivery model that protects investment decisions and delivers customer satisfaction.

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3 Data, Data Model and Exchange of Data

3.1 Overview of CAV data ecosystem

Exchange of data between different Connected and Automated Vehicle (CAV) stakeholders is one of the most crucial requirements for successful deployment of Connected and Automated Driving (CAD). It can be beneficial for all parties involved in the exchange. For instance, Original Equipment Manufacturers (OEMs) use HD maps developed by navigation service providers and share their vehicles' sensor and vision data with the navigation service provider that provides the HD map to improve the accuracy of the map. There are many other possibilities for data exchange that could facilitate successful deployment of CAD in the future. Clear examples of such exchanges between different CAV stakeholders are exchanging data of HD maps (developed by map providers) and digital twin of roads (developed by road authorities, and V2I communications, which could improve safety for all road users. However, there are many challenges in productive exchange of data between various CAV stakeholders, such as standards and protocols for data sharing, clear definitions of data quality, and clear liabilities for (inaccurate) data.

In order to provide a systematic overview of the issues involved with data sharing, we discuss several topics separately. First, we discuss the main categories of data related to CAVs and mention how and for which applications they can be exchanged. Then, we discuss real-time and non-real-time exchange of data. Next, we review different categories of existing and developing standards for data exchange within C-ITS as well as data exchange models and formats. Finally, we discuss challenges related to exchanging each category of data and identify gaps and future research directions. In Appendix, we provide a comprehensive overview of C-ITS service classifications. An overview of CAD standards within the EU is provided in (CAD Knowledge Base, 2021).

3.1.1 Categories of CAV data

We categorise CAV data into four main classes, namely vehicle sensor data (perception information), traffic safety data (associated with road safety-related traffic information (SRTI)), real-time traffic data (linked to real-time traffic information (RTTI)), and HD map data (related to digital infrastructure, HD maps and digital twins). In the following sections we discuss each one separately. It should be noted that there is overlap between different data types mentioned. Our categorisation is based on their main application.

3.1.2 Vehicle sensor data

CAVs are equipped with variety of sensors such as radar, lidar, camera, GNSS (e.g., GPS), ultrasonic sensors and inertial measurement unit (IMU). Each Automated Driving System (ADS), depending on how it operates and what type of information it requires for its operation, uses a subset of mentioned sensors to collect and process data. This data is used for two main purposes, namely, positioning and environment perception (Wang, Liu and Kato, 2019).

For positioning, Lidar, GNSS, IMU, and HD maps (which will be described later) are the commonly used sensors. Lidar, which is sometimes also called 3D laser scanner, determines rage by emitting light waves to the environment and processing the reflection. Global Navigation Satellite System (GNSS) is defined by a group of satellites transmitting signals from space that provide positioning and timing data to GNSS receivers, which is used by the receivers for determining location (*EU Agency for the Space Programme*, no date). Global Positioning System (GPS by NAVSTAR), Galileo (Europe), Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS by Russia) and BeiDou Navigation Satellite System (China) are examples of existing GNSS (*EU Agency for the Space Programme*, no date). Inertial measurement unit (IMU) measures vehicles' motion and acceleration and can aid in positioning, especially when the other sensors fail.

For environment perception, Lidar, radar, cameras and ultrasonic sensors are the common sensors used in CAVs. Radar and Lidar are used to determine distance and velocity of objects, cameras can provide images and videos of the surrounding environment, and ultrasonic sensors estimate position and shape of objects by emitting high-frequency sound waves to the environment and processing the reflections.

An ADS uses data from a combination of mentioned sensors as well as the data provided by HD maps and other sources of traffic data to build a dynamic image of its environment and position itself accurately within that environment. Environment perception is one of the most challenging tasks for existing ADSs.

3.1.3 Traffic safety data

This type of data is obtained by combining multiple sources of data collected by CAVs. According to the expert interviews conducted within the DiREC project, CAVs could collect two different types of data that could be used to improve traffic safety (DiREC, 2022). The first one is related to dangerous infrastructure situations, both static (e.g., lack of lane marking in critical places) and dynamic or real-time (e.g., slippery road segment). The second type is related to dangerous behaviour situations, such as near misses and state of the driver. The second type of safety data usually includes historical data and is not real-time. Some OEMs, to some extent, collect such data but standardisation, large-scale collection and sharing such data can have significant positive impacts on safety of CAVs by creating new possibilities. If the vehicles collect and store contextual information before and during near misses or accidents, this information could revolutionise safety research and accidentology by enabling new research and design methods that were not possible before (DiREC, 2022). For instance, currently the cycle time for redesigning vehicles to improve safety is 4-7 years due to the fact that the safety redesign is currently happening based on ex-post analysis of accidents and improving the design in the next generation of vehicles. But traffic safety data collected by CAVs could reduce this cycle time to a few weeks, for two reasons: 1) safety data could become available in much higher quantity and almost in real-time, and 2) safety could be improved through software (which could be updated over the air) rather than hardware redesign (which only affects the next generation of vehicles).

3.1.4 Real-time traffic data

Positioning and perception data that is constantly collected and processed by CAVs has the potential for use in real-time traffic estimation and management as well. Data collected by CAVs could be fused with loop detector data, Remote Traffic Microwave Sensor (RTMS) data, and Automatic Vehicle Identification (AVI) data for various traffic applications (Kashinath *et al.*, 2021). This category of data might include historical as well as real-time traffic state information.

3.1.5 HD map data

An ADS requires a high level of detail and centimetre-level precision in representation of environments for localisation and real-time path planning (Simeon, Ferrero and Etcheverry, 2018). This requires HD maps with detailed and precise static and dynamic information about the road network. There is no consensus on the type of information content and the level of accuracy required for HD maps. While some researchers simplify the requirements into three criteria: centimetre-level accuracy, storage efficiency, and usability (Gwon *et al.*, 2017), according to (Kalaiyarasan *et al.*, 2020), apart from centimetre-level accuracy, other characteristics of an HD map include:

- the location of static information (e.g. traffic lights, crosswalks, traffic signs, etc.);
- dynamic information (i.e. traffic) and provides real-time updates;
- supplementary information (i.e. traffic rules);
- 3-dimensional (3D) geometric information; and
- vehicle-to-everything (V2X) communication technology for real-time updates and to improve accuracy.

The information required for HD maps is usually collected via mapping (or probe) vehicles, satellite imagery, vehicle sensor data, government data, and community feedback (HERE, 2018). However, both static and dynamic elements of infrastructure and environment change in time (e.g., due to new lane markings, constructions and road works). Therefore, maintenance of HD maps and keeping them updated present immense challenges. Near-real-time crowdsourcing of update information potentially could provide a solution (Wong, Gu and Kamijo, 2021). Complementary to this solution, an important source that could significantly improve accuracy and richness of the information represented by HD maps is data collected by CAVs. This data can include all types of information mentioned above such as sensor data, safety data and real-time traffic data.

3.2 The need for data exchange and communication in CAD environments

Automated vehicle sensors' inherent limitations such as short perception range and limited usability in certain conditions make it necessary to augment their data with other information sources to improve the performance of ADSs (Wang, Liu and Kato, 2019). In addition, there are many CAD applications that could be enabled using data fusion, connectivity and multisource data collection. (Maalej *et al.*, 2017) studied object detection, recognition and mapping based on the fusion of stereo camera frames, point cloud LIDAR scans, and Vehicle-to-Vehicle (V2V) Basic Safety Messages (BSMs) that are exchanged using Dedicated Short Range Communication (DSRC) using a multimodal framework. (Cruz *et al.*, 2017) attempts to improve vehicular ad hoc networks (VANETs) in terms of localisation with the goal of leveraging vehicle communications and smartphone sensors. This has applications in positioning, traffic control and accident detection and is achieved via V2V and V2I communications. Enhancing cooperative localisation performance can be achieved by Vehicle-to-vehicle communication using dedicated short-range communication (DSRC). (Liu and Wang, 2017) proposed integration of DSRC and GNSS to improve the performance of the data fusion under uncertain sensor observation environments. (Kashinath *et al.*, 2021) provides an overview of multisource data fusion models used for traffic state estimation and traffic flow analysis.

Besides, there are many novel possibilities for research and developments that could be enabled by using multisource data collected by CAVs. For instance, new research methods in accidentology and traffic safety research enabled by near-miss and accident data collected by CAVs (DiREC, 2022). Finally, one of the common methods to collect data for HD maps is using probe vehicles (Gwon *et al.*, 2017). These vehicles are equipped with sensors such as radars and 3D lidars to collect information about the roads. Such sensors are found in CAVs as well, which means data collected by CAVs could be used to improve HD maps if this data is exchanged with map providers. All mentioned possibilities show the potential benefits from exchanging data and connectivity within CAD environments.

3.2.1 Types of data exchange

In this section, we briefly explain different types of data exchange between CAVs and other stakeholders within CAD environments based on the communication type. The two main categories of data exchange type based on communication delay are real-time data exchange and non-real-time data exchange. They are discussed below. More detailed information regarding different types of communication and cooperation within C-ITS is provided in the **Error! Reference source not found.**

Real-time data exchange

Most real-time data exchanges among CAVs and other entities are expected to happen using vehicular ad hoc networks (VANETs). VANETs are defined in the moving vehicle domain and follow the essential principles of mobile ad hoc networks. The main principle is the free creation of a wireless network of mobile devices. Based on communicating entities, there are four main types of communications within VANETs (Wang, Liu and Kato, 2019):

- vehicle to vehicle (V2V)
- vehicle to infrastructure (V2I)
- vehicle to pedestrian (V2P)
- vehicle to network (V2N).

V2V and V2P communications include exchange of ITS messages between vehicles and pedestrians for cooperative driving and safety reasons. An extensive dictionary of ITS messages that could be exchanged using V2X communication is provided by SAE International (SAE International, 2020b). V2I communication includes communication between CAVs and infrastructure elements such as traffic lights, roadside units (RSU) and base stations (BS). The content of such V2I communication could include, for instance signal cycle times and variable message sign (VMS) content. V2N communication provides CAVs with general access to internet for various types of data exchange such as ADS software updates and HD map updates. In absence of VANETs, most data exchanges between CAVs and other entities are of V2N type. This includes regular connection of CAVs to internet using cellular connection or Wi-Fi as well, which is currently the main medium for existing data exchanges within CAD environments.

Non-real-time data exchange

This category of data exchange includes exchanges of data between CAVs and other entities for applications that are not time-critical. This type of data exchange can occur using a variety of mediums including (but not limited to) cellular networks, Wi-Fi, Bluetooth and cable connection. ADS software updates, sensors and ADS performance data, historical safety-related data (e.g., contextual data related to near-misses, dangerous situations and accidents) and HD map related data exchanges are examples of non-real-time data exchanges between CAVs and other entities. Note that when the infrastructure for real-time data exchange is available, some data exchanges mentioned above (e.g., sending and receiving HD map data updates) could be done in real time or near-real-time (within a few minutes) as well.

3.3 Data exchange standards within C-ITS

In this section, we first provide a high-level overview of all C-ITS standards developed in the EU. Then we focus on three main types of standards that are the most crucial ones for CAV data exchange, namely, traffic safety related data exchange standards, real time traffic related standards, and HD map related data exchange standards. These standards are developed by the European Committee for Standardization (CEN).

There has been a great effort in recent years for standardisation of CAD technologies. Figure 5 shows the number of standards developed in EU for each category of CAD subfield. Figure 6 and Table 3 show total number of standards developed in each year. As it can be observed, there is an exponential increase in the number of standards since 2015 showing the increasing need for standardisation within CAD. As of August 2021, 175 CAV-related standards were published, and 51 CAV standards were under development (CAD Knowledge Base, 2021). The comprehensive list of all CAD standards published and under development is provided in (CAD Knowledge Base, 2021). A summary of the key CAV standards and priorities for future developments is provided in (BSI Group, 2022).

In the following sections, we focus on specific standards related to three main categories of CAD data mentioned earlier (i.e., safety data, traffic data and map data) and discuss them in detail.

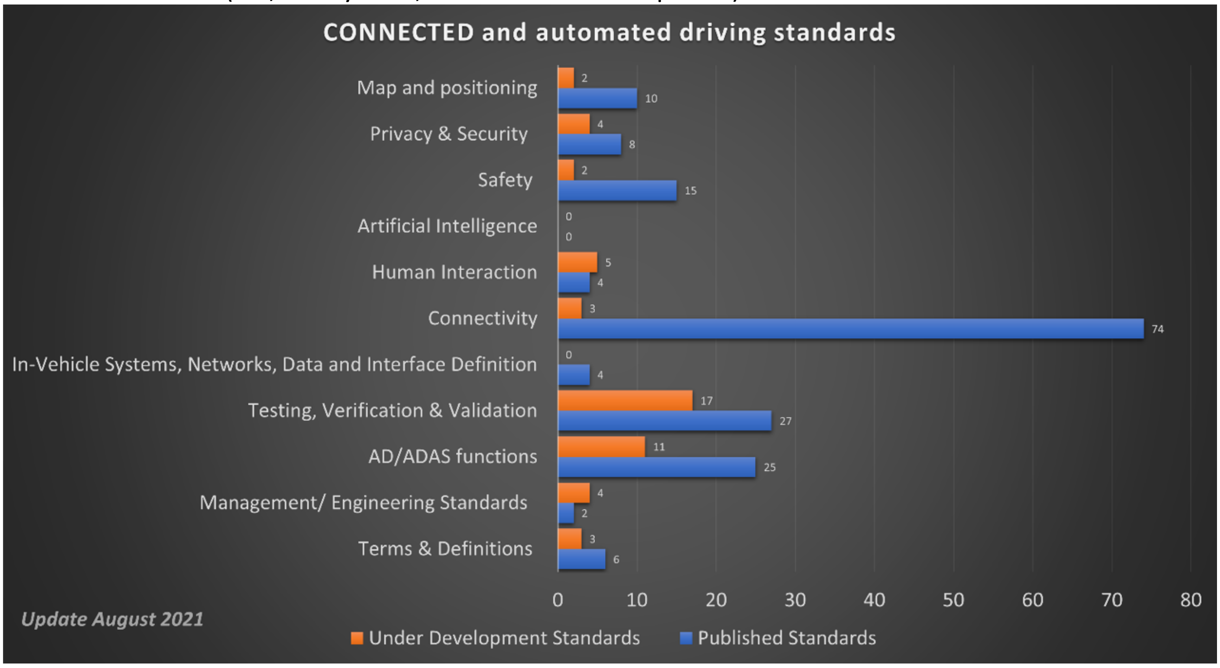

Figure 5 CAD standards in EU (CAD Knowledge Base, 2021)

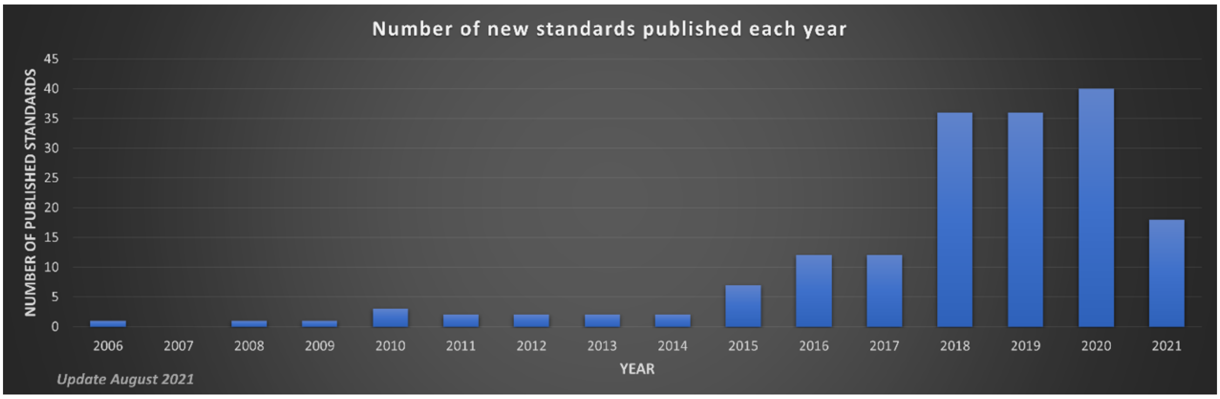

Figure 6 Number of new CAD standards published each year (CAD Knowledge Base, 2021)

Table 3 Number of new CAD standards published each year (CAD Knowledge Base, 2021)

Year	Number of Standards
2006	1
2007	0
2008	1
2009	1
2010	3
2011	2
2012	2
2013	2
2014	2
2015	7
2016	12
2017	12
2018	36
2019	36
2020	40
2021	18

3.3.1 Traffic safety data exchange standards

When it comes to CAV traffic safety data, the most important standard is stipulated within "COMMISSION DELEGATED REGULATION (EU) No 886/2013" (EC, 2013). Another recently published standard regarding automated vehicle safety is FGAI4AD-02 (ITU, 2021), which concerns automated driving safety data protocol in terms of Ethical and legal considerations of continual monitoring. It provides recommendations for safety requirements of artificial intelligence (AI) systems that are used in CAVs with ethical considerations as well as guidelines for regulating such systems and evaluating their safety. It provides rather detailed guidelines for liability matters of ADS software as well but it does not specify data exchange formats.

(EC, 2013) attempts to establish essential stipulations and definitions for guaranteeing compatibility, interoperability and continuity for usage and provision of road safety-related minimum universal traffic information within the EU. "road safety-related minimum universal traffic information means any extracted, aggregated and processed road safety-related traffic data, offered by public and/or private road operators and/or service providers to end users through any delivery channels" (EC, 2013).

The following is the list of road safety-related events or conditions as well as the specified information content (EC, 2013).

Table 4 list of road safety-related events or conditions and the related information content (EC, 2013, Article 3)

Events and condition
temporary slippery road
animal, people, obstacles, debris on the road
unprotected accident area
short-term road works
reduced visibility
wrong-way driver
unmanaged blockage of a road
exceptional weather conditions
Information content
location of the event or the condition
the category of event or condition as referred to in Article 3 and, where appropriate, short description of it
driving behaviour advice, where appropriate

Based on (EC, 2013), DATEX II (CEN/TS 16157) format (and other data formats compatible with DATEX II) is the preferred format of data exchange between service providers and public/private road users. This data shall be shared and exchanged between mentioned parties via an access point.

"'Access point' means a digital point of access where the road safety-related traffic data necessary for generating the road safety-related minimum universal traffic information are collected, formatted, and made available for exchange and reuse" (EC, 2013).

Member States are expected to establish and manage a national access point (NAP) that aggregates all other access points provided by all public and private actors within their territory. More details related to data formats mentioned above and NAPs is provided in section 3.3.4.

This regulation provides the first step in defining what types of events and information contents could be collected and shared. Moreover, it includes general statements on data formats and repositories (NAPs) for storing and sharing safety data. However, the information specified in the document is very high-level and insufficient for defining a framework for sharing safety data at EU level. An elaborate discussion on this account is provided in section 3.3.4 and the remaining challenges are mentioned in section 3.4

3.3.2 Real-time traffic data exchange standards

"COMMISSION DELEGATED REGULATION (EU) 2015/962" embarks on establishing the stipulations and definitions required for availability, sharing, and update of road and traffic data intended for EU-wide real-time traffic services (EC, 2015). The information includes static road data, dynamic road status data and traffic data.

According to (EC, 2015), in order to utilise smooth sharing and exchange of data, road authorities and service providers should make real-time traffic data as well as road data available to other stakeholders via a common access point, which could be a portal, repository or a similar data storage point. Access points were described in the previous section of this report. The recommended format for this type of is DATEX II or other compatible formats.

The following three tables show the data content and the recommended update content for the three types of data addressed in (EC, 2015), namely, static road data, dynamic road status data, and traffic data.

Table 5 Data and update content for static road data (EC, 2015)

Data content for static road data
road network links and their physical attributes, such as: (i) geometry; (ii) road width; (iii) number of lanes; (iv) gradients; (v) junctions
road classification

traffic signs reflecting traffic regulations and identifying dangers, such as: (i) access conditions for tunnels; (ii) access conditions for bridges; (iii) permanent access restrictions; (iv) other traffic regulations
speed limits
traffic circulation plans
freight delivery regulations
location of tolling stations
identification of tolled roads, applicable fixed road user charges and available payment methods
location of parking places and service areas
location of charging points for electric vehicles and the conditions for their use
location of compressed natural gas, liquefied natural gas, liquefied petroleum gas stations
location of public transport stops and interchange points
location of delivery areas
Update content for static road data
the type of static road data mentioned above
the location of the condition concerned by the update
the type of update (modification, insertion or deletion)
the description of the update
the date on which the data has been updated
the date and time when the change in a given condition has occurred or is planned to occur
the quality of the data update

Table 6 Data and update content for dynamic road status data (EC, 2015)

Data content for dynamic road status data
road closures
lane closures
bridge closures
overtaking bans on heavy goods vehicles
roadworks
accidents and incidents
dynamic speed limits; 23.6.2015 L 157/30 Official Journal of the European Union EN
direction of travel on reversible lanes
poor road conditions
temporary traffic management measures
variable road user charges and available payment methods
availability of parking places
availability of delivery areas;
cost of parking
availability of charging points for electric vehicles;
weather conditions affecting road surface and visibility
Update content for dynamic road status data
the type of dynamic road status data mentioned above and, where appropriate, a short description of it
the location of the event or condition concerned by the update
the period of occurrence of the event or condition concerned by the update
the quality of the data update

Table 7 Data and update content for traffic data (EC, 2015)

Data content for traffic data
traffic volume
speed
location and length of traffic queues
travel times
waiting time at border crossings to non-EU Member States
Update content for traffic data
the type of traffic data mentioned above and, where appropriate, a short description of it
the location of the event or condition concerned by the update
the quality of the data update

This regulation rather clearly defines the types of information and events that should be recorded, stored and shared. Similar to (EC, 2013), in (EC, 2015) the recommended form of repository is NAPs and the recommended data format is DATEX II. Since different location referencing methods are currently in use in different EU countries, use of different location referencing methods is encouraged in (EC, 2015). Despite the clear definition of information and events in (EC, 2015), different actors' responsibilities are not clearly defined. Moreover, data formats specified are too general. Data formats and their implications are discussed in section 3.3.4.

(EC, 2015) is scheduled to be repealed from January 2025 and be replaced by (EU) 2022/670 (EC, 2022) with the exception of some articles which will be enacted from 2027. The main changes imposed by (EC, 2022) include the extension of the geographical scope (from Trans-European Transport Network (TEN-T) to all public roads where motorised traffic is permitted) and the data formats (INSPIRE and TN-ITS). A clarification on what this revision means for operation of road operators is provided in (van Dijck, 2022).

3.3.3 HD map data exchange standards

In this section, we mention the standards related to data exchange for HD maps in the context of ITS. The source of these standards is the European Committee for Standardization (CEN); and more specifically, subcommittee CEN/TC 278 - Intelligent transport systems. The following are the main standards related to exchange of data for HD maps (Kalaiyarasan *et al.*, 2020):

Table 8 Main standards related to exchange of data for HD maps (Kalaiyarasan et al., 2020)

• CEN/TC 278/WG 7: ITS spatial data ○ CEN/TS 17268:2018 Intelligent transport systems - ITS spatial data - Data exchange on changes in road attributes
• CEN/TC 278/WG 8: Road traffic data (RTD) ○ EN 16157-1:2018 Intelligent transport systems - DATEX II data exchange specifications for traffic management and information - Part 1: Context and framework ○ EN 16157-2:2019 Intelligent transport systems - DATEX II data exchange specifications for traffic management and information - Part 2: Location referencing ○ EN 16157-7:2018 Intelligent transport systems - DATEX II data exchange specifications for traffic management and information - Part 7: Common data elements ○ EN ISO 14825:2011 Intelligent transport systems - Geographic Data Files (GDF) - GDF5.0 ○ CEN ISO/TS 19468:2019 Intelligent transport systems - Data interfaces between centres for transport information and control systems - Platform independent model specifications for data exchange protocols for transport information and control systems
• CEN/TC 278/WG 16: Cooperative ITS

○ CEN ISO/TS 21177:2019 Intelligent transport systems - ITS station security services for secure session establishment and authentication between trusted devices ○ CEN ISO/TR 17424:2015 Intelligent transport systems - Cooperative systems - State of the art of Local Dynamic Maps concepts ○ EN ISO 18750:2018 Intelligent transport systems - Co-operative ITS - Local dynamic map
• BS ISO 20524-2:2020: Intelligent transport systems. Geographic Data Files (GDF) GDF5.1 - Map data used in automated driving systems, Cooperative ITS, and multimodal transport.

We briefly explain above-mentioned standards below. Comprehensive explanations related to these standards is provided in (Kalaiyarasan *et al.*, 2020).

CEN/TS 17268 specifies the content for road-related spatial data exchange and related updates. Regarding the data exchange, physical exchange format (structure and encoding) is also defined in this standard. Moreover, required web services for making the data available are defined.

EN 16157-1:2018 determines components necessary for supporting the exchange of traffic and travel data. This entails the framework and context for the modelling approach for DATEX II, data content, data structure and relationships for traffic and travel information that are relevant to the use of road networks and C-ITS systems.

EN 16157-2:2019 concerns the implementation of the location referencing systems. It determines the required structures, roles, relationships, attributes as well as the related types of data.

EN 16157-7:2018 concerns publishing information within the DATEX II framework. It defines common information structures, roles, relationships, attributes along with the related types of data required.

EN ISO 14825:2011 deals with GIS data for ITS services and defines the encoding formats as well as the logical model for related databases.

CEN ISO/TS 19468:2019 is concerned with traffic and travel data, their sharing and exchange. It defines the structure for data exchange and communication in a platform-independent way.

CEN ISO/TS 21177:2019 is meant to guarantee the information source authenticity and information exchange reliability between different ITS stations as well as other entities involved in the information exchange.

CEN ISO/TR 17424:2015 provides an overview of the local dynamic maps status in terms of standardisation and implementation architecture.

EN ISO 18750:2018 defines the functions of a local dynamic map in the context of the "Bounded Secured Managed Domain".

ISO 20524-2 is concerned with GIS data in ITS services. Regarding databases, it identifies the physical encoding formats and possible data contents. Regarding the data itself, it defines conceptual models, representation and metadata.

HD map data quality standards

(Kalaiyarasan *et al.*, 2020) has identified a number of mapping standards currently being used in the HD map industry, such as the Navigation Data Standard (NDS), ADASIS, Vector Tile 3 (VT3) by Mapbox, and the Open AutoDrive Forum (OADF). Other standards include the ISO/PAS 21448, ISO 8000, ISO 19157:2013, ISO 19115:2003, ISO/IEC 27001:2013, ISO 26262, ISO/PAS 21448:2019 (SOTIF), and Automotive Safety Integrity Level (ASIL). They are briefly explained below.

Navigation Data Standard (NDS) is co-developed by OEMs and suppliers for map data in the automotive eco-system and is a global standard (HERE, 2018; Hubertus *et al.*, 2019). It is currently being used by several map data providers as well as OEMs developing and testing automated vehicles. It supports compatibility and interoperability, separation of application and software and map data, and incremental updates (Kalaiyarasan *et al.*, 2020).

SENSORIS managed by ERTICO, represents a collection of 28 key players in the global automotive industry, map providers, data providers, sensor manufacturers and telecom operators (HERE, 2018). Its standard, which was originally put forth by HERE as a component of the sensor data interface specification, is now being managed as an interface specification that is standardised (Kalaiyarasan *et* *al.*, 2020).

Mapbox's Vector Tile 3 (VT3) specification was meant for powering HD vector maps as an open standard (HERE, 2018). It provides information related to file formats and extensions, projections and bounds, and the internal structure of vector tiles.

The Open AutoDrive Forum (OADF) is the main organisation managing various map standard initiatives, such as SENSORIS, NDS and ADASIS (HERE, 2018). Its aim is to synchronise the flow of data and promote interoperability between data formats.

Advanced Driver Assistance Systems Interface Specifications (ADASIS) is a map based ADAS standard that defines a suitable interface for the communication between vehicle map database, ADAS and automated driving applications (HERE, 2018). The ADASIS v3.0 standard, focusing on automated driving, was recently released by ERTICO (HERE, 2018).

Automotive Safety Integrity Level (ASIL) is defined by the ISO 26262 - Functional Safety for Road Vehicles standard (ISO 26262-9, 2011). It is a scheme for classification of risk, and it defines minimum safety requirements according to the ISO 26262 standard. Four levels (A, B, C and D) are recognized by the standard where ASIL A indicates the lowest level of quality requirements and ASIL D implies the highest level.

3.3.4 Data exchange models and formats

All C-ITS applications process data. Some generate data that needs to be stored and shared, and some use data generated by others. Harmonised exchange of data among multiple stakeholders within CAD environments necessitates standards on data formats and data models. As mentioned earlier, almost all standardisation documents within the ITS Directive and the related delegated regulations for traffic data mainly recommend the use of DATEX II as the standardised data format for C-ITS applications (excluding C-ITS messages, which have dedicated standards).

"DATEX II is the electronic language used in Europe for the exchange of traffic information and traffic data. The development of DATEX II was initiated in the early 90s because of the need to exchange information between traffic centres of motorway operators. Soon there was the need to open this information to service providers. DATEX I was somewhat too limited for this and used outdated technical concepts. Which is why DATEX II was developed in the early years of this millennium. By means of DATEX II, traffic information and traffic management information are distributed in a way that is not dependent on language and presentation format. This means that there is no room for misunderstandings and / or translation errors by the recipient, but the recipient can choose to include spoken text, an image on a map, or to integrate it in a navigation calculation." (DATEX II, 2022a)

"The stakeholder cooperation maintaining DATEX II is hosted by CEDR (Conference of European Directors of Roads) per the 1st of January 2016. Some activities of the DATEX II organization are funded by EU CEF Programme Support Action (PSA) Agreement number MOVE/C3/SUB/2015-547/CEF/PSA/SI2.733309 RWS. DATEX II is a multi-part standard, maintained by CEN Technical Committee 278, Road Transport and Traffic Telematics (see www.itsstandards.eu). The first six parts of the CEN DATEX II series CEN/TS 16157 have already been approved as Technical Specifications in 2011-2015. The first three parts and the seventh part of the CEN DATEX II series are under approval as European Standards." (DATEX II, 2022a)

A common misperception regarding DATEX II or delegated ITS regulations that suggest the use of DATEX II is considering DATEX II as a data model or assuming delegated regulations define a clear data model. This is not the case. Delegated regulations provide rather detailed descriptions of types of data that fall into the scope of a delegated regulation. More specifically, the recommended reference profiles (RRPs) contain the minimum set of data-elements required to provide the information meant by the specific data category in the specific delegated regulation. The regulations recommend using DATEX II for encoding. However, they do not specify a publication model. Also, they do not determine a concrete data profile. This leads to freedom for data suppliers, which could possibly have advantages for them, but the disadvantage is that the data suppliers face many formatting decisions to make and the data receivers possibly have to deal with diversity in data models and profiles (6th DATEX II Forum, 2020).

Data exchange can be via NAPs or not. As mentioned earlier, according to regulations, NAPs only need to provide repositories of meta-data. Different countries do this differently. Detailed information about the usage of DATEX II in different countries for storing and sharing Safety Related Traffic Information (SRTI) and Real-Time Traffic Information (RTTI) is provided in (DATEX II, 2022b), which indicates some NAPs within EU do not use DATEX II and some countries have not implemented any NAP.

3.4 Data exchange challenges

In this section we discuss different challenges related to the exchange of data between multiple stakeholders in CAD environments based on the category of data they concern. Since exchanging traffic safety data and real-time traffic data categories generally face the same challenges, we discuss them together in section 3.4.1. Then we discuss challenges related to HD map data in section 3.4.2.

3.4.1 Traffic safety and real-time traffic data exchange challenges

The challenges related to exchanging traffic safety data could be classified into two main types; challenges related to collection of traffic safety data, and challenges related to sharing traffic safety data.

Traffic safety and real-time traffic data collection challenges

According to (DiREC, 2022), there are four main challenges related to collecting CAV traffic data:

- All events to be recorded need to be clearly defined in advanced with a high level of accuracy (e.g., slippery road). (EC, 2013, 2015) have defined a general list of such events; however, first, this event list does not include all dangerous driving situations such as near misses, and second, the definitions are not specific enough for a machine (e.g., ADS) to distinguish them on the road (e.g., what is the threshold to label a road section as slippery?).
- After clearly defining the events, ADS needs to be trained/adjusted to actively look for them and recognize them. If and when there is a databased of events to look for (in a machine-readable format) and clear methods for recognising each, this is technically feasible. Although it requires training ADSs to look for them and recognise them. However, anomaly detection without specific items to recognise (i.e., expecting ADS to recognise any anomaly in the environment) is an open research topic and not technically feasible at the moment.
- The contextual information and attributes to record when mentioned items are detected should be clearly defined for each situation type. (EC, 2013, 2015) provide the first step in this direction by mentioning location, category and behaviour advice as the contextual information but this is too general and not sufficient for all applications.
- This information needs to be stored and transmitted, which means extra storage and connectivity costs.

Traffic safety and real-time traffic data sharing challenges

Challenges with sharing CAV traffic data include (DiREC, 2022):

- Standard data formats and models for transmitting stored data to relevant repositories; DATEX II is mentioned in (EC, 2013, 2015) as the recommended data format. But as discussed in section 3.3.4, DATEX II does not provide a complete data profile and leaves room for interpretation (6th DATEX II Forum, 2020).
- Clear and standardised repositories; although (EC, 2013, 2015) identify NAPs as the master repository where all meta-data needs to be stored, these regulations leave the freedom for setting up local repositories for detailed data. This means dealing with a variety of repositories at national and local levels. Moreover, as discussed earlier, not all NAPs use DATEX II at the moment, which means operating in different countries, even within the EU, will require dealing with different data formats.

- Connectivity infrastructure is another requirement for automating the exchange of CAV data. In order for events such as slippery road or temporary road closure due to accidents to be detected and shared by CAVs, they need real-time or near-real-time connectivity possibilities, which presents a challenge.
- OEMs' motivation and willingness to share data; last but perhaps the greatest challenge related to sharing CAV traffic data is related to OEMs' motivation for sharing such data. After a series of interviews with OEM representatives and experts, it is concluded in (DiREC, 2022) that OEMs lack the motivation to share such data for the following reasons:
    - Data privacy protection and legal issues that sharing might cause;
    - OEMs know this data is valuable and can give them competitive advantage;
    - Revealing competitive secrets and comparison with other OEMs (e.g., sensor or environment perception performance);
    - Standardization (i.e., what data to collect and with whom to share);
    - Cost of collecting and sharing data;
    - Liability issues (e.g., OEMs can get sued easily for any issue resulting from the shared data);
    - Risk vs. gain; all in all, the risks related to traffic data sharing seem to outweigh the gains for OEMs at this moment.

3.4.2 HD map data challenges

Various challenges related to production, maintenance, standardisation and use of HD map data is identified in different studies (HERE, 2018; Kalaiyarasan *et al.*, 2020; Wong, Gu and Kamijo, 2021; DiREC, 2022). Here we combine the information in mentioned studies to provide a comprehensive list of challenges and possible solutions related to HD maps for CAD.

HD map content and standards

The first critical question related to HD maps for CAD is the information content. The question is: what types of data a map should contain in terms of "must have" and "nice-to-have" information? (Wong, Gu and Kamijo, 2021). Despite ongoing standardization efforts, such as NDS, ADASIS, SENSORIS, etc., maps provided by different suppliers are not interoperable. (HERE, 2018).

Quality control and minimum data quality requirements

Generating error-free maps is still very difficult. The main reasons are complexity of the environment, dynamic nature of the environment, and quality management issues when merging multiple large datasets from various sources (HERE, 2018). When it comes to maps for CAVs, data quality is an essential aspect. Defining minimum data quality requirement for safe operation of CAVs is quite challenging. Another challenge is assessing the influence of poor data quality on CAV functionalities. It is crucial to note that data quality is functionality dependent and it might differ between different applications (Wong, Gu and Kamijo, 2021).

Defining a universal mapping format

There is a consensus that maps are necessary for operation of CAVs. However, there is no agreement on the number of maps or map layers and the appropriate map format for each CAV functionality. While one map will likely not meet the needs of all CAV functionalities, having large number of maps (one for each function) can cause challenges in computation, storage, maintenance, and update. Most likely the main challenge here is to define the smallest number of maps that meet the requirements of all CAV functionalities. (Wong, Gu and Kamijo, 2021).

Size of map data files

In recent year, maps have increased significantly in terms of data size, particularly HD and 3D maps for CAVs. This poses challenges for updating maps wirelessly due to high time, bandwidth and cost requirements as well storage and computational power requirements for the vehicle. Therefore, there is a need for lighter maps with different models of the environment (HERE, 2018). The question of "what is the most efficient and effective framework for storing and sharing mapping data for CAVS and how to build and maintain such infrastructure" is still open for research (Wong, Gu and Kamijo, 2021).

Mapping traffic laws and regulations

Including traffic laws and regulations in digital maps is another major challenge. Although CAVs can detect traffic signage and road markings, when these signs are missing or are not clear, the vehicle still needs to follow the rules. Therefore, traffic regulations in digital form must be available for CAVs (Wong, Gu and Kamijo, 2021). Apart from curating such information, data representation is also a challenge when it comes traffic rules, for instance, where is the exact boundary of a speed limit on the map.

Improving navigation information integrity

CAVs are equipped with many sensors to perceive their environment. Having multiple sensors implies that some level of redundancy is built into the vehicle in case of failure in one or more sensors. Sometimes it is possible to enhance reliability via sensor fusion. However, when the sensors perceive contradictory information, this causes a problem of deciding which sensor to rely on. Therefore, map data used by CAVs must be reliable and authoritative to make sure the vehicle is capable of complying with traffic rules based on the map data (Wong, Gu and Kamijo, 2021).

Collaborative mapping

Crowdsourcing or collaborative mapping could occur in different forms and overcome some of the mapping challenges. It could be via different CAVs using the same mapping service (DiREC, 2022) or a group of volunteering vehicles collecting information about the environment and transmitting git back to the map provider (Wong, Gu and Kamijo, 2021). The main advantages are cost-effectiveness as well as increased scalability and robustness of the information. The main challenges are having enough vehicles on the roads to collect information (DiREC, 2022) and the process of aggregation and reconciliation of the information continuously collected by multiple sources (Wong, Gu and Kamijo, 2021).

Scalability: building maps at the national or international scale

CAVs require maps at city, region, and national levels. However, building a map that can scale well, be easily updated, and work under all environmental conditions is very challenging. There is ongoing research on maps with wider coverages; however, creating national or international maps remains challenging. Differences in road geometry, signage, road markings and traffic regulations is the main part of the challenge (Wong, Gu and Kamijo, 2021).

Update and maintenance

A perpetual challenge is updating and maintenance of maps for CAVs. Two important aspects here are determining what triggers a change and how often a map should be updated (Wong, Gu and Kamijo, 2021).

Business models, monetization and production cost

Given the high production cost of maps due to the need for global coverage, manual verification and complexity of generating maps, monetising map production is becoming increasingly challenging, particularly since there are many competitive free maps and navigation solutions (HERE, 2018).

Preserving privacy

Privacy of location and movement data of individuals is an accepted expectation. On the other hand, location-based services benefit from detailed location and movement information of individuals. When it comes to mapping for CAVs, the question is can the system operate safely if the person's location information need to be hidden? Should a map be allowed to use past movement information to improve CAV functionality? Should privacy be prioritised above all other concerns? These are critical questions that need to be answered, especially when it comes to collaborative mapping environments (Wong, Gu and Kamijo, 2021).

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4 Digital Twin

This project looks to create a CAV Ready Framework, a CRF. The CRF is to be used by network operators in order to guide their considerations in terms of their requirements for physical and digital infrastructure.

Digital Infrastructure, or digital transportation is becoming an important stepping stone to achieving a CAV environment, particularly the engagement with Connected Intelligent Transport System devices and systems. The importance of the Digital ecosystem has long been recognised, from the C-ITS Platform final report in 2016 (C-Roads 2016) to the 2020 Sustainable and Smart Mobility Strategy – putting European transport on track for the future (Sustainable Strategy 2020) (Anon., n.d.).

As part of this digital transition and the move to consider more than a physical asset, the Digital Twin as an enabler has received a lot of attention of late. A Digital Twin has many competing definitions, some of which are touched upon in more detail in this report. In its simplest form, the Digital Twin is referred to as '*a digital replica of physical assets (physical twin), processes and systems that can be used for various purposes*.'[Wikipedia].

The following definition of a digital twin is given by (Damerau, 2019):

"A digital twin is a digital representation of an active unique product (real device, object, machine, service, or intangible asset) or unique product-service system (a system consisting of a product and a related service) that comprises its selected characteristics, properties, conditions, and behaviors by means of models, information, and data within a single or even across multiple life cycle phases."

Another approach for characterization of what a digital twin was made by (Jones, 2020). Here, a Google Scholar search with some filtering on "digital twin" resulted in 92 papers that were thematically analyzed. This resulted in 13 characteristics of digital twins. Those are Physical Entity/Twin; Virtual Entity/Twin; Physical Environment; Virtual Environment; State; Metrology; Realisation; Twinning; Twinning Rate; Physical-to-Virtual Connection/Twinning; Virtual-to-Physical Connection/Twinning; Physical Processes; and Virtual Processes. Provided these characteristics a deeper understanding of a digital twins also including its process of operation. A drawback of these characteristics is the lack of a simple definition of a digital twin.

Further, there are efforts to categorize how mature a digital twin is. For technology and society there exist the technology readiness level (TRL) and societal readiness level (SRL). In the same way as these levels capture maturity (Botin - Sanabria, 2022)suggests a maturity level for digital twins rated from 0-5. (Botin - Sanabria, 2022) further presents different digital twin applications in the areas of Smart Cities and Urban Spaces; Smart Manufacturing; Freight Logistics; Medicine; Engineering; and Automotive which are rated using the suggested digital twin maturity level. The rating is generally between 1 to 3 and no digital twin application has a maturity level of 4 or above indicating again the current development in the area.

Perhaps a more detailed explanation, from a CAV perspective, can shine a light on the role it can play going forward. The Construction Innovation Hub's Digital Twin Navigator, presents a detailed definition as follows:

"*Digital Twins are realistic digital representations of physical built **assets** including spaces and structures (buildings, roads, and rail etc), **processes** and **systems**. They unlock value by enabling improved **insights that support better decisions**… which creates the opportunity for **positive feedback into the physical twin**… leading to better outcomes in the physical world… The value proposition is enhanced when Digital Twins are **federated within an organisation** to share and benchmark information an organisation.*"

However, prescribing a too tight definition on what a Digital Twin is and is not can be restrictive. For one scenario and use case, the functional elements of the Digital Twin may well vary quite significantly across form and function. As such, this report looks at Digital Twin from a data representation of a physical asset and how the data can be utilised to benefit AV deployment.

Data however is not the singular approach to ensure a functional CRF for the road authorities. No, it is the ability to go across data sets, capture and then breakdown the various data silos that exist in organisations which can help leverage true value for NRA and travelling public alike.

4.1 Why use a Digital Twin

Consider a piece of physical infrastructure, such as a road. If there was a way to create a cyber equivalent of the road, then autonomous vehicles would be in a position to use the cyber reality to help guide its functionality and decision making, using physical support elements such as signs and lines as safety support points. To create a cyber road, possess a number of challenges, such as the standards used to represent the road, the details included in the data sets, the information and processing required of the data sets and mechanisms for inclusion of data sets with other elements in the CAV domain.

Data, the foundation of a Digital twin is not in itself sufficient to drive change. IT is the ability to convert data to information and extract intelligence from it where the value lies.

From a physical twin perspective, information (not exhaustive) that would be expected to be available in the digital twin version could include:

- Location of road
- Geometry and condition
- Asset type
- Pavement condition
- Gradient/Camber
- Permitted speeds
- Enforcement conditions
- Location of power lines
- Location of signs and lines (fixed assets)
- Communications capabilities
- Traffic light condition
- Mapping location
- Weather data
- Incident data (historic and current)

The information sets outlined above are just some of the data sets that would help provide a static and dynamic representation of the road network. This combination of historic and real time data sets as pertaining to the road on which the vehicle is travelling can be used to improve the safety of the travelling public.

4.2 Current Digital Twin activities

4.2.1 EU work to date

A range of projects across the Connected ecosystem is already underway to harness the power of the Digital Twin.

The AUTOPILOT project was an IoT enabled AV project (AutoPilot, 2018) which investigated the functional characteristics of a digital twin to support AV deployment. It was an EU H2020 Large Scale Pilot Project with the stated ambition to create an IoT-supported Autonomous ecosystem. As part of its work, it looked at the Digital Twin opportunities and in particular development of standards and a contextual model approach for extracting information from the Digital Twin to support the AV ecosystem.

LEAD (LEAD, 2022), an EU-funded project under the CIVITAS Initiative, create Digital Twins of urban logistics networks in six TEN-T urban nodes (Madrid, The Hague, Lyon, Budapest, Oslo, Porto), to support experimentation and decision making with on-demand logistics operations in a public-private urban setting.

DIGITbrain (DIGITbrain, 2022), an EU innovation program which has the vision to unleash manufacturers' innovation potential through Digital Twins, looks to provide Digital Twins to manufacturing companies. The project initially united 36 partners from all over Europe at the project start in July 2020 and is offering opportunities for another 35-40 companies to join the project.

In UK, the National Digital Twin programme (NDTp) was established in 2018 to deliver key recommendations from the National Infrastructure Commission's 2017 Data for the Public Good Report. It highlighted that increasing population, economic growth and climate change are putting significant pressure on infrastructure, and that to address this, infrastructure needs to become smarter. It urged regulators, network operators and utilities to prioritise data, development of a digital framework for infrastructure data, and a roadmap towards a National Digital Twin.

The Centre for Digital Build Britain (CDBB) released a three-part white paper study on the How/What /Why related to Digital Twins:

- How to enable an ecosystem of connected digital twins?
- Why connected digital twins?
- What are connected digital twins?

An overall conclusion from the above elements, in particular those directly related to the Transport question of AVs, such as Autopilot, showcase how a Digital Twin can help in understanding the current situation on the road involving the different relevant actors, look to predict future scenarios and recommend actions. This integration with digital twin will allow for autonomous vehicles to be contextualised not only within its own immediate environment but also look to perceive what is to happen and create significant strategies to deal with them. In the creation of a data driven approach to autonomous echoes, supported by digital models such as NGSI-LD approach to information for publishing, querying and subscribing to context information, the facilitation of an open exchange and sharing of structured information between different stakeholders ensures a functional digital twin for users.

Across these papers, and linked to the topics already discussed and identified, the need for transparent, structured approach to the digital domain is key, and the ability to seamlessly link data across and through silos identified as a key enabler for digitisation of a physical environment.

4.2.2 Industry activity

The realisation of a Digital Twin has been underway in the last number of years, particularly in the Manufacturing, Construction and Design sectors. There, the use of data linked to existing processes is used to help improve efficiencies of activities. This can range from identification of bottlenecks in the design and delivery process and alignment through space in a construction area with business information modelling suites (BIM) to aid design and construction.

4.2.3 Construction

(Opoku, 2021) undertook a research activity to ascertain the use of digital twin technologies within the construction sector. It was found that though there are over 22 recently produced papers on the use and application of the Digital Twin in construction, the lack of a unified approach and standardisation of approach is limiting the opportunities for deployment. That said, integration of Digital Twins with BIM can open a lot of efficiencies for the industry. Whereas BIM, which has been in use for several years, looks at the consolidating data developed for planning and design phases, the Digital Twin builds on this by extending into the construction and operational phase, allowing 'what if' scenarios to be modelled and reviewed.

4.2.4 Rail Industry

(Grieves, 2002) introduced the early concept of digital twins refined into a three-dimensional structure that contain physical entities, virtual models, and data connections. Over time this developed into a five-dimensional model of digital twins (Meng, 2020)which supported the development of a Digital Twin simulation platform framework to be designed for use within the Rail context. The Digital Twin approach, and the link to a framework, allows the Rail Operator to consider the integration of several data sets to increase operations capability as well as comfort for the travelling public. (RSSB, 2019)

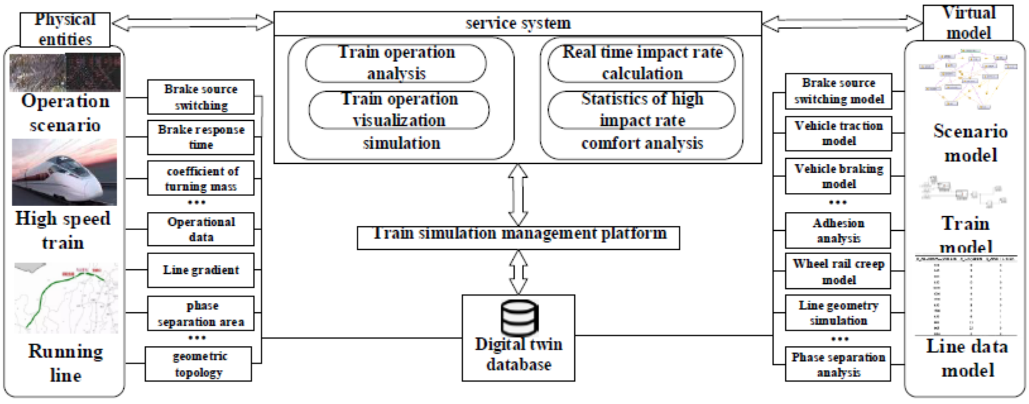


Figure 7 Rail Operator Approaches (Meng, 2020)

This has evolved over time and the typical challenges in rail from a Digital Twin perspective relate to:

- Create a Digital Twin when constructing a new railway
- Define a roadmap to start the development/implementation towards a digital twin to manage assets better, to save time and money
- Understand and exploit the potential benefits of a Digital Twin to under-performing railway operations
- Formulate a response to governmental drive to create a National Digital Twin
- ….with a focus on the immediate next steps of the asset lifecycle

However, as outlined in the diagram below, there is no comprehensive realisation of the digital twin concept that fully delivers on the market expectations but rather there are discreet elements that when connected to other elements can help provide that full digital twin capability.

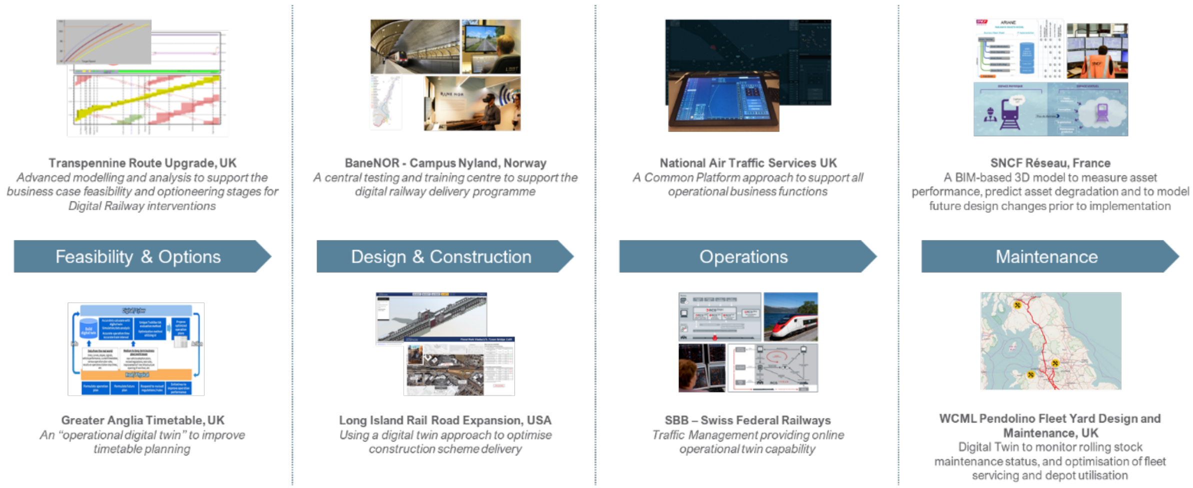


Figure 8 Elements of a Digital Twin within the Rail Environment (Arup)

4.2.5 Manufacturing

Until recently, building a digital twin was considered too expensive to create with limited clarity on the business benefits to be derived for a manufacturing environment. However, with reductions in storage costs, increases in computing capability and the migration to cloud processing run times, it is now considered an opportune time to use Digital Twins to extract value for the industry. (Magomavod, 2020).

It is proposed that this can be undertaken in a number of ways, including:

- Creating a clear link across the whole supply chain and as such allow for greater business insight to be developed around costs at each link in the chain.

- Developing a data rich connected ecosystem that removes silos around operations and allows for an end-to-end environment to be operated more efficiency, such as large manufacturing plants.
- The timely creation of a suite of scenarios that can address in a quantitative fashion the value and costs and impacts of different functions in the manufacturing and identify positive intervention strategies where appropriate.

4.3 Digital Twins: Cities, NRAs and OEMS

Though in an early stage of development, a number of Road Authorities have already looked at how Digital Twins, both in the back-end design elements as well as the front-end deployment considerations have begun to be teased out. Identified below is a snapshot of some of the work done to date in this area.

4.3.1 German Ministry of Transport

The German Federal Ministry of Transport and Digital Infrastructure in collaboration with Ford Mobility, Vodafone and others is developing a digital twin that aims to prepare the city of Aachen for widespread and safe adoption of automated vehicles in a mixed traffic environment. Phase 1 of the project is integrating high-resolution infrastructure data, road user behaviour and vehicle movements, using a mixture of LiDAR sensors and cameras along a 4.3 km stretch of urban and rural highway. High resolution point cloud data allows longer range and improves object classification. Algorithms process these data to classify cars, trucks, pedestrians, two-wheelers and other road objects. Phase 2 is to develop and test V2X simulations on the digital twin.

One goal of the project is to demonstrate real-time communications, where autonomous test vehicles on the network receive information from the digital twin before they “see” it with their onboard sensors, giving them time to adjust. Another is to simulate how autonomous vehicles will impact other road users. Another goal is for real road user behaviours to be stored and analysed to provide information to inform long-term planning for autonomous vehicle applications.

4.3.2 DARS, Slovenia

The DARS Motorway Company in Slovenia have created a digital twin for around 20 km of their 620 kilometer network. They use this for simulation modelling of traffic flows under different scenarios of CAVs of percentage of CAVS on the network, and to identify and measure the safety implications of CAVs. They have one national traffic information centre, which holds data around traffic accidents, incidents etc. all in one system. They also have applications to exchange data in real time with their neighbouring countries.

4.3.3 National Highways (formerly Highways England)

Various National Highways policy and strategy documents from 2019 onwards under the Digital by Default initiative have made mention of digital twins. Each subsequent document has confirmed the general direction in line with the NDTp and the Gemini principles, and has started to flesh out policies, use cases and functionality.

The latest published strategy, the Digital Roads 2025 Roadmap (National Highways, 2021), identifies a “long term ambition to create a digital replica of the strategic road network (SRN) embedded with detailed information on design and operation of our assets, used to monitor the SRN in real-time and provide predictive analysis”. The main themes of the Roadmap are Digital Design and Construction, Digital Operations, and Digital for Customers. Digital Twins are seen as primarily supporting Digital Design, and to support maintenance planning of assets. They are not mentioned in the context of ‘Digital for Customers’ although clearly Digital Twins could support that theme with its activities relating to enhanced data sharing with 3rd parties, improving information channels, and in-vehicle information and connected services.

The most detailed report on digital twins in National Highways is the draft ‘Digital Twins at Highways England’ (Gordon, 2021) which sets out high-level policies. It states that Digital Twins can and should be part of the construction phase, but the current focus of their use in National Highways is on the operation of existing physical assets. Eventually, it aims to be able to simulate traffic flows on the network to optimise flows using signals, and to incorporate data on ongoing operations.

It also states that Digital Twins should provide a range of functionalities, including the ability to run 'what if' scenarios and analyse the impacts on performance of assets, configuration of the network, maintenance policies, traffic management, customer demand, weather, incidents, and disruption to other transport and utility services. It also highlights the importance of exchange of information with other organisations that depend on the strategic road network infrastructure and lays out broad polices relating to governance and ethics of Digital Twins.

There are several pilot projects being drawn up for individual motorways, including parts of the M25 around London. The ultimate aim is for a digital twin that covers the entire network, but it is acknowledged that this will take considerable time.

4.4 Literature (Transport) on Digital Twins

In recent years there has been an increase in the literature dedicated to Digital Twins from a transportation perspective. The approaches are different and multi-faceted, looking at a range of scenarios and use cases to demonstrate the effectiveness and challenges associated with a migration to a Digital Twin capability. A snapshot of the range of research areas are shown below.

(El-Marai, 2021) explored how a digital twin of a road environment can be advantageous to the wider smart city agenda. They looked at utilising a digital box to create a real time view of the road network and integrate it with identification software to ensure the safety of the asset being utilised.

(Dasgupta, 2021) looked at integration of a digital twin along with adaptive traffic management technologies and strategies in order to minimise the wait times at junctions in co-ordination with other road users up stream of the junction itself.

(Munasinghe, 2021) took a different approach again, addressing the opportunities for developing countries to utilise crowd source data and integration with Digital Twin systems to help monitor the road conditions.

What is clear, regardless of the scenario and use case being addressed, is that there is a clear opportunity to harness the power of data, integrate physical infrastructure with a digital equivalent, in order to drive better services and experience for the travelling public. This is linked to work already under way from a modelling perspective, which goes into details on the 'engine' behind the integration of Digital Twins and the approach to data harvesting and utilisation.

Traffic Modelling Approaches

(Sanchez-Vaquerizo, 2021) she identified an approach in developing a city-wide Digital Twin to help manage traffic flow and link to traffic management strategies. He found that the prospective and exploratory power of digital twins in combination with the inclusion of social and behavioural values can become a facilitator of governance and co-creation of cities, expanding human decision-making capabilities by using computation.

Zang's paper (2021) on the utilisation of 3D GIS technology as a basic component of traffic assessment on highways identified the challenges linked to the veracity of data, the types of data and the integration required for common assessment strategies to be put in place.

Tihany (2021) successfully demonstrated the ability, under limited and rigorous control conditions, to link a real-life traffic environment to a digital twin based on data fusion and cloud processing techniques. In its limited case, it demonstrated the feasibility of considering a scalable approach to real life digital twin data management and integration for traffic control.

4.4.1 OEMs

The Car Industry has embraced a number of Digital Twin elements to date. This has primarily been focused on introducing design and manufacturing efficiencies rather than on on-road deployment but that is changing.

Ford utilises a digital twin model as part of their energy management approaches for their manufacturing campus. Ford (Ford, n.d.) have also created Digital Twin guidelines to ensure optimised approaches across the manufacturing lifecycle.

Porsche have utilised Digital Twin (Medium.com, 2021) approaches and technologies to address areas of design and identify optimum replacement and service strategies, which in turn creates a dynamic link to their client base.

Volvo's Digital Twin technology (Volvo, n.d.) in production allowed the creation of a digital thread, across design to manufacturing processes, which supported them in achieving quality control management and risk assessment in their quality control activities.

Nissan has identified a number of improvements brought about by the use of Digital Twin (Nissan, 2021). This has ranged from:

a. Reducing bottle necks in production to minimise downtime on production runs
b. Predictive digital twin assessing the business case around plant expansion linked to a deep data dive into existing processes
c. Minimise purchasing lead time without impacting delivery schedules

Ongoing OEM Developments

Testing of AVs is a vital step in ensuring their safety for deployment in public space. The Testing can be arduous as all test cases have to be considered, both in normal and abnormal operation, and a mixture of simulated and real-life testing being used to date to gather data on performance of sensors and the driving function.

Utilisation of Digital Twin technologies can help reduce the time required for testing as simulation based on digital equivalents of the sensors, linked to a digital road environment, could dramatically increase the time for tests to be undertaken. It will also support a common platform for the exchange of data between NRA and OEM as digital twin equivalents for the vehicle as well as the road can allow for feedback loops to be created to help both parties, in terms of both design and operation etc.

4.4.2 Open Data

Any digital twin will depend on a series of underlying technologies and standards. (Jacoby M., 2020) provide an overview of the classification of different Internet of Things (IoT) and Digital Twin standards. This overview includes descriptions of:

- the Digital Twin Definition Language (DTDL) developed by Microsoft and used in different Azure products including Azure Digital Twins;
- Next Generation Services Interfaces – Linked Data API – which is an IoT standard around entities to represent physical or conceptual objects;
- Open Data Protocol (OData) allows definition of standardised, data model-agnostic RESTful APIs. This was initially developed by Microsoft in 2007 and was standardised in 2014 by the Organization for the Advancement of Structured Information. It concerns describing and accessing of resources or services.
- SensorThings API. This was developed by the OGC SensorThings Standards Working Group as a framework for interconnecting IoT devices, data, and applications over the web.
- Web of Things – the goal of the W3C Web of Things (WoT) Working Group is to counter the fragmentation of the IoT by providing building blocks to complete and enhance existing standards. The WoT Thing Description (WoT TD, or TD) defines a meta-model to describe existing APIs including protocols, payload format, and security in a machine-readable way.

As noted by Jacobs and Usländer, (Jacoby M., 2020) resource discovery is a major topic on the agenda of most standards organisations. None of the existing standards in this area allow direct communication between the consumer and the resource, they are all based on a central repository of resources. Also, there is no consensus about which query language to use. The choice of query language must not be too complex yet needs to include geospatial and temporal parameters. Thus, digital twin standards are still evolving.

Specifically with regard to CAVs, WP 2.3 Data, Data Models and Exchange of Data describes many of the underlying technologies and standards for sensor and camera data, traffic safety data, real-time traffic data, and HD Map data. Any and all of these are likely components of Digital Twins but, as described in WP 2.3, each of these components has many challenges. For traffic safety and real-time traffic data, the main challenges are agreeing specific definitions for dangerous driving situations in such a way as a machine can understand them, training ADS to recognise these situations, understanding contextual information, and storage and transmission of such data in near-real-time. WP 2.3 also highlights issues around OEM's willingness and motivation to share such data.

With regards to HD mapping, although there are ongoing standardisation efforts (e.g. ASAM OpenDRIVE for description of static objects of road networks and ASAM OpenSCENARIO for dynamic vehicle manoeuvres), maps are still essentially proprietary datasets, there is lack of interoperability between map suppliers, and there seems to be little incentive for mapping companies to share their data. It is noted, though, that the Moscow Automobile and Road Construction Institute (MADI) has issued draft standards on architecture and data precision of digital road maps used for administering autonomous traffic. These standards will be applied to mapping of 8,000km (4,970 miles) of Russian federal motorways in 2022, with the intention to expand to mapping of regional roads in 2023 (ICWE, May 2021).

One other key type of information that is likely to be considered for inclusion in a digital twin includes traffic management. The ongoing TM4CAD project (TM4CAD, 2022) argues that an ADS needs to continuously monitor the condition / status of ODD attributes. It is based on the ODD attributes defined in BSI PAS 1883. Some of these ODD attributes are exclusively within the sphere of influence of NRAs. Absence of quality ODD attribute information can be critical to an ADS, potentially causing an unexpected ODD exit, requiring human intervention. It argues that NRAs and other commercial entities would be required to invest in infrastructure to enable the gathering and sharing of the information on various ODD attributes, to implement a Distributed ODD Awareness (DOA) framework.

Thus, in all aspects of potential areas of support for CAVs, there is significant ongoing research, development and piloting. However, there is no overarching vision of the type and level of services that NRAs should provide to support CAVs, nor general agreement on the technologies that should be used, or who should be responsible for implementing those technologies. In short, there is no framework for digital twins for NRAs to support CAVs.

The challenges in relation to digital twins are similar to those related to C-ITS as outlined in WP2.2: Does a digital twin need to provide benefits to the NRA? How will those benefits be quantified? Is there agreement between NRAs and OEMs as to what services should be provided and by who? What are the mechanisms for discussion and agreement?

4.4.3 Standards

As the concept digital twin lacks a common definition of what a digital twin is, it further complicates to find a standard for it. There are other examples of concepts that share similarities with digital twins and for example, internet-of-things shares overlapping in describing, discovering, and accessing resources (Jacoby M., 2020).

Jacoby and Usländer further presents six standards for digital twins or internet-of-things (Jacoby M., 2020) which are Asset Administration Shell; Digital Twin Definition Language; Next Generation Service Interfaces-Linked Data API; Open Data Protocol; SensorThings API; and Web of Things. These six standards were compared, and a consensus between these standards was found regarding the elements the resources consisted of, how they were serialized and which network protocols they used. It was also found that controversial topics were how resources should be discovered (which query language to use) and if geo-spatial, temporal, and historical data should be supported.

The ISO 23247 series defines a framework to support the creation of digital twins of observable manufacturing elements including personnel, equipment, materials, manufacturing processes, facilities, environment, products, and supporting documents. (OBP, 2021)

Under the area "ISO/TC 184/SC 4, Industrial data" a standard was published in four parts in October 2021, the ISO 23247-1:2021[3] (Overview and general principles), 23247-2:2021[4] (Reference architecture), 23247-3:2021[5] (Digital representation of manufacturing elements), and 23247-4:2021[6] (Information exchange). This standard consists of a set of protocols for making and maintaining digital twins in manufacturing. The standard is based on four layers. The first layer describes the items that needs to be modelled. The second layer presents the communication between the items. It collects information from the items and if needed sends back corrections to control when needed. The third layer is the digital twin that is a digital representation of the physical items that are modelled. The last layer handles the user entities. These are the applications that interacts with the physical system to make the manufacturing more efficient.

A suite of associated standards/development work related to Digital Twin is provided below, showcasing the depth and range of elements included within a Digital Twin Umbrella.

Table 1 Standards and Development Documents

Reference	Name	Year
PNST 428	Smart manufacturing. Digital manufacturing twins. Visualization elements of digital manufacturing twins	2021
GOST R 57700.37	Computer models and simulation. Digital twins of products. General provisions	2021
DIN EN 17549-2	Building information modelling - Information structure based on EN ISO 16739-1 to exchange data templates and data sheets for construction objects - Part 2: Configurable construction objects and requirements; English version prEN 17549-2:2021	2020
BS ISO 23247-1:2021	Automation systems and integration. Digital twin framework for manufacturing. Overview and general principles	2021
BS ISO 23247-2:2021	Automation systems and integration Digital twin framework for manufacturing. Reference architecture	2021
BS ISO 23247-3:2021	Automation systems and integration Digital twin framework for manufacturing, Digital representation of manufacturing elements	2021
BS EN ISO 20/30374334 DC	Automation systems and integration. Digital Twin framework for manufacturing. Part 1-4 Overview and general principles	2021
BS EN ISO 23247-2.	Automation systems and integration. Digital Twin framework for manufacturing. Part 2. Reference architecture	2020

[3] https://www.iso.org/standard/75066.html

[4] https://www.iso.org/standard/78743.html

[5] https://www.iso.org/standard/78744.html

[6] https://www.iso.org/standard/78745.html

BS ISO/IEC 30173	Digital Twin. Concepts and terminology	2020
DSF M344322	Building information modelling — Information structure based on EN ISO 16739 1 to exchange data templates and data sheets for construction objects — Part I: Data templates and configured construction objects	2020
DS/ISO 23247-1	Automation systems and integration — Digital twin framework for manufacturing — Part I to Part 4Overview and general principles	2021
IEC JTC1-SC41/260/CD, CEI JTC1-SC41/260/CD, ISO/IEC TR 30172	Digital Twin - Use cases	2021

As such, the standards and guidelines provide a direction for consideration within the Transport network. From establishing a standards-based approach to the contextualisation of various parameters in the digital domain to migrating those to a proactive intervention strategies, the standards and guidelines can help the transport sector in establishing best practice for AVs and Digital twins

Service Level Agreements

For an NRA, a key question relates to the risk exposure for them should data provided from their Digital Twin environment is not at that point in time fit for purpose and as such, leads to a reduction in performance or safety of the Autonomous Vehicle.

To manage the risk, consideration must be given to what if any Service Level Agreement (SLA) would be needed between various actors to ensure a fit for purpose road network.

As SLAs are contract documents, it is very likely that they are not publicly available and could contain highly technical details. In the literature, there are only very few examples of SLAs applied, mainly, to communication networks (Bouillet, 2002). In the specific case of DTs in the transport sector, SLAs would be needed for management purposes and monitor the efficiency of the service being provided. This is done by, for example, establishing events, alarms, and violations of the SLOs. For that, KPIs are established to be monitored in real time. In the case of transport applications, commonly KPIs are end-to-end latency, ration of packet transmission lost, and x-y coordinates (Saifutdinov, 2020). KPIs will depend on the services being provided according to the contract and can include service availability, defect rates, technical quality, security, and business result. Many items can be monitored as part of an SLA, but it could be wise to keep the scheme simple and focus on the most important items to avoid misinterpretations and excessive cost for monitoring as well as for analyzing the data (Overby, 2017). Violations of the SLA requirements can lead to liability issues. See (Bouillet, 2002) for an example where SLAs are used to penalize the service being provided in the telecom sector.

In DTs, end-to-end latency is one of the most important SLA parameters. It requires user data packets to be successfully delivered within certain time constraints to satisfy the end user's requirements. Latency could be impacted by the network capability and network configurations, e.g., configuration of service priority, radio access network (RAN) capacity, network load, number of re-transmissions, wireless channel environment and the processing time of the network functions, etc. These factors may be the root cause of unexpected network performance. Packet transmission latency may dynamically change if one or multiple of these factors change. The latency requirement should be ensured even if some of the network conditions may degrade. Regarding latency analysis for network services, the performance data and fault data are required to be collected, reported and analyzed in near real time (Sun, 2021). See Figure 2 for an outline of a DT based on SLA.

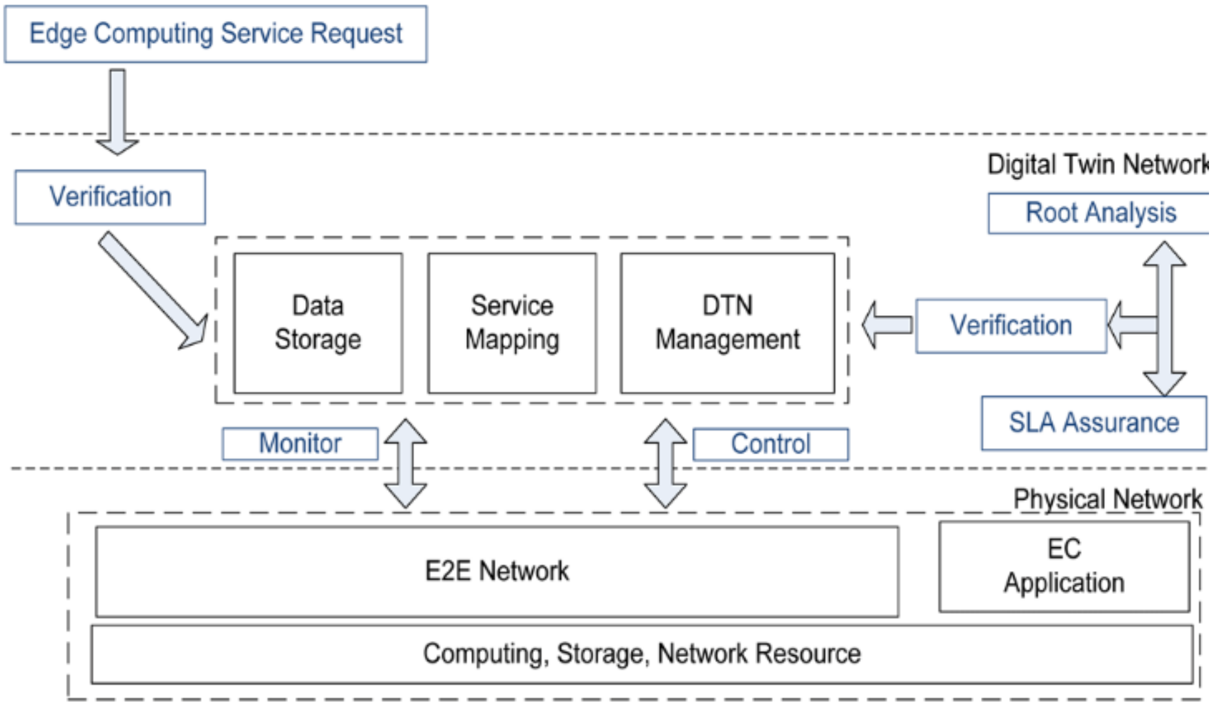


Figure 9 DT network and SLA solution (Sun, 2021)

It is important that SLAs should include agreed upon remedies or penalties, also called service credits, which may need to be enforced in case of non-performance. One method to use when drafting such provision is that the parties agree to put a certain percentage of monthly fees at risk from which service credits are drawn in case of failure to achieve the SLA requirements. The purpose of this approach is to create an incentive for provider performance without being excessively punitive. Others make use of SLA KPIs as an opening for productive discussions on issues of performance, priorities, and the future direction of the contractual relationship. A third method is to agree on a provision allowing the possibility and right to "earn back" paid service credits. This type of arrangement allows providers to earn back the service credits they have given up for previous SLA defaults. Such earn back will apply when the provider has performed at or above the standards service level for a certain agreed-upon amount of time (Overby, 2017).

In summary, SLAs are very important liability documents, and they are considered a necessity between provisioning services, such as data transmission services and end-costumers of highly technical applications, e.g., tele-driving, platooning, connected vehicles. Therefore, SLAs are being used as means to achieve a certain service assurance performance through the agreed upon LoS, which are monitored by relevant KPIs. In such technical applications, DTs can be first used to check the network feasibility (i.e., if the customer requirements can be fulfilled by the network), to make sure the required service agreed in the SLA can be provided before its deployment. Afterwards, if SLA performance is not fulfilled in the current network, the DT can generate suggestions based on the input data from physical network and validated in the DT. The DT can thus simulate all operations in the real physical network and has the capability to analyze and predict the network's future conditions and performance, based for example on artificial intelligence (AI), which can provide for the capability to generate network configuration or modification suggestions once the existing network SLA performance cannot meet customer's requirements.

Legal issues around liability in SLAs in DTs.

Risks emerging from the application of DTs may depend on the nature of the DT which need to be clearly specify in the SLA. Key points (Clemenston, 2021); (Sutton, 2021); (Abou Naja, 2021) to consider are:

- Responsibility for data quality: how to ensure the data is accurate and who is responsible for data accuracy.
- Liability: What happens when the DT does not work properly? What loss can be recovered when a DT is used for key investment decisions, but the prediction was inaccurate?
- Integration: Who is responsible for any integration risk? Legacy infrastructure can be an obstacle to integrating new technology.
- Connectivity and availability: What legal consequences, if any, will be for errors? For example, in power, software, deployments, and connectivity.
- Assurance, governance, and trust: What procedures will be in place to provide assurance that the DT performs as intended? Establishing trust is key to driving uptake.
- Standardisation: The current lack of a standardised approach to modelling for digital twins poses challenges for interoperability between digital twins. What standards will be employed in a digital twin to maximise interconnectivity?
- Ongoing maintenance: Software updates, real-life changes to the physical asset, changes/improvements to the digital twin, etc. means that inevitable ongoing management and maintenance must be factored into the planning, pricing, and contracting for digital twins. As is usually the case with their physical counterparts, the cost of such maintenance and management will likely represent the largest proportion of the total lifecycle cost of the digital twin.

The issue of liability is possibly the most complex legal impact of digital twins. In order to hold someone liable for loss of any kind it is necessary to prove that the liable party did not fulfill its duty leading to the loss or injury. This could be extremely difficult since digital twins are a network of connected systems. Changes in one system could affect the entire model and with multiple data sources, it may be difficult to identify and trace errors. Thus, to this effect attributing liability could be difficult. Also, the errors causing damage or injury could have originated outside the ecosystem of the digital twin, such as from faulty sensors of the physical twin. It is important to acknowledge that real world serious consequences can be a result of a mismanaged or unregulated digital twin, for instance when it is used to monitor or control a complex system, such as a critical transport infrastructure. Therefore, contracts have to govern the specific characteristics of the digital twin solution and cover the most important risks and legal implications but at the same time be flexible to adapt to the evolutions of technology and the real world.

4.5 NRA and the Digital Twin

4.5.1 End to End Capability

It is important that any introduction of Digital Twin capability is driven from the benefits perspective rather than the technical end. Benefits-driven, not technology-driven. In the long term, a full end to end Digital Twin Capability should integrate across both operations and infrastructure maintenance to provide an integrated capability across asset disciplines, and across “road and vehicle”.

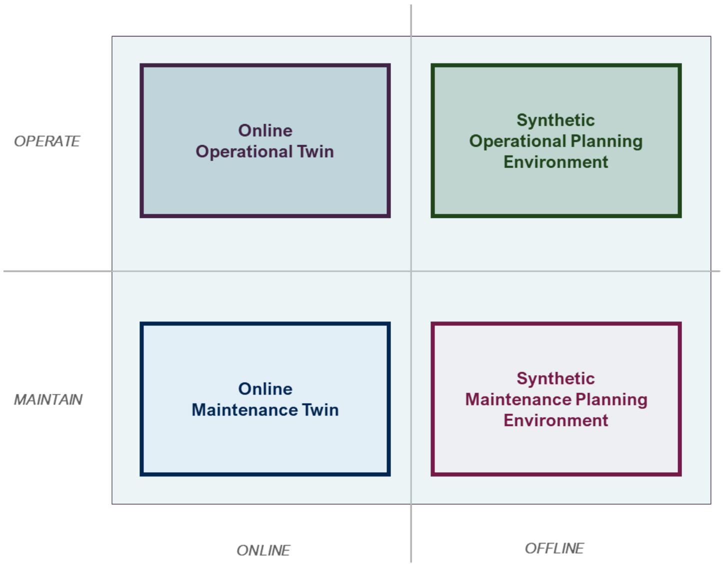


Figure 10 Operation & Maintenance Digital Twin focus areas (Arup)

4.5.2 NRA Operations and Digital Twins

At the apex of the Digital Twin/CAV/Physical infrastructure touch point, it is important to consider how a Twin can provide value across both the Operations and Maintenance roles of the Road authority.

From an Operations Perspective, data sets from real time sources and static elements will need to be harvested, managed and processed in real time. With advances in modelling and utilisation of data lakes and edge-based processing, the data analytics elements will need to be considered both at the front end integration with CAV but also the back end IT systems required by the NRA and integration with legacy approaches and equipment.

From a CAV perspective, there will be significant amounts of data that will require processing. There will be data that will provide useful information but also data that links to baseline operations and as such may be of no immediate use to the Operation of the road network.

Fusion with the synthetic layer, the modelling and virtual presentation of the network will also need to be considered. Will a digital twin be needed for all the network or will key corridors or elements therein be focused on. From a safety perspective, discussions will be needed to understand if the use of a Digital Twin can improve the performance of the road network through real time analytics and interventions taking place across the CAV ecosystem. The NRA will not make an intervention within the vehicle itself, but it can provide a link to data sets both historic and in real time, that can influence driving patterns.

What will need to be layered on top of that is the need to provide suitable Governance and audit functions to ensure transparency of decision making as well as a route back to reviews as part of the daily operation life cycle. As Artificial Intelligence link to Internet of Thing devices look to shape a significant portion of the Digital Twin, it will be important that rules-based interventions and processing are setup in advance of any operation deployment.

Asset Management systems are in use across all road authorities, varying in terms of complexity but all offer insight into the assets deployed, whether identifying installation and lifecycle elements or utilising real data feeds to provide on-going assessment of performance. A Digital Twin can support the maintenance regime through seamless data integration across all the data sets and the creation of a end to end cyber representation of the asset. This will allow for proactive intervention strategies to be undertaken. The integration with the CAV data sets can help provide an extra layer of sophistication around the performance of the assets, such as road degradation etc. This can be undertaken in real time but also form part of a synthetic modelling approach to Digital Twin management of the whole ecosystem.

This does not come without challenges however. The ecosystem itself will need to be defined in detail. The performance characteristics will now be more nuanced and detailed than ever before, requiring necessary technical skills to assess the information being provided. Creating the Operations and Maintenance approach for Digital twins, linking to CAV deployment, will be a significant step for any NRA. It will require engagement across multiple stakeholders, from the IT team, the Network Managers, the Contracts and Procurement etc.

A CAV Ready Framework can support this integration, in terms of identifying the scale of Twin required, the impacts and responsibilities therein as well as the ongoing operational requirements that will be expected.

Maturity of Offering

The diagram below is a sample maturity spectrum framework for digital twins (Evans, 2021). As a digital twin develops, each element increases in complexity, connectivity, and value. These elements are not necessarily linear or sequential, so a digital twin might exhibit features of higher-order elements before (or even without) lower-order ones. Each succeeding level may be significantly more complex or sophisticated than the lower-order level.

Many of the current implementations of twins in the infrastructure sector can be considered to be at Level 2 in the above (Evans, 2021) maturity framework, although other sectors such as smart cities and manufacturing are more advanced. Digital Twins are common in Smart Cities, where they integrate city operations and projects.

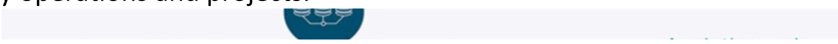
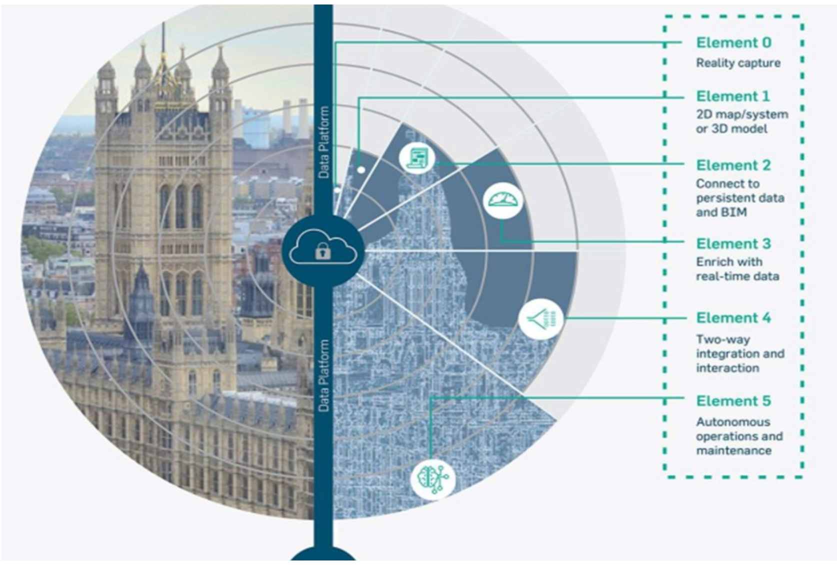


Figure 11 Maturity Levels of Digital Twins (Evans, 2021).



Legal Implications

A 2020 report by (FenwickElliot, 2020) reviewed the inherent complexity of a Digital Twin that addresses all the cyber elements of the physical world. It noted that the complexity therein could potentially create challenges on key issues such as data ownership, causation and liability. T states that these elements as part of a contractual framework will potentially raise contentious issues from a legal standpoint.

This is reflected in the SLA consideration for a NRA, and will also bring in the question the desire by the NRAs to be part of a supply chain that links public and private enterprises together, bodies that have very different business models and success criteria.

(Gilbert, 2021), whilst acknowledging the focus on Digital Twins as part of an overall approach to Digital Transformation, references a range of challenges that will exist, both at a technical and legislative perspective. Questions around data use rights and privacy, as well as the potential exposure from a cyber security perspective when aggregating data sets across multiple domains still need to be ironed out. It isn't to say that these challenges cannot be overcome but it is important from an NRA perspective that the legal implications of the service model they wish to adopt is considered.

(Abou Naja, 2021) reference the use of a Framework to help create a standard approach to a number of legal implications related to data sharing, ownership and governance. From an EU perspective, such a framework would have to be driven at both an EU level but also at a Federated level to ensure seamless adoption and integration with local policies and legislation

For a Digital Twin to be successful across the CAV ecosystem, it will rely on data transparency and data sharing. Again, the concept of a fully transparent data driven ecosystem that links commercial partners, sometimes competing against each other in some areas, with other enterprises will raise challenges. Confidentiality considerations and management of non-disclosure agreements would also have to be considered.

Risks and Mitigations

With a non-standardised approach to what Digital Twins are, it is difficult for the NRA to make decisions about the type, use and business value associated with its creation. There is a risk with all new ventures, particularly in the digital domain, where new technologies and approaches can change faster than an organisations'.

NRAs have limited budget and ongoing day to day operation requirements that will take resource and capital requirements. However, the medium to long term expectation that a digital transport system will be enabled a outlined in the EU's Mobility strategy as well as the work of CCAM and C-Roads, highlights the need for NRAs to begin to consider how best to engage with Digital Twins and develop meaningful case studies before widespread deployment.

4.5.3 CAV Ready Framework: Digital Twin Expectations on Service Provision

An important question that must be addressed is the expectation between the Private and Public sector in the provision of data and the associated dependencies and agreements that must be put in place. This is across both the Operation and Maintenance regimes but also from a legal and service level provision.

WP 1.1 also highlights uncertainty about future uptake of CAVs and future travel demand. This impacts budgeting and planning, and in general causes uncertainty about whether NRAs should support CAD, and the type of support that they should consider. Some NRAs highlighted that there is a need for a collective international NRA approach to say, "These are the levels of service we can provide, and this is how much it is going to cost, and this is how long it will take us to implement on our networks". However, to date, there has been insufficient engagement between NRAs, OEMs, and telecoms providers on the current and future capabilities of vehicle systems. This uncertainty applies across all aspects of potential NRA support to CAVs, and therefore applies too to defining and implementing digital twins.

WP 2.4 and 2.7 look to provide a solid foundation on the intricacies and challenges associated with Digital Twins in order to shape what a CAV Ready Framework (CRF) would need to consider.

The CRF will need to be multi-faceted in order to address and will need to provide guidance for NRAs to plan their infrastructure deployment, consider the organizational structure in place, and create a digital back bone to facilitate the deployment of CAVs. This digital back bone has a number of facets, from mapping, data asset inventory and Digital Twin creation all linked to develop a Service level approach for NRAs to engage with the CAV ecosystem.

This Service level may be a mixture of Control, Control and Inform, Monitor, Control and Inform, depending on the elements achievable within each NRA and the use of the CRF.

From a Digital Twin perspective and the provision of levels of Service, the NRA will, through work to be developed in WP 3 and 4 to crystallize a CRF that will address a number of key elements raised in this report, including but not limited to:

1. What is the 'right' approach to Digital Twin implementation?
2. Is my organisation ready for the migration to a Digital Transportation environment?

3. Are the risks and mitigations known in terms of the business process and skills required?
4. Is there a particular focus area for use of Digital Twin, such as in the Operations side of traffic management or a wider customer engagement piece?
5. Do I have enough data to create a Digital Twin, and do I know what gaps exist in my Data ecosystem?
6. Are the vehicles ready to utilise the digital twin or is it a nice to have?
7. Is it clear the data sets required by the OEMs to drive integration?
8. The costs and benefits of investment, linking improved safety, performance, resilience of the network to investment in technologies and procedures that are relatively early in their development lifecycle
9. What is the legal exposure to my organisation?

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5 Impact of Emerging Technologies

5.1 Introduction and overview of the regulatory landscape

This section reviews the legal and regulatory aspects that affect connected autonomous driving (CAD) and the capability of road infrastructure to support it. It includes a description of regulatory challenges, limitations and gaps. It also includes a review of existing legal and regulatory frameworks in the areas relating to CAD as well as some relevant examples of ongoing regulatory development. The legal and regulatory landscape is important to highlight for a number of reasons. To start with, policy and legislation are considered as one of four pillars and key enablers of connected autonomous vehicles (CAV) readiness, along with technology and innovation, infrastructure, and consumer acceptance (KPMG, 2020). In that respect it is vital that the frameworks are aligned with current technology. Furthermore, the allocation of responsibility and liability is important to enable and ensure safe and effective deployment of CAVs. As such, regulatory frameworks are also crucial for gaining legal certainty, a wider acceptance in society of CAVs and CAD, but also for innovation support and stability for investments in technology and infrastructure.

CAD implies a shift in performance of the dynamic driving task from human-driven vehicles to CAVs. This shift from the human-driven to the automated system gives rise to many legal and regulatory questions. Existing frameworks and laws require review to support the deployment of CAVs on public roads. Such reviews are currently being performed on international, regional, and national levels. The introduction and deployment of CAVs necessitate new and adapted laws and regulations re-defining the roles of human drivers as well as autonomous systems used in vehicles. Also, in order to support stakeholders such as NRAs, OEMs, and service providers, the regulatory timing is vital and can affect the challenges and possibilities of the introduction of CAVs. It is therefore of importance that such stakeholders proactively engage with various consultations and policy development initiatives to ensure a regulatory framework that can address their interests and optimally balance risks against the benefits of CAVs (Baker et al. 2020; Ilková & Ilka, 2017).

It should be noted that the terminology addressing the topic of connected and autonomous vehicles and the necessary infrastructure for its deployment could be somewhat confusing. In this review the concepts of CAV (Connected and Autonomous Vehicles), CAD (Connected and Automated Driving) and ADS (Automated Driving System) will be used. CAV is used with reference to the vehicle, CAD with reference to the vehicle *and* the infrastructure, and ADS is used with reference to the system in the vehicle. It should be noted, though, that other terminology is used in different regulatory instruments, research, discussions and articles. One example is self-driving vehicles which is used in UK legislation.

5.1.1 Categories of rules that are fundamental to support CAV deployment on public roads

From a European perspective, rules relating to and aiming at supporting deployment of CAD and CAV on public roads are reviewed and developed at different levels: international level, EU-level and national level. Rules could also be categorized in levels of international frameworks, laws, regulations, and standards. In this respect, rules also include engineering criteria developed by the technology community, see Table 9.

Table 9: Categories of rules and description of position in legal landscape (adopted from Abubakar & Godsell, 2019)

Type of rules	Description
International frameworks	A structure used internationally to provide a common and global foundation Applies to the countries that have signed up to the framework Example: Vienna Convention on Road Traffic 1968

Laws	System of rules which is applicable in a specific nation Agreed by Parliament Example: Road Traffic Act 1968
Regulations	Mandatory requirements developed by policymakers through delegation Derived from laws, and in turn inform standards and codes of practice Example: Road Vehicles (Construction and Use) Regulations 1986
Standards	Engineering criteria developed by the technology community Specify how a product should be designed or how it should perform Example: ISO 26262

5.1.2 Branches of law that affect CAVs

The regulatory landscape related to CAVs could be described as divided into three separate branches of law: administrative law, civil law, and criminal law respectively, see Table 10 for examples of legal areas covered.

Table 10: Branches of law that affect CAVs

Administrative law	Civil liability	Criminal law
Certification, licensing, technical controls, road traffic rules	Liability for damage and injury, product liability	Criminal responsibility, protection against cybercrime and hackers

Administrative law includes road traffic law and covers aspects such as licensing and certification. Legal challenges of CAD in the area of administrative law include questions such as: Does CAD require a special driving license, are age requirements necessary for CAV users, where should CAD be allowed, should there be dedicated lanes for CAD, should all traffic rules be followed by CAVs and should there be any external indicator on the vehicle when in autonomous mode? (Ilková & Ilka, 2017).

Civil law coverage related to CAVs and CAD consists of both civil liability and product liability challenges. Civil liability concerns liability for damage and/or injury and is closely connected with insurance aspects whereas product liability implies such liability caused by a defective product. A significant question in this respect is if liability for damage and/or injury resulting from CAD should be placed on a human being, such as the driver or user of the CAV, or on a legal entity taking responsibility for the autonomous system, such as the developer, manufacturer, operator, or other entity (Baker et al., 2020).

In the criminal law area, the legal challenges include both criminal responsibility as well as the issue of protection against hackers and cybercrime. A question of concern relating to the CAD context is what crimes may be committed. Other important questions are: who should be held responsible in a situation when a crime is committed, Is it the owner, the manufacturer, the developer or the user of the vehicle or any other person or entity. Thus, corporate criminal responsibility and crimes against life and health needs consideration and review to fit in the CAD context. The protection of vehicle users against hacker attacks has a criminal aspect, to protect against cybercrime, but also an aspect of developing appropriate security systems regulated by standards and technical norms (Ilková & Ilka, 2017; Nynke, 2019; Glancy et al., 2016; Goldstein, 2017).[7]

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[7] For further reading see: Cowger, A, R., Jr. (2018). Liability considerations when Autonomous Vehicles choose the accident victim. The Journal of High Technology Law, Volume 19, no. 1; Jensen, J. B. Self-Driving but Not Self-Regulating: The Development of a Legal Framework to Promote the Safety of Autonomous Vehicles. (2018). Washburn Law Journal, Vol. 57, pp. 579-611; Liechtung, J. *THE RACE IS ON! REGULATING SELF-DRIVING VEHICLES BEFORE THEY HIT THE STREETS,* 12 Brook. J. Corp. Fin. & Com. L. (2018). Available at: https://brooklynworks.brooklaw.edu/bjcfcl/vol12/iss2/6

5.2 UNECE international framework initiatives

At an international level, the United Nations Economic Commission for Europe (UNECE)[8] develop regulations on vehicles and road transport through the Inland Transport Committee (ITC)[9] which is the highest policy-making body in the field of transport. There are two working parties, sub-groups to ITC, which perform work and have formal decision-making responsibilities related to road traffic and vehicles: The Global Forum for Road Traffic Safety (WP.1)[10] and The World Forum for Harmonization of Vehicle Regulations (WP.29)[11]. These working parties also collaborate about automated driving and have constituted subgroups (Working Party on Automated/Autonomous and Connected Vehicles (GRVA) and Informal Group of Experts on Automated Driving (IGEAD)) to assist in the area of CAD. The structure of these working groups is depicted in Figure 12.

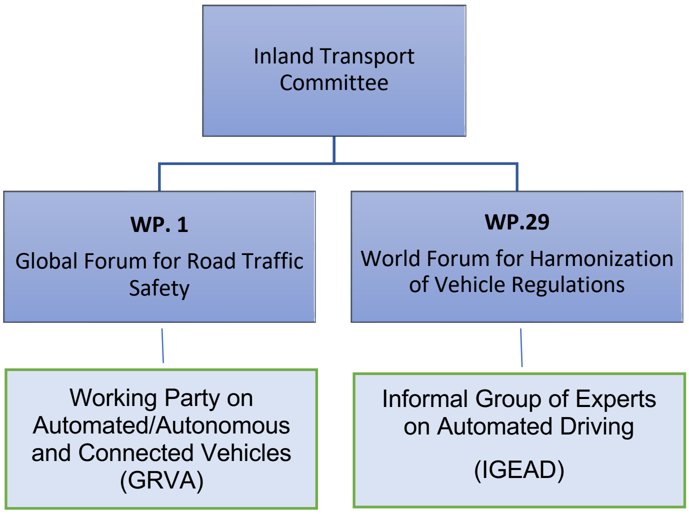

Figure 12: Working groups at UNECE engaged in regulatory work related to CAVs

5.2.1 UNECE Conventions

The Geneva Convention on road traffic of 1949[12] and the Vienna Convention on road traffic 1968[13] as well as the Conventions on Road Signs and Signals (1949 and 1968)[14] are of great relevance in a global perspective to ensure uniform traffic rules across borders, to improve road safety and facilitate international flow of traffic. The contracting parties are obliged to bring their national traffic laws in conformity with these conventions. The conventions are also the fundamental traffic regulation relevant for the European Union (EU). Since the EU does not have legislation on traffic rules the European Commission has recommended its member states to apply and adhere to the international regulation (EC, 2018; Vellinga, 2019).

The Geneva and Vienna conventions are built around the notion of driver, including the requirements that every moving vehicle or combination of vehicles shall have a driver (art.8 paragraph 1) and that every driver, at all times, shall be able to control the vehicle (art. 5 paragraph 5). These requirements have been challenged by the introduction of CAVs and CAD and considered a legal barrier (Vellinga, 2019). The Vienna Convention still requires the presence of a **human** driver who can take control of the vehicle at any time. An adopted amendment, expected to enter into force during 2022, will

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[8] https://unece.org/.
[9] https://unece.org/transport/inland-transport-committee.
[10] https://unece.org/transport/road-traffic-safety.
[11] https://unece.org/transport/vehicle-regulations/world-forum-harmonization-vehicle-regulations-wp29.
[12] https://treaties.un.org/Pages/ViewDetailsV.aspx?src=TREATY&mtdsg_no=XI-B-1&chapter=11&Temp=mtdsg5&clang=_en.
[13] https://treaties.un.org/Pages/ViewDetailsIII.aspx?chapter=11&mtdsg_no=XI-B-19&src=TREATY.
[14] https://unece.org/road-traffic-and-road-signs-and-signals-agreements-and-conventions.

however facilitate the use of automated driving systems (ADS). A new Article 34 bis of the convention sets out that the driver requirement is deemed to be satisfied provided it is using an automated driving system that complies with domestic and international technical regulations, and domestic legislation governing operation.[15] Once in force, the parties to the Vienna Convention may incorporate the amendment into their domestic legal road traffic framework. The amendment is the first binding international law relating to CAVs. It complements the non-binding UN Resolution on the Deployment of Highly and Fully Automated Vehicles in Road Traffic[16] (Department for Transport, 2021).

5.2.2 UNECE Working Parties 1 and 29 and their collaboration and common approaches on automated vehicles

The focus of The Global Forum for Road Traffic Safety (WP.1) is on improving road safety through harmonization of traffic rules and it is responsible for overseeing the application of the Conventions on Road Traffic (1949 and 1968) as well as the Conventions on Road Signs and Signals (1949 and 1968). Due to a growing interest of concerns related to automated driving, the sub-group IGEAD[17] was constituted to assist WP.1 in matters in this area and to assess whether existing conventions are compatible with autonomous vehicles. In September 2018 WP.1 adopted the *Resolution on the deployment of highly and fully automated vehicles in road traffic*[18], based on the work performed by IGEAD and on the priority to provide guidance and support safe deployment of CAVs in road traffic. AGEAD continues to perform work related to automated driving to determine how to best apply the 1949 and 1968 Conventions in this respect. Areas of work involve e.g., remote driving[19] as well as activities other than driving (secondary activities) for drivers of highly automated vehicles[20]. This work may result in additional resolutions to be adopted by WP.1.

The World Forum for Harmonization of Vehicle Regulations (WP.29), hosted by UNECE, is responsible for the regulatory frameworks regarding the safety and environmental performance of vehicles, their subsystems, and parts. It oversees the Agreements (1958 and 1998) which establish global motor vehicle regulations and develops new global technical regulations. Since there is an automatic adoption process of UNECE decisions on new vehicle regulations for the EU, once approved, new harmonized technical regulations automatically go into the Whole Vehicle Type Approval process. The regulatory issues related to CAVs are specifically addressed by the subgroup GRVA.

An informal UNECE document sets out and explains the collaboration and common approaches between WP.1 and WP 29.[21] The purpose and scope of the ongoing collaboration is to facilitate collaboration relating to SAE Level 3 to Level 5 automated vehicles and their safe deployment in the traffic environment. Key activities are focusing on three priority areas: the development of a common glossary of terminology for CAVs, research on human machine interface (HMI) and Human Factors to define activities a driver can engage without compromising road safety, and hosting a joint annual meeting to foster discussion and share knowledge (ECE WP.29, 2020).

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[15] (ECE/TRANS/WP.1/173/Add.1).

[16] https://unece.org/transport/publications/resolution-deployment-highly-and-fully-automated-vehicles-road-traffic.

[17] Established in 2015. https://unece.org/sites/default/files/2021-03/ECE-TRANS-WP.1-2021-Informal-No.9e.pdf.

[18] https://unece.org/DAM/trans/main/wp1/wp1doc/WP1_Resolution_Brochure_EN_web.pdf.

[19] There is a Proposed Draft Resolution on Remote Driving (ECE/TRANS/WP.1/2019/2) and an Informal document, replacing the proposed draft, on situations when a driver operates a vehicle from the outside of the vehicle (ECE-TRANS-WP1-2021-Informal document 1).

[20] There is a draft resolution on the concept of activities other than driving (ECE-TRANS-WP1-2020-Informal-No.7) as well as an informal document with comments and suggestions for improvement of the draft (ECE-TRANS-WP1-2021-Informal-No.5).

[21] Collaboration and common approaches between WP.1-WP29 on automated vehicles, Informal document No. 3/Rev.1, WP.29-179-05 (WP.1), https://unece.org/179th-session.

5.2.3 Regulatory initiatives of WP.1

WP.1 has developed and adopted several regulatory instruments related to CAVs. In 2018, through the work of IGEAD, WP.1 adopted the Resolution on the deployment of highly and fully automated vehicles in road traffic, adapting the guiding principles of the 1949 and 1968 Conventions on Road Traffic to the CAD environment. The resolution includes definitions of highly and fully automated vehicles in order to allow operation without the need for human intervention. In addition, it provides recommendations for automated driving systems in highly and fully automated vehicles as well as recommendations for users of such systems. The resolution also calls on governments to incorporate the recommendations into their domestic legal and policy frameworks for road traffic.

In 2019, a draft resolution of remote driving was published for discussion purposes within WP.1 to facilitate progress in this area. The draft resolution provided definitions and recommendations for remote driving systems and remote drivers respectively. In 2021, the draft resolution was replaced with an "Informal paper on remote driving – Situations when a driver operates a vehicle from the outside of the vehicle".[22] The paper considers the situation where full dynamic control of the vehicle is performed by a remote driver who is in control of a single vehicle at any time. In addition to providing requirements for remote driving systems and remote drivers, it provides requirements for service providers, developers, manufacturers, and passengers in a vehicle driven remotely. For the purpose of future work, the paper also acknowledges, in an annex, scenarios where a remote operator may provide support, monitoring or assistance to more than one vehicle at a time.

In 2021, WP.1 developed and proposed a resolution on "activities other than driving" in the context of automated driving. It provides safety considerations for such other activities undertaken by the driver when the automated driving system is exercising dynamic control. The draft resolution provides recommendations regarding automated driving systems issuing transition demands and for manufacturers of such systems. It also provides recommendations for drivers and contracting parties. According to the resolution drivers should, for example, be required to respond to a takeover request by exercising dynamic control in an appropriate and timely manner when required to do so by national regulations, traffic rules or guidance; refrain from activity other than driving if that activity may impede this response or is unsafe; and refrain from interfering with the automated driving system in a way that could compromise safety.

5.2.4 Regulatory initiatives of WP.29

With regard to technical vehicle regulations, WP.29 has developed three UN Regulations relevant to CAD and CAVs which entered into force in January 2021: The UN Regulation No. 155 on Cyber Security and Cyber Security Management Systems[23], the UN Regulation No. 156 on Software Updates and Software Updates Management Systems[24], and UN Regulation No. 157 on Automated Lane Keeping Systems (ALKS)[25]. These regulations are applicable in the contracting parties (i.e., countries) to the 1958 Geneva Agreement, including in the EU.[26]

The ALKS regulation is the first regulatory step for automated driving in traffic. It contains

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[22] Informal documents are not binding regulatory instruments but drafted by different working groups and submitted to the WP meetings for consideration. The documents i.e., put forward suggestions or recommendations on regulatory aspects that need to be resolved, amendments to regulations or new proposed draft regulations. As such, the informal documents are part of a process of regulatory discussion and development

[23] https://unece.org/sites/default/files/2021-03/R155e.pdf.

[24] https://unece.org/sites/default/files/2021-03/R156e.pdf.

[25] https://undocs.org/ECE/TRANS/WP.29/2020/81.

[26] Agreement concerning the Adoption of Harmonized Technical United Nations Regulations for Wheeled Vehicles, Equipment and Parts which can be Fitted and/or be Used on Wheeled Vehicles and the Conditions for Reciprocal Recognition of Approvals Granted on the Basis of these United Nations Regulations, Geneva, 20 March 1958.

administrative provisions for type approval, technical requirements, audit and reporting provisions and testing provisions. According to the regulation, "ALKS can be activated under certain conditions on roads where pedestrians and cyclists are prohibited and which, by design, are equipped with a physical separation that divides the traffic moving in opposite directions and prevent traffic from cutting across the path of the vehicle". The Regulation defines safety requirements for emergency manoeuvres, takeover requests, and minimum risk manoeuvres. It also includes the obligation for car manufacturers to introduce Driver Availability Recognition Systems as well as the obligation to equip the vehicle with Data Storage System for Automated Driving (DSSAD) to record when the ALKS is activated. Compliance with cybersecurity and software update regulations is also a requirement for the use of ALKS functionalities. In a first step, the ALKS regulation limits the operational speed to 60 km/h maximum and applies to passenger cars and vans, a use case applicable to assist in traffic jam or other situation of slow-moving traffic. Through an amendment which is expected to enter into force in June 2022 the ALKS regulation will extend its scope and apply to additional vehicle categories. The draft amendment proposes an extension of the maximum speed for ADS for passenger cars and light duty vehicles up to 130 km/h on motorways, and to allow automated lane changes. It stipulates an obligation for the ADS to comply with local traffic rules and a Data Storage System for Automated Driving (DSSAD), a "black box" which records information such as when the ADS is activated, will be required to record lane changes initiated by the system. The draft will be submitted for adoption at the June session 2022 of the World Forum for Harmonization of Vehicle Regulations and, if adopted, it will enter into force in January 2023 and apply in those contracting parties which decide to apply it.[27]

WP.29 has also in 2019 adopted a "Framework document on automated/autonomous vehicles" (FDAV) developed by GRVA to provide guidance to working by identifying key principles for the safety and security of automated/autonomous vehicles level 3 and higher. It includes working principles, safety vision and lists key issues to prioritize. The safety vision sets out that the level of safety to be ensured by automated/autonomous vehicles implies that such vehicles shall not cause any non-tolerable risk, meaning that the ADS shall not cause any traffic accidents resulting in injury or death that could reasonably be foreseen or prevented. System safety is also listed as the number one priority. Other listed prioritized key issues are failsafe response, human machine interface, object event detection and response, operational design domain, validation for system safety, cybersecurity, software updates, and event data recorder and data storage system for automated driving vehicles. (UN, 2019).

Four Informal Working Groups are assigned to perform work according to the program defined by the FDAV[28]:

- Functional Requirements for Automated Vehicles (FRAV)
- Validation Method for Automated Driving (VMAD)
- Event Data Recorder and Data Storage System for Automated Driving (EDR/DSSAD)
- Cyber Security and Over-The-Air issues

5.3 Regulatory European Union and national initiatives on CAV – an overview

At the EU level, the EU Commission is working very actively on creating the relevant legal framework for ADS but has also addressed the urgent legal challenges related to artificial intelligence (AI), cybersecurity, and data exchange and governance.

At a national level, many countries are in the process of regulatory initiatives to support the adoption of CAVs. Some of the forerunners in Europe of developing legislation and regulations in the area of

[27] ECE/TRANS/WP.29/2022/59/Rev.1. *Proposal for the 01 series of amendments to UN Regulation No. 157 (Automated Lane Keeping Systems).*

[28] https://unece.org/transport/vehicle-regulations/working-party-automatedautonomous-and-connected-vehicles-introduction.

CAVs are the UK, France, the Netherlands and Germany. In sections 5.3.2 and 5.3.3 the regulatory landscapes of Germany and UK will be given account of.

5.3.1 EU law – Main legal instruments

Product Liability and Motor Insurance Directives

The Product liability directive[29] (PLD) and Motor Insurance Directive[30] (MID) are two main civil law instruments related to CAD and CAVs. The PLD sets out European regime of strict liability for defective products that have caused personal injury or damage to property of consumers. The introduction and use of CAVs will entail the emergence of new risks and some risks are likely to become significantly more prevalent. Such new risks relating to liability issues associated with CAVs include:

(1) failure of the operating software that enables the CAVs to function,
(2) network failures (CAV inability to obtain data or communicate with other traffic participants owing to network problems),
(3) hacking and cybercrime, and
(4) programming choice (damages resulting from programming failures).

It has been concluded that these risks are not sufficiently addressed under the current PLD or MID framework (EPRSA, 2018). Shortcomings related to the PLD were also identified in the European Commission's 2018 evaluation of the PLD (European Commission, 2018).

Proposals to revise the PLD seek to address the shortcomings identified and the European Commission is moving forward to revise the PLD and national implementing legislation. The European Parliament has also, in the resolution with recommendations on a civil liability regime for AI, urged the European Commission to assess whether the PLD should be transformed into a regulation (European Parliament, 2020). A publication of a draft PLD revised legislation is expected during the autumn 2022. Specific areas of revision concern updates to address challenges posed by new technologies and AI. Potential revisions may include extension of strict liability rules to cover intangible products, such as software and digital content, that cause physical or material damage. In addition, revisions may address defects resulting from changes to products after they have been put into circulation, e.g., software updates. Moreover, revisions are expected to address connectivity and cybersecurity risks and defects resulting from interactions with other products and services, e.g., internet of things (IoT).

In a report on a proposal to amend the MID[31] the European Commission identified four key areas of appropriate amendments:

- insurance checks of vehicles by Member States;
- compensation of parties involved in an accident where the insurance undertaking (insurance company) involved is insolvent;
- minimum obligatory amounts of insurance coverage; and
- use of policyholders' claims history statement by a new insurance undertaking (insurance providers should in principle treat claims history statements, issued in another Member State, equally to domestic statements, for determining premiums and apply any discounts available).

Amendments, following a revision of the MID were published on 2 December 2021, and brought about significant changes with the purpose of ensuring that motor insurance legislation within the EU is brought in line with present realities and risks. The new MID also aims at ensuring that injured parties

[29] Council Directive 85/374/EEC of 25 July 1985 on the approximation of the laws, regulations and administrative provisions of the Member States concerning liability for defective products.

[30] Directive 2009/103/EC of the European Parliament and of the Council of 16 September 2009 relating to insurance against civil liability in respect of the use of motor vehicles, and the enforcement of the obligation to insure against such liability.

[31] Report on the proposal for a directive of the European Parliament and of the Council amending Directive 2009/103/EC of the European Parliament and the Council of 16 September 2009 relating to insurance against civil liability in respect of the use of motor vehicles, and the enforcement of the obligation to ensure against such liability (COM(2018)0336 – C8-0211/2018 – 2018/0168(COD)).

are protected through effective arrangements for compensation and improving the rights of policyholders.

Data exchange and AI frameworks

Data and data exchange as well as artificial intelligence (AI) are crucial in the context of CAVs and CAD. As described in the Connected, Cooperative and Automated Mobility Roadmap (ERTRAC, 2022), combined data from the vehicle, other vehicles infrastructure and back offices could be involved in complex scenario decision making and "include critical situations, traffic management, emission management, charging of vehicles and provision of many new and emerging mobility services". Data reliability is explicitly pointed out as a major challenge for infrastructure and vehicle alike both in the mixed traffic situation and the situation of full automation. From a regulatory perspective the EU Commission has, based on the EU Digital Strategy[32] and the EU Data Strategy[33], with the purpose of encouraging and promoting data exchange, been active to highlight the need for legal certainty and regulatory support. This activity has resulted in an extensive list of regulatory initiatives. Table 11 includes a number of such EU regulatory initiatives. Applicable regulations and directives as well as proposals that affect or will, once enacted, be eventually affecting CAVs and CAD are listed.

Table 11: Data exchange regulatory frameworks supporting and affecting CAVs

Subject matter	***Regulatory framework***
Data protection	Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing Directive 95/46/EC
Free flow of non-personal data	Regulation (EU) 2018/1807 of the European Parliament and of the Council of 14 November 2018 on a framework for the free flow of non-personal data in the European Union
Open Data	Directive (EU) 2019/1024 of the European Parliament and of the Council of 20 June 2019 on open data and the re-use of public sector information
Cybersecurity	Regulation (EU) 2019/881 of the European Parliament and of the Council of 17 April 2019 on ENISA (the European Union Agency for Cybersecurity) and on information and communications technology cybersecurity certification and repealing Regulation (EU) No 526/2013
Data Governance	Proposal for a Regulation of the European Parliament and of the on European data governance (Data Governance Act) COM/2020/767 final
Access to and Use of Data	Proposal for a Regulation of the European Parliament and of the Council on harmonised rules on fair access to and use of data (Data Act) COM/2022/68 final
Intelligent Transport Systems	Directive 2010/40/EU of the European Parliament and of the Council of 7 July 2010 on the framework for the deployment of Intelligent Transport Systems in the field of road transport and for interfaces with other modes of transport
Road safety-related traffic information	Commission Delegated Regulation (EU) No 886/2013 of 15 May 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

An important instrument regulating data sharing and use of data is the proposed EU Data Act, which was published on 23 February 2022 (European Commission, 2022). The proposal is part of the

[32] European Commission. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. *Shaping Europe's digital future.* Brussels, 19.2.2020 COM/2020/ 67 final.

[33] European Commission. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. *A European strategy for data.* Brussels, 19.2.2020, COM/2020/ 66 final.

European Commission's data strategy[34] and the purpose of the proposal is to ensure a fair value allocation of data between different actors, as well as to promote access to and use of data. The proposal includes, among other things, measures that will make it possible for users of connected devices to access such data that is generated by them, and which today is often only collected by the manufacturers. In addition, the proposal includes measures to enable users to share such data with third parties so that they can provide aftermarket services or other data-driven innovative services. Furthermore, the proposal includes measures to give small and medium-sized enterprises a better negotiating position by preventing contractual imbalances from being misused in data sharing agreements. The idea is that the Data Act will protect companies from unfair contract terms written by a party with a much stronger negotiating position. The proposal also includes tools for public authorities to access and use data held by the private sector, but which are necessary in exceptional circumstances, or when public authorities need data in order to fulfill a statutory task and this data is not available in any other way. The proposal also introduces new rules that make it possible for customers to easily switch between different cloud service providers and introduce protective measures against illegal data transmission (European Commission, 2022).
For AI, the EU regulatory initiatives consist of two parts, a safety framework and a liability framework. The safety framework consists of a proposed Artificial Intelligence Act (European Commission, 2021). As set out in Figure 13, the liability framework for AI-systems includes both a proposal for a regulation on a civil liability regime for AI and the Product liability directive. The proposed civil liability regime is based on a division on strict liability for operators of high-risk AI-systems and fault-based liability for operators of other AI-systems. Under the regime, AI-systems used in CAD and CAVs are considered high-risk AI-systems (European Parliament, 2020).

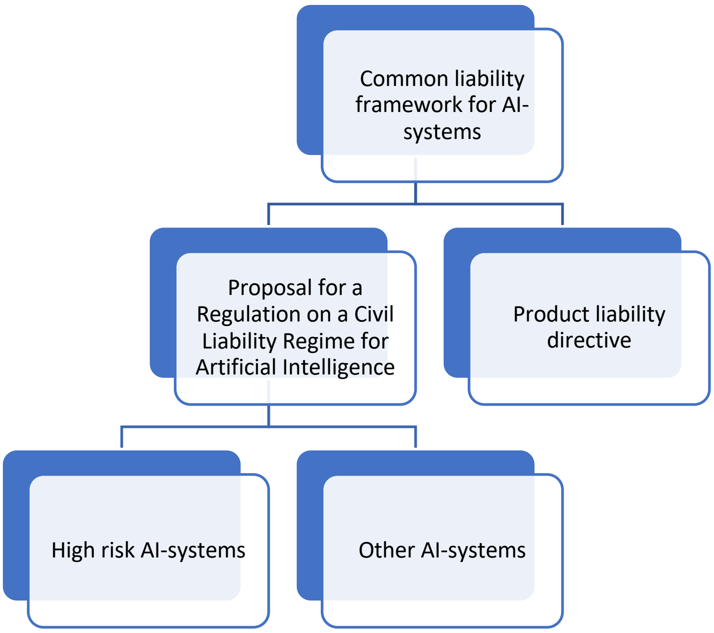

Figure 13: Liability framework for AI-systems relevant to CAVs

A draft EU ADS Regulation

The Type-Approval Framework Regulation (EU) 2018/858 is applicable in all EU member states. It provides harmonized rules for the approval and market surveillance of motor vehicles and for trailers,

[34] European Commission. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS, A European strategy for data COM/2020/66 final.

systems, components, and separate technical units intended for such vehicles. The regulation does not yet provide any rules for CAVs.

There is, however, a draft EU ADS Regulation which sets the requirements for the type-approval of ISO/SAE Level 4 vehicles with regard to their ADS. It is expected to enter into force during 2022. The aim with the new ADS Regulation is to amend Regulation (EU) 2018/858 and to significantly reduce deaths and serious injuries on European Union (EU) roads by introducing state-of-the-art safety technologies as standard vehicle equipment, and to enhance the competitiveness of EU car manufacturers on the global market by providing the first ever EU legal framework for automated and fully automated vehicles. The scope of the ADS Regulation is, for now, expected to be limited to small series and certain use cases e.g., shuttles of dedicated roads.[35]

5.3.2 Germany

Act on Automated Driving

The German Government has passed two acts, 1) Act on Automated Driving and 2) Act on Autonomous Driving, amending the German Road Traffic Act to pave the way for automated driving in Germany (Deutscher Bundestag, 2017; 2021).

The Act on Automated Driving, entered into force on 21 June 2017, and made it possible for automated systems (SAE Level 3) to take over the task of driving under certain conditions. For higher levels of automation, permits may be given on an individual basis. Under the Act, a person who activates a highly or fully automated driving function and uses such a function to control the vehicle, even though she/he does not control the vehicle manually, shall be deemed to be a driver. In addition, the German Act allows limited distractions when an automated driving system is engaged provided that the system is used in accordance with the intentions of the manufacturer. The driver may divert his attention from other traffic and control of the vehicle but must remain sufficiently alert at any time to be able to take over control of the vehicle and the driving task. According to the Act the driver must do so without delay when prompted by the system or when the driver realizes that, due to obvious circumstances, the conditions for using the automated driving functions for their intended purposes are no longer being met. When the amendments were being considered in the German Government this provision was subject to debate. Road signs and inclement weather were cited as examples of things that might be considered obvious but would require very different levels of readiness and perception. It is also unclear whether obvious circumstances will include conditions requiring some situational awareness, such as where the vehicle begins to veer between lanes, or crossroad markings. This will likely need to be decided on a case-by-case basis by the German courts. Importantly, the Act also states that the driver who engages such a feature always remains the driver, even when the system is exercising control over the vehicle. This implies that drivers might remain directly liable for the full range of road traffic offences. (Deutscher Bundestag, 2017).

Act on Autonomous Driving

On 10 February 2021, the German Federal Government adopted a draft law on autonomous driving to create a legal framework allowing highly automated vehicles of at least SAE Level 4 to be used in regular operation in defined areas. The German law on autonomous driving entered into force on 28 July 2021 and amended the German Road Traffic Act. The ambition is that the law on autonomous driving will apply until superseded by European or international regulation. As set out in the law, vehicles with an autonomous driving function does not require a person to drive the vehicle during operation. However, a responsible person is still required to comply with current international regulation. Therefore, the law introduces a new legal actor, a technical supervisor, who will be

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[35] COMMISSION IMPLEMENTING REGULATION (EU) …/... laying down rules for the application of Regulation (EU) 2019/2144 of the European Parliament and of the Council as regards uniform procedures and technical specifications for the type-approval of the automated driving system (ADS) of fully automated motor vehicles https://eurlex.europa.eu/legalcontent/EN/TXT/?uri=PI_COM%3AAres%282022%292667391&qid=1653306780635.

responsible for ensuring that the traffic law obligations are complied with. The technical supervisor is a natural person who will in most cases be located remotely rather than in the vehicle. Moreover, the technical supervisor is responsible for ensuring that the obligations under road traffic law are always complied with, even if permanent monitoring of the driving operation is not required.

The technical supervisor is a natural person, whose responsibilities include oversight and emergency maneuvers. In particular, responsibilities include activation of alternative driving maneuvers and assessment of transmitted data of vehicle and taking the necessary measures for traffic safety including immediate deactivation of the autonomous driving function in case of technical problems. Another responsibility is contacting passengers and taking necessary measures for road safety when vehicle is placed in minimum risk state - meaning greatest possible road safety. (Deutscher Bundestag, 2021).

5.3.3 United Kingdom

The UK has chosen a different regulatory approach. The Law Commission of England and Wales and the Scottish Law Commission have been commissioned to carry out a three-year project to develop the UK's regulatory framework for automated vehicles and their use. The project has included three public consultation rounds.

The Law Commission's consultation paper and report on a regulatory framework for automated vehicles

In the third consultation the law commission introduced three legal key actors associated with CAVs, see description in Table 12.

Table 12: Key legal actors (Law Commission, 2022)

<table>
<tr><td colspan="2">ASDE (Authorised Self-Driving Entity)</td></tr>
<tr><td colspan="2">Required for all on-road CAVs. Puts the ADS forward for legal categorization and is legally responsible for how the ADS performs the dynamic control.</td></tr>
<tr><td>User-In-Charge (UIC)
A UIC is a human in the vehicle with access to the controls</td><td>No-user-in-charge (NUIC) Operator
The entity that oversees vehicles without a UIC</td></tr>
<tr><td>UIC requirements:
• Be qualified and fit to drive
• Be receptive to a transition demand
• Be responsible for the condition of the vehicle
• Report Accidents</td><td>Operator requirements:
• Be of good repute
• Have appropriate financial standing
• Have centre of operations in GB
• Be professionally competent
• Submit a safety case</td></tr>
</table>

Firstly, it suggested that every automated driving system (ADS) put forward for authorization should be backed by an entity to vouch for it (for the design of the system). Thus, an Authorised Self-Driving Entity (ASDE), puts the ADS forward for legal categorization and is legally responsible for how the ADS performs the dynamic control. The ASDE must have been closely involved in assessing the safety of the ADS and have sufficient funds (e.g., to organise a recall). This may be the vehicle manufacturer or software designer or a joint venture between the two. In the event of a problem, the regulator would have powers to apply a range of regulatory sanctions to the ASDE, including improvement notices, warnings, fines or (in serious cases) withdrawal of approval. The emphasis is on understanding what happened and to apply such learning to improve future safety. The ASDE must register with the safety assurance regulator and is the first point of contact if things go wrong.

Secondly, in a first regulatory path the commission dealt with CAVs that can only be used with a so-called user-in-charge (UIC). A UIC is a human who has access to the controls of an automated vehicle and is in the driving seat of the vehicle. The UIC is not a driver while the automated driving system is correctly engaged but must be qualified and fit to drive. The main role is to take over following a transition demand (a request from the system to intervene). The UIC would also have obligations relating to non-dynamic driving task requirements including duties to maintain and insure the vehicle, secure loads carried by the vehicle and report accidents. An automated vehicle would require a UIC unless it is authorized to operate without one. At the end of a transition demand period the UIC should re-acquire the legal obligations of a driver, whether or not they have taken control of the vehicle; and if, following a failure to respond to a transition demand, the vehicle stops in a manner which constitutes a criminal offence, the UIC should be considered a driver and should therefore be liable for that offence. Thus, the UIC who takes over control of the vehicle is considered a driver.

Thirdly, in a second regulatory path the law commission addressed remote operation, CAVs that can be used without a user-in-charge, referred to as "no-user-in-charge" (NUIC). They must be associated with a licensed NUIC operator, that is an organization rather than an individual, who will take responsibility for operating vehicles which are authorized for use without a UIC. All vehicles authorized for use on roads or other public places with NUIC should either: (a) be operated by a licensed operator; or (b) be covered by a contract with a licensed operator for supervision and maintenance services. All operators of such vehicles are required to be qualified, operate remote supervision, maintain and insure the vehicle, install safety-critical updates and maintain cybersecurity and report accidents and near misses. Additional duties could apply to the operator if, for example, they are providing a passenger service or operating heavy goods vehicles. If there are people in the vehicle these are merely passengers with no obligation to intervene and no legal responsibility for the way the vehicle drives (Law Commission, 2021).

Proposed Highway Code amendments for introduction of CAVs

In January 2022, The Law Commission for England and Wales published a joint report with recommendations for a new legal framework that would facilitate the use of CAVs on public roads in the UK, which require a new act. The government is currently considering the recommendations and expects to have a full framework in place by 2025. However, measures are needed in the interim and, therefore, amendments to the Highway rules on the safe use of on CAVs on Great Britain's motorways code are proposed. (Law Commission, 2022).

The amendments give guidance to the user, enforcement authorities and the courts, on legal expectations on the safe use of CAVs. Firstly, while a vehicle is driving itself, the driver is neither responsible nor do they need to pay attention to the road. The driver must, however, be ready to take back control of the vehicle when the vehicle prompts the driver to do so. The driver is also obliged to follow the manufacturer's instructions about when it is appropriate to use the ADS. Secondly, the driver retains all other aspects of the driver responsibility, such as ensuring they are fit to take back control of the driving task from the vehicle and ensuring the vehicle is roadworthy. Also, even if the driver may divert attention away from the road to view content through the vehicle's built-in infotainment apparatus the driver will still not be allowed to use a hand-held mobile phone. These amendments are intended to provide for CAVs in a near future. (Department of transport, 2022)

5.4 Legal implications – Specific challenges related to CAV/CAD

5.4.1 Road signs' machine readability and Road marking reflectivity

The main challenges, in machine-readable traffic signs and road marking reflectivity, are standardisation and harmonisation of infrastructure elements. The main reason is that physical infrastructure is not standardised in Europe. Different countries have different standards for different road types, which makes it difficult to define a clear classification for physical infrastructure. Some initiatives to standardise flat and structured markings are in place but comprising only specific regions within Europe. For instance, the Nordic certification system for road markings[36], which is based on three European standards: EN 1824 (materials), EN 1436 (performance), and EN 12802 (laboratory methods). The focus is on quality assurance, meaning that companies, commissioned to install or paint

[36] https://trimis.ec.europa.eu/project/nordic-certification-system-road-marking-materials

road markings, guarantee a certain quality regarding reflected luminance, friction, and colour. However, these standardisation initiatives do not consider the capabilities of CAV systems, if camera systems will be able to detect signs and markings under all weather and traffic conditions. In other words, standardisation initiatives do not test for ODD requirements of ADSs. Clear definitions of ODDs for each ADS functionality are required for guaranteeing the safe operation of ADSs as well as for safety standardisations. However, clearly defining ODDs is still a major challenge given that many factors affect ODDs and the performance of ADSs in different ODDs. To some extent there is an assumption that the best way to support CAVs would be through digitising traffic regulations, or digitising signage data, rather than physical or operational improvements. There may be opportunities for modification with regards to width of road markings and reflectivity of paints, but further research is needed. We believe that there is still time to review any design standards and operational practices to help prepare for higher levels of automated driving. In this regard, legal frameworks are essential to support road signs' machine readability with clear traffic rules which are geographically unambiguous. The rules need to be understood by a computer and, for example, be indicated on a digital map or provided with coordinates.

The ITS Directive is relevant in this respect, providing a framework for the adoption of common standards and specifications in the EU for the creation of Intelligent Transport Systems. Through a legislative initiative by the European Commission in 2021, an updated ITS Directive has been presented following a report[37] to the European Parliament and the Council which highlighted *"(i) the need to further improve coordination in accessibility of data; (ii) the need to take into account the emergence of new ITS themes and challenges; and (iii) the need to improve the availability of key data types on the whole road transport network (i.e. by making these data types available in digital machine-readable format)*" (European Commission, 2021).

The draft law introduces amendments to Directive 2010/40/EU on the framework for the deployment of Intelligent Transport Systems in the field of road transport that may increase the requirements for traffic information data – including certain traffic rules. Also, it expands the scope of the directive and additional rules are introduced to facilitate alignment with evolving practices and standards.

On 2 February 2022, the EU Commission also presented a Delegated Regulation supplementing the ITS-Directive 2010/40/EU with regard to the provision of EU-wide real-time traffic information services.[38] The Regulation establishes the specifications necessary in order to ensure the accessibility, exchange, re-use and update of data by data holders and data users for the provision of EU-wide real-time traffic information services, and to ensure that these services are accurate and available across borders to end-users.[39] Accessibility of the data is defined in the regulation as a possibility to request and obtain the data at any time in a digital machine-readable format.[40]

The Delegated Regulation deals with the accessibility, exchange, and re-use of data on infrastructure, data on regulations and restrictions, data on the state of the network and data on the real-time use of the network respectively. In the annex of the Regulation the types of data and crucial types of data has been listed and sorted under these categories, see examples in Table 5.

Table 13: Examples of types of data and crucial data listed in the Commission Delegated Regulation (EU) 2022/670 Annex 1.

Data on infrastructure	Crucial data on	Other types of data on	Crucial data on the state	Other data on the state of the	Data on the real-time use of the

[37] Report presented on 8 October 2019 by the European Commission on the progress made towards the implementation of Directive 2010/40/EU (the ITS Directive).

[38] Commission Delegated Regulation (EU) 2022/670 of 2 February 2022 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.

[39] Article 1 (1).

[40] Article 2 Section 2 (4).

	regulations and restrictions	regulations and restrictions	of the network	network	network
Road network links and their physical attributes	Static and dynamic traffic regulations, where applicable, such as i.e. access conditions for tunnels and bridges; speed limits; one-way streets and permanent access restrictions	Location and identification of traffic signs reflecting traffic regulations and identifying dangers	Road closures	Bridge closures	- Traffic volume - Traffic speed - Location and length of traffic queues
Road classification	Traffic circulation plans	Identification of tolled roads, applicable fixed user charges and available payment methods	Lane closures	Accidents and incidents	- Travel times - Waiting time at border crossings
Location of tolling stations			Roadworks	Poor road conditions	-Availability of delivery areas
Location of service areas			Temporary traffic management measures	- Weather conditions affecting	-Availability of recharging points and stations for electric vehicles -Availability of refuelling points and stations for alternative fuel types
Location of recharging points for electric vehicles					-Price of ad hoc recharging/refuelling

The articles of the Delegated Regulation refer to different standards for the provision of data. For example, the Regulation states that road authorities, road operators, tolling operators and recharging and refueling related stakeholders shall provide the data on infrastructure they collect in a standardized format such as the INSPIRE data specification on transport networks, TN-ITS

(CEN/TS17268 and subsequently upgraded versions) or DATEX II (EN 16157, CEN/TS 16157 and subsequently upgraded versions).[41]
According to the Regulation, each Member State shall set up a national access point (NAP). The NAP shall constitute a single point of access for data users to the data listed in the Annex I, including data updates.
The Commission Delegated Regulation (EU) 2022/670 shall apply from 1 January 2025[42] (European Commission, 2022).

5.4.2 Accuracy and currency of HD mapping

In general, NRAs are not investing in HD mapping, although they can deliver data to 3rd party suppliers to create HD maps. NRAs liability issues of concern are potential provision of incorrect or out-of-date mapping data. Furthermore, there is currently no regulation to enforce data sharing among different map providers. Therefore, without a clear business interest in HD map providers and in absence of regulations to enforce collaboration, data sharing among different map providers will be hard to see in place.
However, there are some quality standards for HD maps (e.g., ASIL and ADASIS) but the current maps do not meet these standards at the required level for CAVs in a reasonably extended scope. Quality standards such as Automotive Safety Integrity Level (ASIL) and Advanced Drivers Assistant System Interface Specifications (ADASIS) could be used to assess the quality of HD maps. But current maps do not meet such standards at a level that OEMs consider sufficient. This is because the road infrastructure is constantly changing, creating the map mismatch problem or out-of-date maps. To keep the maps updated with all the dynamic changes in the infrastructure, large fleets of CAVs must be on the roads to collect dynamic infrastructure data.
The previously mentioned Commission Delegated Regulation (EU) 2022/670 with regard to the provision of EU-wide real-time traffic information services is also relevant and applicable in relation to the area of HD maps. The regulation declares that "*accessibility and regular update of data by road authorities and road operators are essential for enabling the production of up-to-date and accurate digital maps that are a key asset for reliable ITS applications*." It also encourages digital map providers to timely integrate relevant data updates into their existing map and map update services. Furthermore, it is stressed that digital map providers and service providers should collaborate with public authorities to correct inaccurate data in order to comply with public policies on road safety (European Commission, 2022).
Liability issues of concern to some NRAs are the potential provision of incorrect or out-of-date mapping data. This is also a concern in other areas, for example if data on road signs or markings are of poor quality or missing. In the Delegated Regulation on real-time traffic information services, the Commission sets out that Member States and ITS stakeholders should be encouraged to agree on common definitions of data quality and argues that common data quality indicators, such as the completeness, accuracy and up-to-dateness of the data, the acquisition method and location referencing method used, as well as quality checks applied should be used. Moreover, the Commission encourages stakeholders to establish associated methods of quality measurement and monitoring of the different types of data.
Also, the Commission recognizes that a cost-effective way for road authorities and road operators to improve tasks such as traffic or infrastructure management, road safety and infrastructure maintenance is to make use of data and real-time traffic information provided by private service providers and holders of in-vehicle generated data. The Commission advocates that common fair, reasonable, and non-discriminatory terms, so called FRAND terms, should be used by public authorities when receiving data or services from private providers for the mentioned type of tasks.

[41] See Article 4 (1).
[42] The regulation was published in the Official Journal of the European Union on 25 April 2022 and entered into force on the twentieth day following that of its publication.

Member states and relevant stakeholders are, therefore, encouraged to create and define such FRAND terms for the performance of such public tasks.

In the Delegated Regulation it is pointed out that private service providers may use data collected by road authorities and road operators as input data for their own real-time traffic information services and that it should be left to the parties involved to decide on the specific terms and conditions applicable for such re-use of these data without prejudice to the provisions of the EU Open Data Directive.[43] It is also stated that "certain data types provided by road authorities and road operators, such as traffic circulation plans, traffic regulations and restrictions and temporary traffic management measures, should be re-used by private service providers in order to ensure the accessibility for road users to the relevant information via real-time traffic information services" (European Commission, 2022).

5.4.3 Timely information provision on incidents, events and crises

The main challenges with connectivity are reliability of the connection in different environments (e.g., in places where there is wave interference from the environment), and reliability of the information received to making critical decisions. Another challenge with connectivity is standardisation of radio access technologies and their quality of service. These challenges are likely to result in liability issues in case of inaccurate information or loss of connectivity. This requires many commitments and close collaboration, which OEMs seem to be pessimistic at the moment.

The information provided via V2X connectivity will not always be available and reliable. Therefore, ADSs should not be designed to rely on connectivity information for their core functionalities, at least at this moment. Moreover, liability issues in case of accidents caused by inaccurate information received via V2X connectivity are not resolved now. When decisions of an ADS are made based on the information received from external sources, some form of trust or procedure for verifying the accuracy of the information should be in place. How this should be integrated into the decision-making process, is an open topic for research. See for example the section on Service Level Agreements (SLAs).

5.4.4 Cybersecurity for digital twins or I2V communications

Cybersecurity, or the practice of defending computers, servers, mobile devices, electronic systems, networks, and data from malicious attacks, is a substantial challenge to the deployment of CAVs and CAD. This is, thus, also the case for digital twins (DTs) or I2V communications. These are construed by use of systems which are vulnerable to cyber threats through features such as high connectivity, mobile networks with sensors, cameras, GPS, onboard computers and vehicle to everything (V2X) communication. Thus, strict and robust IT security is necessary in the vehicles and throughout the intelligent infrastructure from a safety perspective as well as from a trust and confidence perspective to gain acceptance for the use of CAVs. Legal frameworks are of great importance to secure safety aspects and to allocate responsibilities and possible liability in case of damage or injury resulting from cyber-attacks.

NRAs are not using DTs at the moment but they are building parts of it for different purposes, e.g., planning, maintenance, asset and traffic management.

Regulatory initiatives regarding legal aspects and implications of cybersecurity have been initiated by the EU. In 2019, the Cybersecurity Act entered into force.[44] The Act is an EU Regulation which establishes a comprehensive system for product certification, processes, and services to ensure that they comply current standards for cybersecurity. The certification is initially voluntary but will become

[43] Directive (EU) 2019/1024 of the European Parliament and of the Council of 20 June 2019 on open data and the re-use of public sector information.

[44] Regulation (EU) 2019/881 of the European Parliament and of the Council of 17 April 2019 on ENISA (the European Union Agency for Cybersecurity) and on information and communications technology cybersecurity certification and repealing Regulation (EU) No 526/2013.

mandatory in the EU for particularly important products and activities. The actual certifications are under development. In addition to the Cybersecurity Act, EU has introduced instruments to protect electronic communications networks, including the Directive on Security of Network and Information Systems (NIS Directive). The Directive includes mechanisms for cooperation at EU level, measures to increase national capabilities and obligations for operators of essential services and digital service providers to adopt risk management practices and report significant incidents to the national authorities (European Parliament, 2019). The legal aspects of cybersecurity and digital twins have also been addressed and discussed in contribution 2.4.

In research, it has been argued that the use of DTs raises cybersecurity concerns and stressed the importance of best practice cybersecurity compliance when integrating DT technology into the Industry 4.0 domain. But it has also been argued that the concept of a cyber digital twin (CDT) could be relevant from a cyber defence perspective. A CDT could be used for security analysis as well as monitoring when this is not a feasible option on the physical counterpart without causing disruption. Significant benefits have been suggested, such as performing security assessments without accessing the physical environment and simulations of security attacks and defence scenarios which would be difficult or even impossible to perform in the physical environment. Through advanced system and security testing opportunities, improved risk management, active cyber defence, advanced training and incident response capability, anomaly detection and predictive analytics the CDT is a possible instrument to address legal and other challenges and risks such as lack of adequate asset management and inadequate system design consideration, integrity, confidentiality, data ownership and Intellectual Property leakage (Holmes et al., 2021).

5.5 Brief comments on stakeholder views, and conclusions on legal and regulatory aspects

Based on the interviews from stakeholders (WP1), with respect to legal framework, CAD legislation in Europe is lagging the technology developments. A comprehensive functioning legal basis for CAVs is not on sight, which is a major challenge in large-scale success of consumer CAVs. The uptake of CAVs is likely to be driven by legislation. Once the legislation is in place, then trust and acceptability are likely to increase, and people's behaviours will likely change quickly. Therefore, for a successful deployment of CAVs, there is a need of favourable legislations and standards to clearly define responsibilities for each actor within the CAD ecosystem, e.g., NRAs, OEMs, Telco, 3rd service providers.

Liability issues are of concern to some NRAs over potential reckless protection systems and reckless data storage which may lead to data leakage or cyber-attacks.

Even though stakeholders perceive that the CAD legislation in Europe is lagging the technology developments and that the lack of legislation and standardisation is a major challenge, this review has highlighted that there is extensive and intensive regulatory activity taking place on both an international level and a European Union level addressing these challenges of CAV introduction and deployment. Important regulatory initiatives expected to be adopted in a near future are the draft amendment of UN Regulation no. 157 on Automated Lane Keeping Systems and the draft EU ADS Regulation.

There are also ongoing regulatory initiatives in many European countries as well as other countries around the world. For example, Germany and the UK have taken a proactive approach and introduced regulatory initiatives in a broad sense. Germany has, with reference to SAE levels 3 and 4-5 respectively, adopted both a framework for automated vehicles and an interim legal framework enabling vehicles with autonomous driving functions to use public roads in Germany for as long as no internationally harmonised regulation exists. The UK has adopted a more step-by-step regulatory method, taking interim measures with a view of a full framework in place by 2025. The UK initiative is also divided into two regulatory paths: one path directed to the scenario with a human user in the vehicle and a second path directed to remote operation. Both legal systems have elaborated and introduced new complementary legal actors and concepts like Technical Supervisor, Authorised Self-

Driving Entity, User-In-Charge, and No-User-in-Charge.

The list of regulatory initiatives and frameworks illustrated and mentioned in this review is not exhaustive. It is of importance, though, to stress that the regulatory development is a careful process and that it also must take safety aspects and the technical development into account. Regulating too early could be detrimental to the willingness to invest and result in a failure to secure a fair and well-balanced framework of risk sharing.

From a stakeholder perspective it is of importance to be aware of the ongoing regulatory initiatives and work processes on different levels, so that NRAs, OEMs, Telco, and service providers can make informed decisions. But it is also of utmost importance to actively participate in the ongoing regulatory discussions, contribute to the regulatory process, and support the lawmakers with valuable knowledge, information, and perspectives. Such contribution and support are indispensable for the lawmakers to be able to safeguard different interests and to address relevant and necessary aspects.

Certain legal aspects are of particular importance and urgency to address and resolve to facilitate CAV uptake. This review has pointed out the legal challenges of data sharing and cybersecurity. In this area, the EU has been very active and taken many regulatory initiatives. Some of these have already entered into force whereas other initiatives are in a proposal or a development stage. It is too early to assess if these initiatives sufficiently will address risks, increase data sharing and result in public acceptance.

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6 Legal and Regulatory Aspects

6.1 Introduction

The connectivity needs of automated vehicles depend on assumptions on the level of automation, the use case to be realized and expectations on the operational design domain of the vehicle. The results of the stakeholder consultation carried out in WP1 indicated that there is no consensus on the service concept to be provided by the road operator to support connected and automated driving (Öörni 2022). While vehicle manufacturers aim to make their vehicles as independent as possible, there are also requirements which are unlikely to be fulfilled without connectivity. The connectivity requirements of connected and automated vehicles were explored in DiREC task T2.2. A summary of the connectivity requirements for different deployment scenarios of automated driving is provided in this chapter. This chapter also describes the connectivity technologies available for road infrastructure and their impact on road network coverage.

6.2 Connectivity

6.2.1 The connectivity deployment options

The development of connectivity options was started by identifying the deployment options of automated driving. In this case, connectivity options were considered to be combinations of technologies which can be used to meet the needs of CAD in its different deployment scenarios. For all deployment scenarios, the following connectivity needs were considered:

- communication with traffic control systems (e.g. traffic lights),
- remote operation of vehicle
- communication between vehicle occupants and automated vehicle control centre
- vehicle software and map updates
- monitoring of vehicle cargo.

For the deployment options, the business cases described in Annex H of (Smit et al. 2021) were used as a starting point. The identified deployment options are described in Table 1. For each of the deployment options, assumptions were made on the expected operating environment of the vehicles, levels of automation (for definitions of levels of automation, please see: SAE 2021), use of a pre-defined route and level of infrastructure support likely to be available for automated driving.

Table 1: Deployment options for identifying connectivity requirements.

Number	Deployment option	Expected area of operation	Level of automation	Pre-defined route	Infrastructure support for automated driving
1	Automated shuttle providing a local public transport service	Urban or suburban roads and streets	SAE4/SAE5	Yes	Moderate (dedicated lane may be provided for a part of the route)
2	Automated vehicle used for local goods delivery	Roads and streets between local distribution point and consignee	SAE4/SAE5	Yes/No	Low
3	Automated truck	Interurban roads, logistics terminals, roads and	SAE4/SAE5	Yes	Low/Moderate (dedicated lane may be provided for a

		streets in industrial areas			part of the route)
4	Highly automated vehicle as robotaxi	Roads and streets in an urban area	SAE4/SAE5	No	Low
5	Highly automated passenger car	Urban roads and streets, interurban and rural road network	SAE4/SAE5	No	Low
6	Passenger car, automated driving in limited situations	Urban roads and streets, interurban and rural road network	SAE3	No	Low

After the deployment options had been identified, their connectivity requirements were summarised - Table 2. When identifying the connectivity requirements, the main focus was on the levels of automation which are likely to have the largest economic impact and which are likely to be most dependent on connectivity (SAE4 and SAE5).

Table 2. Connectivity requirements in different deployment options

Number	Deployment option	Communication with traffic control systems (e.g. traffic lights)	Remote operation of vehicle	Communication between vehicle occupants and automated vehicle control centre	Vehicle software and map updates	Monitoring of vehicle cargo
1	Automated shuttle providing a local public transport service	Optional	Yes (SAE4)	Audio or video	Yes	-
2	Automated vehicle used for local goods delivery	Optional	Yes (SAE4)	-	Yes	Optional
3	Automated truck	Optional	Yes (SAE4)	-	Yes	Optional
4	Highly automated vehicle as robotaxi	Yes	Yes (SAE4)	Audio or video	Yes	-
5	Highly automated passenger car	Yes	Yes (SAE4)	Audio or video	Yes	-
6	Passenger	Optional	-	-	Yes	-

	car, automated driving in limited situations					

When drafting the connectivity options (Table 3), existing technologies such as 4G (LTE), 5G and ITS-G5 were considered. Both 4G (LTE) and 5G include support for V2X communications (Garcia-Roger et al. 2020, Alalewi et al. 2021). ITS-G5 based on IEEE802.11p physical and data link layers is a known and mature technology developed for vehicular communications. While 5G coverage is still imperfect, it has been assumed to increase fast in near future. According to the Ericsson Mobility Report, 5G coverage of the population of the world is expected to grow from about 15% in 2020 to 75% in 2027 (Cerwall, Jonsson and Carson (ed.) 2021).

C-ITS services specified by ETSI will act as building blocks for communication between automated vehicles and other entities such as roadside infrastructure and other road users. The connectivity requirements of different C-ITS services have been summarised in the report of task T2.2. During development of the connectivity options, different communication technologies described in T2.2 and T2.6 were seen as parts of the evolution of mobile networks (e.g. 4G, 5G, 6G) and to have complementary roles (for example in terms of coverage provided, use cases supported and business model) rather than mutually exclusive solutions.

When developing the connectivity options, it has been assumed that a solution can be found to challenges related to LTE sidelink and ITS-G5 (IEEE802.11p) operating on the same 5.9 GHz frequency band. According to simulation results, the effective communication range of ITS-G5 will be reduced in situations in which LTE sidelink (PC5) and ITS-G5 are used in the same frequency band without supporting infrastructure (Bazzi et al. 2020). The results of a simulation study indicate that use of different channels or frequency bands for the technologies would be a preferable solution (Ruder et al. 2021). Starting from 3GPP release 16, sidelink communication may take place also FR1 and FR2 5G frequency ranges in addition to the 5.9 GHz frequency band (Garcia at al. 2021).

It was assumed that remote operation of vehicles will be needed on SAE level 4. In practice, remote operation requires a video stream from the vehicle to the vehicle operation centre and transmission of control data from the vehicle operation centre to the automated vehicle. The data connection for the video signal must have low latency and low jitter to allow the remote operator to maintain situational awareness of the movements of the vehicle. The bandwidth requirement is affected by the density of automated vehicles and the vehicles' ability to operate without the need for remote operation.

Table 3. Mapping different deployment scenarios to the connectivity options

		Connectivity Option #1: ITS-G5, combined with LTE connectivity	Connectivity Option #2: C-V2X combined with LTE connectivity	Connectivity Option #3: 5G-V2X, including connectivity via LTE and 5G
Automated shuttle providing a local public transport service				
	Communication with traffic control systems (e.g. traffic lights)	ITS-G5	PC5 sidelink	NR Sidelink
	Remote operation of vehicle	LTE *	LTE *	5G or LTE *
	Communication between vehicle occupants and automated vehicle control centre	LTE	LTE	5G or LTE

	Vehicle software and map updates	LTE	LTE	5G or LTE
	Monitoring of vehicle cargo	-	-	-
Automated vehicle used for local goods delivery				
	Communication with traffic control systems (e.g. traffic lights)	ITS-G5 (optional)	PC5 sidelink (optional)	NR sidelink (optional)
	Remote operation of vehicle	LTE *	LTE *	5G or LTE *
	Communication between vehicle occupants and automated vehicle control centre	-	-	-
	Vehicle software and map updates	LTE	LTE	5G or LTE
	Monitoring of vehicle cargo	LTE (Optional)	LTE (Optional)	5G or LTE (optional)
Automated truck				
	Communication with traffic control systems (e.g. traffic lights)	ITS-G5 (optional)	PC5 sidelink (optional)	NR sidelink (optional)
	Remote operation of vehicle	LTE *	LTE *	5G or LTE *
	Communication between vehicle occupants and automated vehicle control centre	-	-	-
	Vehicle software and map updates	LTE	LTE	5G or LTE
	Monitoring of vehicle cargo	LTE (Optional)	LTE (Optional)	5G or LTE (optional)
Highly automated vehicle as robotaxi				
	Communication with traffic control systems (e.g. traffic lights)	ITS-G5	PC5 sidelink	NR sidelink
	Remote operation of vehicle	LTE *	LTE *	5G or LTE *
	Communication between vehicle occupants and automated vehicle control centre	LTE	LTE	5G or LTE
	Vehicle software and map updates	LTE	LTE	5G or LTE
	Monitoring of vehicle cargo	-	-	-
Highly automated passenger car				
	Communication with traffic control systems (e.g. traffic lights)	ITS-G5	PC5 sidelink	NR Sidelink
	Remote operation of vehicle	LTE *	LTE *	5G or LTE *
	Communication between vehicle occupants and	LTE	LTE	5G or LTE

	automated vehicle control centre			
	Vehicle software and map updates	LTE	LTE	5G or LTE
	Monitoring of vehicle cargo	-	-	-
Passenger car, automated driving in limited situations				
	Communication with traffic control systems (e.g. traffic lights)	ITS-G5 (optional)	PC5 sidelink (optional)	NR Sidelink (optional)
	Remote operation of vehicle	-	-	-
	Communication between vehicle occupants and automated vehicle control centre	-	-	-
	Vehicle software and map updates	LTE	LTE	5G or LTE
	Monitoring of vehicle cargo	-	-	-
* Remote operation of vehicle over LTE network only with low vehicle speed or dedicated LTE network				

6.2.2 Current Status and future development of C-V2X and 5G-V2X

LTE-V2X appeared as a part of ETSI Release 14 (3GPP 2018). Release 14 reached status “freeze” in June 2017. After a new release has reached the status “freeze”, no new functionality can be added, but corrections to specifications are still possible. LTE-V2X introduced in Release 14 includes two modes of V2X communication: V2X communication over PC5 interface and V2X communication over LTE-Uu interface. V2X communication over PC5 sidelink is possible while the vehicle is located inside the coverage area (network scheduled operating mode) of a E-UTRAN network and outside network coverage (autonomous resources selection mode). In case of V2X messages sent over the LTE-Uu interface, the vehicle may send unicast messages to a V2X application server (using the LTE-Uu uplink) and receive V2X broadcast or unicast messages from the application server (using the LTE-Uu downlink). V2X communication using LTE sidelink takes place on the 5.9 GHz frequency band (E-UTRA band B47), while V2X messages sent over the LTE-Uu interface may be transmitted and received on several LTE frequency bands.

The support for V2X services in LTE services was improved further in ETSI Release 15 (3GPP 2019). The improvements introduced in Release 15 included e.g. packet duplication in PC5 sidelink communication to increase reliability, improvements in radio resource management such as support for carrier aggregation in PC5 sidelink communication and more strict latency requirements (time between packet arrival at layer 1 and reservation of resources for transmission, reduced from 20 ms to 10 ms). Release 15 reached status “frozen” in June 2019. A review of the studies on the performance of LTE-V2X (PC5) sidelink in the autonomous mode has been provided in a review paper (Bazzi et al. 2021).

The 5G system was introduced in 3GPP Release 15 (3GPP 2019). The first phase of 5G included requirements for 5G such as enhanced mobile broadband (eMBB), critical communications (CC), ultra-reliable and low latency communication (URLLC), massive internet of things (mIoT) and flexible network operations. Two deployment options for 5G were also provided: architecture for situations in which 5G is deployed in coexistence with existing 4G infrastructure (non-stand alone, NSA architecture) and architecture for stand-alone deployment of 5G (stand alone, SA architecture). The 5G system includes three elements: user equipment (UE), (radio) access network (RAN) and the core network (5GC or 5GCN). Instead of network entities, the architecture of 5G uses the term “network functions", as it is based on the principles of Service Based Architecture (SBA). The 5G access network consists of gNB (gNodeB) entities which are connected to the 5G core network via NG interface and may be connected to other gNB entities via Xn interface and 4G eNB (Evolved NodeB) entities via X2 interface. New features of 5G core network include local hosting of services, edge computing and network slicing. In case of edge computing, services may be implemented inside the core network close to the point where the user is accessing the network. This reduces latency and improves reliability of communications. Network slicing allows different applications to be provided different quality of service by the 5G network. A network slice has been defined as "a (set of) element(s) of the network specialised in the provisioning of a certain (type of) service(s)" (3GPP 2019). Specifications of 5G include three pre-defined slices: type 1 (for support of eMBB), type 2 (for URLLC) and type 3 (MIoT). Other slices may be defined by individual operators. The 5G system includes a new radio interface NR (New Radio). In total, 36 frequency bands were specified for NR in 3GPP release 15 between 663 MHz and 40 GHz. Most of the frequency bands were specified for frequency division duplex (FDD) or time division duplex (TDD) transmission while others are used as supplementary uplink (SUL) or supplementary downlink bands. While 3GPP release 14 introduced support for V2X services in LTE, release 15 defined enhancements for support of V2X scenarios. These included vehicle platooning, advanced driving, extended sensors and remote driving.

Release 16 (3GPP 2022a) of 3GPP reached status "frozen" on 3rd July 2020 (3GPP 2022b). Release 16 introduced 5G-V2X (fifth generation vehicle to everything) and sidelink communication with the NR (new radio) interface used in 5G. NR sidelink communication includes two modes of resource management in a way similar to LTE sidelink. In NR sidelink mode 1, resources are granted dynamically to user equipment (UE) by the gNB. In NR sidelink mode 2, the resources to be used for transmitting are selected by the user equipment. The NR sidelink may operate on the 5.9 GHz frequency band for ITS as well as licensed frequency bands specified for 5G. It is also foreseen that NR V2X sidelink and LTE sidelink may co-exist in the same user equipment.

In addition to NR-V2X (5G-V2X) sidelink communication, release 16 provides also other improvements specifically developed for V2X communication:

- improvement of V2X service handling
- architecture enhancements for 3GPP support of advanced V2X services
- application layer support of V2X services.

Work item "improvement of V2X service handling" has provided requirements for quality of service support for vehicular communications. The aim of the planned feature is to inform a V2X application on the anticipated or estimated change in the quality of service (QoS). This would allow the V2X application to react to changes in QoS in communication (e.g. platooning vehicles to reduce headways between vehicles). (3GPP 2022a)

Work item "architecture enhancements for 3GPP support of advanced V2X services" has defined two reference points for V2X communication in its architectural reference model:

- PC5 reference point (NR PC5 RAT, LTE PC5 RAT)
- Uu reference point (NR, E-UTRA). (3GPP 2022a)

The characteristics of the reference points are summarized in Table 4.

Table 4. PC5 and Uu reference points in New Radio (NR) and LTE (Long-term Evolution).

	LTE PC5	**LTE Uu (E-UTRA)**	**NR PC5**	**NR Uu**
Unicast mode	Yes (3GPP 2021)	Yes (3GPP 2020)	Yes (3GPP 2021)	Yes (3GPP 2021)
Groupcast mode	Yes (3GPP 2021)	No (3GPP 2020)	Yes (3GPP 2021)	No (3GPP 2021)
Broadcast mode	Yes (3GPP 2021)	No (no broadcast transmission by UE, V2X application server may send	Yes (3GPP 2021)	No (3GPP 2021)

		broadcast messages via MBMS (multimedia broadcast multicast service) (3GPP 2020)		
Available when UE served by E-UTRA	Yes (3GPP 2022c)	Yes	Yes (3GPP 2021)	No
Available when UE served by NR	Yes (3GPP 2022c)	No	Yes (3GPP 2021)	Yes
Available when UE not served by E-UTRA and not served by NR	Yes (3GPP 2022c)	No	Yes (3GPP 2021)	No

The development of the 5G and NR-V2X (5G-V2X) continues in 3GPP Release 17 which is expected to reach status "freeze" in summer 2022 (3GPP 2022b). The release will include e.g. enhancement of NR sidelink, improvements of Industrial IoT / URLLC communication, NR sidelink relay functionality, enhancements to V2X services and specification for edge computing in the 5G system (3GPP 2022d). The work carried out by 3GPP on V2X, with focus on radio access network (RAN), is summarised in Figure 1.

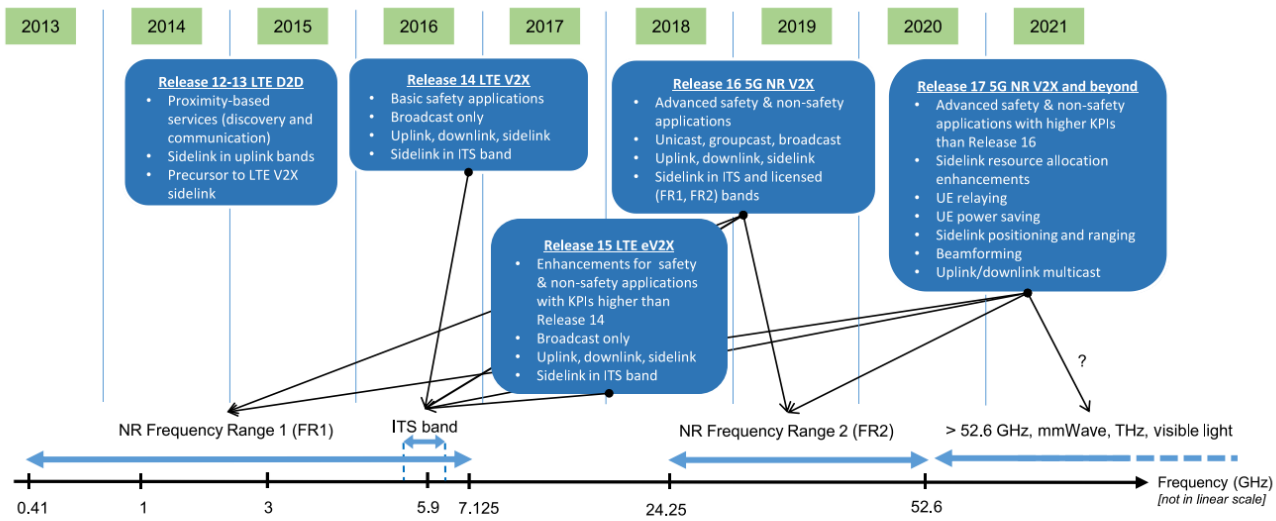

Figure 1. Progress of 3GPP work on V2X with a focus on RAN (Garcia et al. 2021) (the figure is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/).

6.2.3 Plans for 6G

The development of vision for 6G networks and identification of requirements has already started. Expected new usage scenarios include super-high-definition (SHD) and extremely-high-definition (EHD) video, extremely low latency communications for industrial internet, support for Internet of Nano-Things and Internet of Bodies, support for underwater and space communications, consistent service experience in emerging scenarios (e.g. hyper-high-speed railway) and improvements in 5G vertical applications such as autonomous driving. The requirements identified for 6G include 10-fold increase in bandwidth when compared to 5G, latency of 10–100 us (for physical layer) combined with high mobility (speed 1000 km/h or higher), support for high connection density (up to ten mission devices in km^2) and improvements in energy efficiency and spectrum efficiency compared to 5G. (Zhang et al. 2019)

Critical challenges have been identified for 6G (Tataria et al. 2022). These include (e.g). implementation of radio transceiver components and antennas in frequency bands planned for 6G, achieving low communication latencies and maintaining backwards compatibility with earlier technologies such as 5G.

6.2.4 Current status and future development of ITS-G5

The C-ITS architecture supports several physical and data link layer technologies. One of them is IEEE802.11p based communication on the ITS-G5 5.9 GHz frequency band (ETSI 2020). The specification for IEEE802.11p physical and data link layers was published in 2010 (IEEE 2022a).

In 2018, IEEE started the development of a new specification for V2X communications, IEEE802.11bd (IEEE 2018). The approval of the IEEE802.11bd specification is expected at the end of 2022 (IEEE 2022b). According to the results of a simulation study, IEEE802.bd will provide substantial improvement over IEEE802.11p in terms of maximum transmission range and a slightly increased robustness against interference (Jacob et al. 2020). On the other hand, the use of the dual carrier modulation and range extension features increase the possibilities of congestion of the radio channel (Jacob et al. 2020).

6.2.5 The reliability of communications

The INTERCOR project evaluated C-ITS services implemented with ITS-G5, LTE uu interface and a hybrid communication solution (Crockford et al. 2020). The evaluations were carried out in four pilot sites (Belgium/Flanders, France, The Netherlands and United Kingdom). The technical evaluation carried out in the project included communication performance, PKI (public key infrastructure) used in C-ITS, quality of information provided to the user and service-level aspects such as interoperability and continuity of service. For measuring communication performance, four key performance indicators (KPIs) were used: communication delay, communication range and neighbourhood awareness ratio (V2I communication only). For I2V messages transmitted over the LTE uu interface, the average latency was near 150 ms. For some messages, latency was more than 1s. For V2I messages, the corresponding average latency was 169 ms, and the highest observed latency was 95.293s. The packet delivery ratio was 92% of I2V messages for the areas not fully covered by LTE network, 90% for V2I messages for areas not fully covered by LTE network and 100% in urban environments. For ITS-G5, the latency was 5–81ms for I2V messages. For V2I messages transmitted over ITS-G5, the largest observed latency was less than 1s. In the French test site, the mean of the latency was 236.9ms. In the Belgian test site, the median of the latency was 4 ms. The effective communication range (ECR) of ITS-G5 was about 200m on a motorway on the Dutch test site. In the UK test site (corridor on M2), the effective communication range was about 450–550m, but this was reduced to about 250–300m for roadside units near a railway line. At another location on the UK test site (Kent), the effective communication range was 800m. On the Belgian test site, different RSUs were found to have different effective communication range (275–650m). In this study, effective communication range was defined as a distance corresponding to packet delivery ratio of 75%.

A comparison of 5G-V2X, LTE-V2X, IEEE802.11bd and IEEE802.11p physical layers has been carried out in a study based on a theoretical analysis of the technologies and simulations. The simulation results showed that LTE-V2X and 5G-V2X achieved higher packet reception ratios in the analysed scenarios (packet size of 100 or 1500 bytes, distances 0–500m, modulating and coding schemes evaluated in the paper). (Anwar, Franchi and Fettweis 2019)The latency of data transmission over LTE PC5 sidelink, ITS-G5 and LTE uu interface in V2I and V2V scenarios has been compared in a recent study carried out in real highway environment (Maglogiannis et al. 2022). For vehicles traveling to the same direction, the latency in V2V scenario was 30ms or less for more than 90% of packets transmitted over PC5 sidelink provided by C-V2X. For packets transmitted over ITS-G5, the latency was 5ms or less for more than 90% of packets. The overall picture was very similar in I2V scenarios: 90% or more of packets transmitted over C-V2X sidelink from RSU to vehicle arrived in 30ms, while about 95% or more of packets transmitted over ITS-G5 arrived in 5ms.

Communication latencies in eMBB (enhanced mobile broadband) scenario of 5G were measured in a field test carried out in Finland. The mean latency from IP network to vehicle was between 65.9 ms and 130 ms, depending on vehicle speed (measured for 5, 10, 15, 20, 30 and 40 km/h) (Kutila et al. 2021). In the URLLC (ultra reliable low latency communications) scenario of 5G, latencies are expected to be substantially smaller.

6.2.6 Connectivity options – Costs of providing connectivity and impact on road network coverage

The costs of installation of ITS-G5 roadside units and upgrading of roadside ITS systems on highways to support ITS-G5 communication have been estimated by Degrande et al (2021). The assumed costs of roadside units are summarized in Table 5 and Table 6. The cost values presented in the tables were used as a starting point before taking into account the decrease of unit cost with increase in volume or any learning curve effects. When the analysis was carried out, it was also assumed that electric power and fibre optic connections are available along roads to be equipped, and a TMC already exists. The unit cost values provided in the tables apply to both installation of new RSUs and upgrading existing RSUs. The authors also concluded that unit costs of RSU deployment are likely to decrease with increasing number of deployed RSUs.

Table 5. Capital expenses of C-ITS RSUs, adapted from (Degrande et al. 2021), (the table is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/)

Cost category	RSU type	Amount [€]	Source
Hardware	Upgrade	3000	(Asselin-Miller et al. 2016)
Hardware	New	6000	Interviews within the CONCORDA project (Connected Corridor for Driving Automation)
Installation	Upgrade	5600	Based on (Asselin-Miller et al. 2016), interviews within the CONCORDA project (Connected Corridor for Driving Automation)
Installation	New	28000	Based on (Asselin-Miller et al. 2016), interviews within the CONCORDA project (Connected Corridor for Driving Automation)
Hardware – replacement	New/Upgrade	3000	Based on (Asselin-Miller et al. 2016)
Installation – replacement	New/Upgrade	5000	Based on (Asselin-Miller et al. 2016)
TMC (traffic management centre) integration	New/Upgrade	1500	Based on (Asselin-Miller et al. 2016)

Table 6. Annual operating expenses of C-ITS RSUs, percentages based on capital cost in Table 5, adapted from (Degrande et al. 2021), (the table is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/)

Cost category	RSU type	Amount [€]	Source
Hardware	New/Upgrade	5%	(Asselin-Miller et al. 2016)
Software maintenance TMC	New/Upgrade	10%	(Asselin-Miller et al. 2016)
Energy	Upgrade	15	Based on (Asselin-Miller et al. 2016)
Energy	New	35	Based on (Asselin-Miller et al. 2016)
Communication license	New/Upgrade	15	Interviews within the CONCORDA project (Connected Corridor for Driving

			Automation
Communication security	New/Upgrade	40	Based on (Asselin-Miller et al. 2016)

The costs of 5G deployment on road networks have been estimated by The 5G Infrastructure Public Private Partnership (5G PPP) Automotive Working Group (5G PPP Automotive Working Group 2019). Assumed costs of 5G implementation on the road network are summarized in Table 7. In the techno-economic analysis carried out, distance of 1km between 5G sites has been assumed.

Table 7. Costs of 5G implementation on the road network, data according to (5G PPP Automotive Working Group 2019).

Cost item	Value	Unit
Capital expenses		
5G site	64,000	EUR/site
Civil works	20,500	EUR/site
Fibre backhaul	23,000	EUR/km
Operating expenses		
Network operation	10	percent of total capital expenses
Site lease	5,700	EUR/site

More unit cost values for 5G deployment for V2X communication have been published in a business feasibility study by the 5G PPP (The 5G Infrastructure Public Private Partnership 2019). The report identified four deployment scenarios (Minimum 5G scenario, Classic 5G Scenario, Breaking 5G Scenario and Future proof 5G Scenario) and provided unit cost values for roadside backhaul network, 5G cellular network and V2I infrastructure (roadside units) (Table 8).

Table 8. Deployment costs of a 5G corridor, data according to (The 5G Infrastructure Public Private Partnership 2019).

Cost item	Value	Unit
Backhaul network	12000–19000	EUR/km
5G cellular network, site cost including installation	90,000	EUR/site
5G cellular network, 5G site upgrade (upgrade of existing radio site)	40,000	EUR/site
Roadside Unit cost, including installation	5000–20000	EUR/site

The costs of V2I communication implemented with C-V2X and ITS-G5 have been compared in a study funded by 5G Automotive Association (5GAA) (Nokes et al. 2020). The study analysed four deployment options: A (solution based on LTE uu interface), B (LTE uu interface and roadside unit equipped with IEEE802.11p), C (LTE uu interface and roadside unit equipped with LTE sidelink) and D (LTE uu interface and roadside unit with IEEE802.11p and LTE sidelink). The main focus of the study was in C-ITS applications described by the European C-ITS Platform. Of the analysed technologies, IEEE802.11p and LTE sidelink (PC5) were considered to meet the requirements for latency and reliability of communications of the V2I services listed in the report (mainly Day-1 and Day1½ C-ITS applications). The latency of communication via LTE uu interface was concluded to meet applications' requirements for latency most of the time, but it was seen as uncertain whether the requirements for latency can be met everywhere on the road network all the time.

6.3 Position technologies for CAD

Positioning is required in the global sense for routing and in the local sense to enable the vehicle to plan its exact path. For global routing, a GNSS-based solution is enough, as this is already in use in many non-automated vehicles. However, automated vehicles have requirements for accuracy, availability and integrity that are difficult to cover with pure GNSS-based solutions. No consensus exists yet on a solution covering all of them (Rehrl & Gröchenig, 2021). The requirements depend on the manoeuvre performed or use case targeted, but the requirements of 10-50 cm of accuracy, update rate of 100 times a second, integrity of 10^{-8} per hour, and availability of 99% have been proposed (Reid et al., 2019; European Commission, 2018; Jing et al., 2022).

The current GNSS constellations do not provide this level of accuracy. Moreover, the availability requirements also pose a problem, since the GNSS signal can suffer from interference or be blocked completely, especially in urban setting. In order to meet the requirements, the positioning system of the vehicle could utilize information from either other sensors or from other vehicles or infrastructure.

The GNSS signal can be augmented in various ways. GNSS receivers at known locations can be used to estimate errors and provide correction information (DGPS), cellular networks can be used to reduce delay in obtaining the position (AGPS), dual-frequency GPS receivers with known base stations can be utilized to estimate the position with centimetre level accuracy (RTK-GPS) (Kuutti et al., 2018; Yurtsever et al., 2020; Jing et al., 2022; European Commission, 2018). These, however, still suffer from common GNSS availability and reliability problems and require extra infrastructure that is unlikely to be available everywhere. The GNSS signal is also often enhanced with an Inertial Measurement Unit and other sensors that report information about the orientation and forces applied to the body of the vehicle and, for example, wheel speed and steering wheel position. When the last known GNSS location is combined with this information, the current location can be estimated more accurately.

These methods rely on the availability of the GNSS signal and, thus, do not meet the performance requirements of automated vehicles due to atmospheric conditions, multipath interference and signal blocking by infrastructure or tall buildings (Yurtsever et al., 2020; Bresson et al., 2017). The vehicle should use information about the environment that is available in situations where the GNSS signal is not available. The object detection system of the vehicle uses various sensors (e.g. cameras, lidar and radar) and the utilization of them for positioning has been studied. There are two general approaches: matching the sensor information to a priori known map information and Simultaneous Localization and Mapping (SLAM), where the ultimate goal is to perform both the map making and localization at the same time without any a priori high definition map available.

A common approach with a map matching to a known map is landmark search (Yurtsever et al., 2020; Kuutti et al., 2018), where the system uses the same object detection system already in use in the vehicle to extract landmarks out of the sensor data and then match those to the landmark objects stored in the map. Knowing the distance to a known landmark will give the position and orientation of the vehicle. This has been shown to provide positioning that is accurate enough to meet the requirements (Kuutti et al., 2018). However, the approach cannot work if there are no suitable landmarks, and installing them will increase the costs of relying on such a system. Landmark search performance is also degraded by harsh weather conditions. Comparing the whole point cloud map provided by the sensors to a point cloud map leads to better performance, but is more computationally expensive, and still suffers from poor weather conditions. Both methods are also difficult to implement for whole road networks, since the map of the environment has to be known beforehand and the creation of the map for the whole world is an expensive undertaking.

The ultimate goal of Simultaneous Localization and Mapping (SLAM) approaches is to avoid the map creation process completely and allow the vehicle to drive automatically from the very first time and iteratively improve the map in consecutive passes of the area, perhaps in collaboration with other vehicles by sharing the map data (Bresson et al., 2017; Yurtsever et al., 2020). This would offer the major benefit of being able to work anywhere. SLAM approaches have been shown to work for indoor mobile robots, but the current methods are not there yet and are not sufficient for autonomous driving setting (Bresson et al., 2017). Even though SLAM is one of the key enabling technologies when making automated driving functions adaptive to new environment, there are lot of challenges related to reliability. The main issues are sufficient resolution vs. range of the sensing devices and performance degradation due to adverse weather. Mapping itself is well known technology from indoor robotics but recognising an object reliably in safety critical on-road situations remains

unsolved. However, sensing devices are steadily improving and we may assume that collaborative sensing where more than one vehicle is updating mapping data will enhance SLAM within next 5-10 years.
Since on-board positioning systems have drawbacks, cooperative positioning techniques have been suggested to augment the sensor information of individual vehicles, either with V2V or V2I. Positioning by V2V uses the positioning information and signal characteristics from multiple adjacent vehicles as well as the distance to the adjacent vehicles to calculate the position of the "ego" vehicle (the vehicle whose sensor inputs and movements are being analysed) via multilateration (also known as hyperbolic positioning - the process of locating an object by accurately computing the time difference of arrival (TDOA) of a signal emitted from the object to three or more receivers).
The higher the penetration rate of cooperative positioning techniques the better the positioning accuracy, but this relation is not linear. The communicating vehicles in the fleet require self-positioning methods to share their own position. Thus, some of the vehicles in the fleet require a way to get an accurate position and multilateration alone is not adequate for automated driving, which is why it should be seen as a redundant positioning system that, when integrated with the on-board sensors, enhances the overall positioning accuracy. In V2I solutions the vehicles communicate with roadside units or cellular base stations with known, fixed locations. 5G-based V2I appears to meet the requirements for automated vehicles, but the high cost of the infrastructure required to provide the position reliably and in a way that guarantees high availability is a major disadvantage. For both V2V and V2I the optimization of the network parameters and routing protocols will be a challenge, since poor communication greatly reduces the effectiveness of the positioning, but the parameter modifications can lead to channel congestion, and because the driving behaviour and density of the vehicles is different in urban and motorway environments. (Kuutti et al., 2018).
As can be seen from the review of the recent material above, each positioning technology comes with its benefits and tradeoffs, as well as conditions where they perform well, in a degraded way or not at all. Few of the technologies work well enough to meet the accuracy requirements alone and when they do, they are not guaranteed to always be available. Thus, a fusion of technologies is the most likely solution to develop a positioning system that can provide an accurate location across the whole road network. This fusion will happen both within the vehicle and between the vehicle and its environment. GNSS-based systems provide the backbone and rough position estimate, which is then enhanced with on-board sensors and possibly V2X technologies. Improved GNSS signal from newer generation of satellites and using multiple constellations will enhance the base level position, but other methods are still required for environments where the GNSS signal is not available and reliable. All the various approaches that can be used in positioning calculations have their strengths and weaknesses, and thus a combination of GNSS, sensor-based enhancements, V2V-based support, and targeted V2I-based solutions for carefully selected road environments seems like the most cost-effective way to provide a road network wide coverage. If the research on SLAM-based methods succeeds to provide a solution where the vehicle is able to drive, locate and map its environment from the very first pass, then that would be the most cost-effective way, since it would require limited infrastructural investments and no a priori map generation of the whole network, but certain environmental conditions could still pose a problem given the reliance on sensor data.
It is unlikely that GNSS-based solutions will provide many extra services, apart from timing information. Galileo provides the Search and Rescue Service, which transmits the location of the user to the authorities and acknowledgement message back to the sender that the request for help was successfully received, but the search did not find any new services planned specifically for automotive use. The on-board sensors of the vehicles are utilized for many reasons to enable automatic driving, but whether they provide services is a matter of definition. For V2X-based solutions, it is perhaps more appropriate to see positioning as a service that they can provide, rather than V2X positioning technologies providing extra services.
We have only considered the positioning of the ego vehicle. However, it should be noted, that same

sensors in a non-cooperative approach and same V2X technologies in a co-operative approach can be used to determine the relative positioning of other road users and there, too, the fusion of both approaches appears to offer the largest benefits (de Ponte Müller, 2017).

6.4 Road-side infrastructure

The objective of the activity was to identify the roadside infrastructure which could support and improve the performance of automated vehicles. Potential roadside systems were identified based on the results of a literature study, results of stakeholder consultation carried out in WP1 and the knowledge of the authors.

A number of infrastructure services have been described in the ETSI Basic Set of Applications (ETSI 2021). These include the Traffic Light Manoeuvre service (TLM), Road and Lane Topology service (RLT), Infrastructure to Vehicle Information service (IVI), Traffic Light Control service (TLC) and GNSS Positioning Correction service (GPC) (ETSI 2021). The Traffic light manoeuvre service provides information on the timing and phase of traffic signals at controlled intersections. The Road and lane topology service provides information on the geometry of lanes in defined areas of road infrastructure (e.g. an intersection) and the allowed manoeuvres. Infrastructure to vehicle information service (IVI) provides information on traffic signs such as speed limits and road works sites. Traffic light control (TLC) service allows a public transport vehicle to request traffic signal priority by sending a message to roadside ITS station and allows an emergency vehicle to request traffic signal pre-emption. GNSS Positioning Correction service (GPC) provides GNSS position correction data over short-range radio connection or mobile network from roadside stations to mobile stations. The messages used to provide the service support allow position corrections to be provided with different options (e.g. RTK, GPS and GLONASS).

In case of highly automated vehicles, the vehicle may be able to read many elements in the road network with its own sensors. These include, for example, the ability to use a camera to detect the status of traffic lights, read static and variable traffic signs and read the lane markings. However, the availability of the same information as standardized messages is likely to improve the robustness of vehicle operation. In a dynamic traffic environment, traffic lights may be occluded by other vehicles. In complex intersections, selecting the right lane may require reading and interpreting the names of road signs with names of cities or other destinations. In winter conditions, an automated vehicle may be unable to identify lane markings on a road surface covered by ice and snow. A highly automated vehicle will likely be able to identify traffic signs using a camera. However, optical detection of traffic signs is likely to be affected by heavy rain, snowfall or fog. The digital map available in an automated vehicle may also include information on traffic signs and traffic rules. However, this information is not necessarily updated in real time. For example, temporary traffic signs are frequently used at road works sites to warn of possible hazards and to set a temporary speed limit.

Magnetic guidance systems for lateral control of automated vehicles have been developed since 1950s (RCA 1958). In addition to lateral guidance, magnetic systems are also able to provide information about longitudinal position of the vehicle (Kamewaka and Uemura 1987). At least one car manufacturer has recently been studying the use of road magnets as a positioning solution for highly automated vehicles (Volvo Cars 2014). Magnetic guidance systems can be expected to be relevant especially in situations in which lane markings on the road surface cannot be assumed to be visible (e.g. winter conditions), positioning based on identification of landmarks is unreliable (e.g. due to lack of suitable landmarks or poor visibility conditions) and GNSS signals are not available. These include situations with unintentional radio frequency interference and deliberate attacks on GNSS such as jamming or spoofing of GNSS signals.

More opportunities to support automated vehicles with roadside systems were identified in the stakeholder consultation carried out in WP1. Some roadside ITS stations may be equipped with accurate sensors measuring environmental conditions and status of the road surface. These stations could provide sensor calibration services to automated vehicles passing by. Roadside stations with known location could also be equipped with GNSS receivers to detect jamming of GNSS signals or unintentional radio frequency interference, e.g. by comparing the known position of the roadside station to the position obtained from the GNSS receiver.

6.5 Vehicular technologies that support CAD

Vehicular technologies focusing on different levels of Automated Driving (AD) have rapidly developed. Widely used levels of driving automation (levels 0–5) have been defined by SAE (SAE 2021). Today, most passenger cars are on levels 1-2, where drivers are still in charge of the driving task, and Advanced Driver Assistance Systems (ADAS) helps the driver or provides partial automation. The first level 3 automated driving vehicles are now starting to emerge on the roads. The road infrastructure will need to support both human drivers (with ADAS) and AD vehicles for many years to come.

ADAS and Automated Driving features use similar in-vehicle technologies. The systems are based on the information from various sensors. The data coming from the sensors is typically processed in vehicle computing units locally. The vehicle sensors measure motion, speed, acceleration, etc. Environment perception sensor systems (such as cameras, radars and LiDARs) are used to detect lane and road markings, detect and classify traffic signs, obstacles and other road users (vehicles, pedestrians and other vulnerable road users). In addition, the same sensors are used in automated driving to detect free drivable area, driving path and even state of the traffic lights as well as for landmark-based localization of the vehicle. In this chapter we focus only on environment perception sensors which are linked to the road infrastructure and therefore NRAs. Road weather information systems are also mentioned in the end of this chapter.

6.5.1 Sensors and their limitations

Cameras are the most widely used sensor for environment perception in vehicles. Automotive image sensors provide full colour high resolution video images. However, cameras need (visible) light. Therefore, they do not work in darkness and their operating conditions are limited in poor weather conditions (like rain, fog, etc.). In addition, an excess of light causes overexposure and sudden changes of lighting conditions can blind the cameras.

Automotive Radar (Radio Detection And Ranging) detects and localises objects using radio waves. It also provides the speed of the detected objects. Radar is widely utilized for ADAS and AD. A major drawback of radar is that it provides quite low-resolution information about the detected objects, and is very sensitive to metal which can lead to false positive detections (Chen et al. 2021). LiDAR (Light Detection And Ranging) is a relatively new and still quite expensive sensor in the automotive sector and has been adopted to only a few passenger cars on the market today (Arstechnica 2020). LiDAR can provide accurate 3D data around a vehicle and detect lane markings through reflectivity. It is less sensitive to lighting conditions than a camera but LiDAR's performance also degrades under harsh weather conditions.

Sensor fusion is used to bring together inputs from multiple sensors and balance their strengths and limitations. State-of-the-art sensor fusion provides some enhancements for vehicle environment perception but there are still limitations in certain conditions. Artificial Intelligence (AI) is used more and more in environment perception sensors and in sensor fusion. Machine Learning (ML) is utilized especially for detection and classification applications. In good conditions, the performance is very good but there are some lighting and weather conditions where the performance still is not adequate for safe automated driving.

In addition to sensors and sensor fusion, ADAS and especially automated vehicles use high-definition (HD) maps, which are typically used for AD path planning together with Global navigation satellite system (GNSS), LiDAR, radar and camera to localize the vehicle. HD maps provide a detailed map of pre-recorded road geometry and infrastructure including landmarks which the vehicle sensors should be seeing.

In-vehicle sensor fusion may be employed to add redundancy for detecting objects. Of the different in-vehicle sensors, only cameras can be used for detecting traffic signs and road markings and determining the driving path of an automated vehicle in real time. For adding redundancy, a high-definition map will be needed to support the processing of camera data (Mobileye 2022).

Typically, road authorities will not own or operate HD or digital maps but may have input into attributes and changes in the map (Somers 2019). Another method to increase redundancy with vehicle sensors is to utilize V2X communication which is especially needed to communicate with critical local infrastructure such as traffic lights (status information).

6.5.2 Road infrastructure machine readability

The quality of the road infrastructure design and maintenance may influence the performance of vehicle sensor systems. When considering the limitations of the in-vehicle sensors, machine learning and sensor fusion systems mentioned above, we can try to identify some requirements that are related to the machine readability of the physical road infrastructure. Mihalj et al. (Mihalj et al. 2022) have listed limitations and advances of the road infrastructure related to camera-based traffic sign recognition systems (TSRS) and lane support systems (LSS) in their road infrastructure challenges for Automated Driving review. Both TSRS and LSS are mature technologies which are widely used in the vehicles today, but similar technologies are utilised as important components in many more advanced ADAS and future AD features. Tables 9 and 10 present a list of road infrastructure limitations for TSRS and LSS and requirements for NRAs. The lists are modified from Mihalj et al. review study by selecting the factors related to NRA's infrastructure and adding new requirements for NRAs. More details about these issues have been discussed in the section contribution of task T2.1.

Table 9. Road infrastructure limiting, advance factors and NRA potential involvement for TSRS (modified from Mihalj et al. 2022)

Limiting factor	**Advances**	**NRA potential involvement**
Even small changes in the traffic sign appearance caused by damage or graffiti result in low performance Incorrectly positioned signs, such as irregular lateral distance or severe angular rotation, rotated by more than 75 degrees, causes issues for TSRS	Digital maps and short-range communication provide a link between vehicle and road while introducing additional redundancy and robustness	Traffic sign maintenance needs to be enhanced Automated (crowdsourcing) monitoring of the quality of traffic signs should be considered Provide up-to-date digital map information about static traffic signs and consider V2X
Different retroreflectivity levels may impact the detectability and readability of traffic signs	Higher grade retroreflective material (sheeting) improves overall visibility under all environmental conditions and increases robustness regarding sign degradation over time	Utilize and update signs with higher retroreflection class
Flickering of electronic signs		Refresh rate of the VMS need to be checked
TSRS systems cannot currently interpret text qualifications		Consider V2X messaging
Traffic sign design issues for TSRS: Co-located traffic signs that apply to different motorists or are time-dependent and weather-based Similarity in shape between the	Digital maps and short-range communication provide a link between vehicle and road while introducing additional redundancy and robustness	Provide up-to-date digital map information about static traffic signs and consider V2X (International) Harmonization of traffic signs

numerals (e.g., 30, 60 and 80 km/h) Similarity in shape and colours Signs not installed by traffic authorities: signs printed on rubbish bins, heavy vehicles		

Table 10. Road infrastructure limiting, advance factors and NRA potential involvement for LSS (modified from Mihalj et al. 2022)

Limiting factor	Advances	NRA potential involvement
Challenging weather and light conditions are strongly negatively correlated with lane detection. Foggy conditions are much more of an issue than rain. Multiple lane markings, such as at construction sites or residuals of old markings, can lead to misinterpretations Road surface with debris, potholes or cracks can be misinterpreted by the lane detection system	To ensure good visibility of road markings, the luminance coefficient night-time visibility should be kept at least in the range between 100 and 150 mcd/lx/m2, while daytime visibility should be between 130 and 160 mcd/lx/m2 (and with a contrast ratio of 3-to-1) *Retro-reflectivity in wet conditions should be between 50 – 75 mcd/lx/m2	Real-time road weather systems with state-of-the-art visibility measurements Automated (crowdsourcing) monitoring of the quality of the road surface and lane markings should be considered Lane marking and road surface maintenance need to be enhanced
Some coloured road markings lower the contrast ratio between markings and pavements Discontinuous markings (e.g., intersections) and lanes that are not normal result in worse performance of lane detection methods	Increasing the width of markings from 100 to 150 mm makes them easier to detect Using profiled or agglomerate markings to raise profiles with retroreflective materials in order to reduce flooding and promote water drainage Implementation of all-weather marking that uses high-quality optics to provide a high level of visibility under diverse weather and visibility conditions	(International) Harmonization of road markings Lane marking maintenance need to be enhanced

* (Somers 2019)

6.5.3 Potential NRA involvement

Tables 9 and 10 listed some requirements for NRAs related to better detection of traffic signs and lane markings needed for many ADAS and AD features. The traffic signs and lane markings need to be in good condition, visible, clean and in correct position, therefore high level of road infrastructure maintenance is needed to increase the reliability of environment perception systems. As stated in task T2.1, improved road signs and markings provide support to CAVs as well as improve safety for non-connected or automated vehicles. The quality of road infrastructure can be monitored in real-time with the similar AI technologies (e.g. camera or LiDAR-based road surface defect measurements) by utilizing crowdsourcing which enables reduced costs and on-demand maintenance (Vaisala 2022). Harmonization of traffic signs and road markings in EU or global level is needed, and their design needs to take into account ML technologies. Unharmonised traffic signs and lane markings in different countries result in higher efforts and data collection costs for ML training. Improving traffic signs, lane markings or sensor systems will not completely remove the previously mentioned limitations regarding harsh weather conditions or poor or damaged signs or markings. V2X communication and/or digital maps (with accurate location information) are needed for redundancy. NRAs have to provide inputs for these.

For specific road sections, there may be some additional requirements. For example, in tunnels new lighting requirements might be needed to avoid problems with the change of brightness or glare in tunnel entries and exits. In addition, animal fences are still needed for ADAS equipped and AD vehicles even though some progress has been made to detect large animals like moose or deer with automotive vision systems. In Nordic countries, winter maintenance (e.g. snow removal) is needed and has to be agreed with AD vehicle operators in the area.

The European ITS Platform has defined a roadmap and action plan to facilitate automated driving on TEN road network (EU EIP 2020). In this report, authors have defined a concept of ODD-aware traffic management, where ODD refers to Operational Design Domain that is a description of the operating conditions under which a driving automation system or feature is specifically designed to function. The report describes three kinds of information needs of highly automated vehicles (EU EIP 2020):

1. Real-time information on incidents, roadworks, events, congestion, and other traffic disturbances
2. Information on the rules and regulations of any restrictions concerning automated driving.
3. Information on likely ODD termination risks due to events, incidents, weather forecasts or other issues

These three types of information could be provided by NRAs, but there are other sources where they also may be obtained.

A recent study by the Finnish Transport Infrastructure Agency on automated driving on motorways included an estimation of the impact of weather condition on automotive sensing performance (Innamaa et al. 2021). The study concluded that the most likely reasons for putting an automated vehicle outside its ODD are poor visibility and low friction caused by ice on the road surface (in Finland). Road maintenance carried out by the road operator or road authority and local road weather forecasts provided with ease of access and via standardised interface will support both manual and automated vehicles. While automated vehicles have no means to determine individually their perception capabilities and friction, this could be provided by the local traffic management system. The road weather stations could be enhanced e.g. with a system measuring signal attenuation on relevant sensor frequencies and frequency bands. The measurement could be carried out across the road at height of about one meter from the ground to take into account the effect of snowfall and spray or mist raised by passing vehicles. This real-time information could be added to the road weather information delivery to all ADAS equipped AD vehicles. (Innamaa et al. 2021)

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7 Benefit and Costs

7.1 Introduction

National Road Authorities (NRAs) are responsible for managing the Strategic Road Network for their respective Member States. To do so, NRAs maintain key road assets including road surfaces, bridges, markings and signs, gantries and road lighting etc. Proposed CAD schemes can impact these traditional asset classes, but also create new ones such as roadside infrastructure for CAD. This chapter aims to support NRAs when making spending decisions on their Strategic Road Network assets with respect to CAD.

It is assumed that the cost-benefit analysis will aim to address the need for effective use of public money to deliver a safe, smooth, reliable network, which supports environmentally friendly travel. In addition, proposals related to CAD may have wider implications – for example not directly associated with the assets affected, but the wider economy and society. NRAs should articulate these wider impacts to their respective economic ministries. A review mechanism should also be included within the cost-benefit analysis to evaluate the actual vs intended impacts of proposed schemes.

In order to ensure consistency in the analysis of the direct implications for the highway asset it will be necessary to adhere to the NRA's national economic appraisal guidance and transport modelling guidelines. It may also be necessary to build assumptions into the analysis such as uptake of the technology and the level of acceptance by the public. Authorities must assess the impact of such technologies over the agreed appraisal period. This exercise would typically result in the production of a range of Benefit Cost Ratios (BCRs) and Net Present Values (NPVs) for the proposal based on a range of uptake or effectiveness scenarios. Informed decisions can then be made based on the ranking of these metrics.

Further articulation would be required to understand the wider impact of emerging technologies. For example, driverless and other related technologies have the potential to fundamentally alter the economic and industrial landscape of the transport sector (e.g. potentially reducing the size of the driver workforce). However, they may also enable the domestic economy to become a development hub of new technologies (i.e. leading to growth in other sectors). The economy might also need to import new technologies, meaning further potential shifts in economic activities elsewhere. Although it is difficult to be confident of the order of magnitude, NRAs should make efforts to communicate possible development scenarios to their respective ministries. These scenarios could be precursors to future environments that are materially different to the status quo, in terms of the balance of costs between delivering and maintaining the road infrastructure and the other economic benefits achieved.

7.2 General methodology for appraising CAD on Strategic Road Networks

7.2.1 The key steps in the CBA process

This section focuses on establishing a general framework for NRAs conducting cost-benefit analyses. The structure of this process is not dependent on the scale of the scheme under review, i.e. a change to a single junction and a change to the whole strategic road network can be evaluated using the same process. The proposed steps of this methodology can be seen in

Figure *14*:

Figure 14: Cost-Benefit Analysis Flow Chart for National Road Authorities

The process starts with understanding the organisational core objectives. They can vary across states, but broadly speaking refer to managing roads to ensure safe, smooth, reliable and environmentally friendly travel. In some states, NRAs may have more direct responsibilities over the wider economic and social impacts. In that case, this should impact the NRAs' core objectives against which the cost-benefit analysis will be measured.

The second step is to list the options and document the assumptions underlying those options. Technology penetration, uptake, etc., will lead to very different scenarios for the realisation of the benefits. For proposals where NRAs have a low level of confidence over scenarios, NRAs could conduct workshops and stakeholder engagement to build consensus.

The third step is to tabulate the impacts of the proposed scheme on the core objectives. These impacts may include journey safety, average journey times and user costs. As part of presenting proposal impacts, NRAs need to document major assumptions concerning CAD proposals. This is further discussed in section 7.1.2.

The fourth step is to carefully model the magnitude of those impacts in accordinace with national economic appraisal guidelines. For many member states, the appraisal period is typically 30 years. The economic model will have schedules of annual benefits and costs. This stage of the process produces the core metrics of the Cost-Benefit Analysis. They include Net Present Values (NPVs) and Benefit Cost Ratios (BCRs).

NRAs do not always decide whether a project is worth pursuing in its own right. Often, the onus for NRAs is on prioritising projects with a fixed budget from the state's finance minstry. In determining which proposals should receive funding NRAs should rank proposals according to NPVs and BCRs, as well as capital investment requirements. Decisions can then be made based on objective criteria such as the highest NPVs. But NRAs should also consider the proposals' "additionality" effect. This is because approving certain proposals as a package might bring about more benefits or reduce costs than when individually implemented.

Having quantified the direct impacts, the NRA should then articulate the wider impacts to state and federal government bodies. These are mentioned above, and further discussed below. The authority or central government concerned can then make an informed decision on funding based on the quantified metrics (NPVs and BCRs) and the wider impacts. Finally, a review mechanism should be put in place as part of the Cost-Benefit Analysis to monitor how the outturns compare with forecasts. This forms part of the continuous improvement process for NRAs to understand how realised benefits and costs differ from predictions.

7.2.2 Establishing and documenting the options and assumptions (step 2)

In order to identify and quantify direct impacts, several major assumptions need to be reviewed, which are discussed in this subsection.

Communication and infrastructure needs of CAD

It is important for NRAs to grasp the key needs of CAD to understand the infrastructure needs. When defining CAD, consideration should be given to Connectivity as well as to Automation, and it is important to delineate between the various levels of automation in place. Figure 4 in WP2.3 describes the possible combinations between automation and cooperation levels set out by the Society of Automotive Engineers (SAE). For the highest levels of cooperation (Class D) and automation (Level 5), the Connected-Autonomous Driving System has full authority to decide, adhering to communication between on-road/on-vehicle sensors and the vehicles.

However, a Connected Vehicle may not require or utilise any level of automation. It may interact with infrastructure and other vehicles for sharing information such as accidents, weather, incidents, etc. To allow the connection to take place, there will be a need for a source layer to be established to allow the data to be transmitted. This layer will depend on the technologies utilised by the vehicle and also the dependencies (or not) on localised infrastructure, such as Roadside Units. Utilisation of mobile phone technology, either through integration of a user's phone with the system or through an existing SIM capability within the vehicle, will also need to be considered.
The ecosystem for a Connected vehicle may therefore include, amongst other things:

- Roadside Units
- In-vehicle units
- Mobile phone
- Mobile phone infrastructure (antennae)
- Cloud based processing
- Data Analytics/ Use of A.I
- Messaging control centre
- App (3rd party/ public units)

To establish a business case and cost benefit analysis for a Connected Vehicle, it is important to ascertain at first the cost associated with the elements outlined above and the savings of scale achievable should there be widespread adoption of CV services. This cost will then have to be measured against the savings or benefits introduced from Connected Vehicles, including:

- Improved safety through messaging between vehicles
- Reduction on use of infrastructure (such as variable message signs)
- Improved efficiency through co-ordinated and widespread equitable responses to prompts/guidance from NRAs.

However, it will be important also to assess how the market diverges in terms of service offering. Such divergence can originate depending on the band/model an individual purchases. For example, a top-end vehicle may come with a subscription service that provides more timely and accurate information than those who are on a non-premium information package. NRAs need to understand its role in CAD proposals as to how the private sector could/would utilise data. NRAs may find it more efficient to provide a facilitation role, rather than a direct engagement role. But this may change. Certainly, from a Roadside Unit (RSU) perspective, NRAs are actively involved in creating the service to exchange information, and this can also be linked to 3rd party elements.
An AV, or rather those vehicles that offer a level of automation, may or may not be connected. For user engagement and operational management, it is likely that the majority of AVs will include connected services. That said, there is also the possibility, from a cyber security perspective, that some elements or even all in relation to connectivity may not be made available. As such, the vehicle will operate in isolation from its environment. From a commercialisation perspective, however, this is not expected to be a wide percentage of the travelling public.
For AVs that are connected, a number of further challenges exist in terms of:

1. Utilisation of shared or full mixed mode utilisation
    a. Will the NRA require level-4 automated vehicles or above to use dedicated lanes? If not, there may be 'spring' effects as AVs look to conform to the law whereas other road users may not. If separate lanes are required, capacity might be restricted for non-AVs.
2. Physical environment requirements
    a. For some AVs, the utilisation of signs and lines will be required. For others, all sensors will be on the vehicle itself and therefore the requirements on the NRA will be less onerous. However, in either scenario, there is an implication on the readability of the infrastructure to facilitate automated operation. This will require the asset management process to be linked to the requirements of the automated vehicles and

may impact on the scheduling of infrastructure upgrades and the management of the condition of the signs and lines.

3. Digital Environments
    a. Is the NRA expected to support or cover the cost of communication technology (e.g., 5G) to support AV and CV, if the service being provided is undertaken by a private body?
    b. From a data and network operations perspective, will the NRA require necessary and new skills to allow for the provision of the data and at the same time, development of the data analytics to improve key performance indicators? This would improve operational efficiency but have an immediate short-term impact on staff requirements.
4. Digital Twins
    a. Will NRAs maintain a newly created digital twin in addition to existing maintenance regimes?

Influence of uptake

The uptake of CAD will affect road network infrastructure and connectivity requirements. For example, many car users value the flexibility offered by a private car. But the purchase price of highly automated vehicle will be higher than conventional ones. This may make vehicle ownership less attractive. In addition, the Covid-19 pandemic has had an impact on travellers' preferences (e.g., due to fear of infection using public transport), and probably also on travel demand (e.g., increased remote work).

Regarding infrastructure requirements by NRAs, the number of lanes needed might also be different between private ownership and sharing scenarios. Fewer vehicles and lanes could be needed if ridesharing becomes common. Therefore, long-term capital investment needs for maintenance could be lower if social preferences and price differentials encourage the creation of an autonomous ridesharing ecosystem.

Restrictions and technology levels

It is likely that for a long transitional period there will be a mix of traffic incorporating automated, connected, and traditional vehicles. The impacts of connected and automated driving will to some extent be dependent on the restrictions set for the circulation of automated vehicles by local and national authorities. The need to introduce restrictions may arise for several reasons. First, the circulation of automated vehicles may be restricted for safety reasons. For instance, the requirements of the operational design domain (ODD) of the vehicles might not be met on certain roads.

Second, restrictions in the operation of automated vehicles may be considered due to their potential to increase congestion. The increase in congestion may be related to increased travel demand induced by the new transport option. But congestion can also arise from changes in shares of different transport modes and the defensive driving nature of CAVs. In addition, a fully automated vehicle may also consume road capacity without a human driver. An extreme example of this would be an automated vehicle traveling around empty to avoid parking fees. In areas with severe congestion problems the circulation of privately owned automated vehicles may be restricted to reduce adverse impacts on shared modes and to prevent unsustainable levels of congestion. Empty trips made by automated vehicles may also be restricted to reduce energy consumption. Deployment scenarios with different combinations of restrictions for circulation of automated vehicles have been presented in Smit et al. (2021).

7.2.3 Identifying proposal impacts and quantifying direct impacts (step 3)

This subsection discusses the various categories of benefits and costs NRAs should focus on. We also suggest how NRAs might consult research papers and experts to quantify those impacts. These are essential to constructing the cost benefit model outlined in 2.7.1.4.

Considering proposal impacts

Enhanced Safety

Ensuring the safety of road users is one of the NRAs' key responsibilities, and hence the influence of CAD implementation on localised or overall safety on a network is an important component of the assessment. Farah et al (2018) highlighted that, although autonomous vehicles have the potential to enhance safety, there is uncertainty around "new" safety risks. NRAs should not allow the adoption of technological development without appropriate risk assessment. However, where NRAs are satisfied that proposed changes would enhance safety, economic modelling needs to be carried out.

On the benefit side, the relevant economic model would project the baseline Killed and Seriously Injured (KSI) trajectory under a Do Minimum scenario. This Do Minimum would reflect the "Business As Usual" that the NRA has already committed to. Against this Do Minimum scenario, NRAs would produce a Do Something series. This is an estimate that shows the projected figures resulting from the CAD proposal. NRAs can achieve this by studying the safety effects relevant technologies might have on their network over the duration of the agreed appraisal period.

These Do Minimum and Do Something figures should then be applied to the average KSI values for the NRA to obtain quantified safety values for the "Business As Usual" and proposed CAD scheme. By comparing the two resulting Present Values, NRAs would obtain an objective assessment of the safety impact of the CAD proposals.

Maintenance

NRAs carry out both routine and emergency maintenance to deliver safe, smooth and reliable road networks. To understand the impact of a CAD-related proposals on maintenance expense, NRAs would firstly establish the Do Minimum maintenance cost schedule. Then NRAs would focus on how the CAD proposals might impact the *overall* maintenance of the asset. For example, CAD infrastructure will require procurement and maintenance. However, this infrastructure also provides connection with connected and autonomous vehicles which may provide information on road condition. This could support a reduction in targeted surveys and/or improved or more efficient maintenance.

CAD may also improve the efficiency of road use. Similar to smart motorways with variable speed limits, a CAD scheme may be able to increase the consistency of flow. For instance, a proposal that allows truck traffic to be programmed at a certain flow rate may enhance structural robustness of the network. This may elongate the life of existing roads (reducing wholelife spending on maintenance). Furthermore, the road layout for CAD may be different to that required for manual vehicles. The design of junctions and roundabouts could change. Where relevant, NRAs could review the design requirements, e.g., the need for grade separated junctions, the geometry markings and signs. A streamlined design with improved efficiency (such as fewer instances of harsh braking and lower rates of minor collisions and reduced infrastructure complexity) could lead to less repair work over time.

Having considered the maintenance impacts the CAD proposals may have, NRAs can then produce the Do Something maintenance cost schedule. As

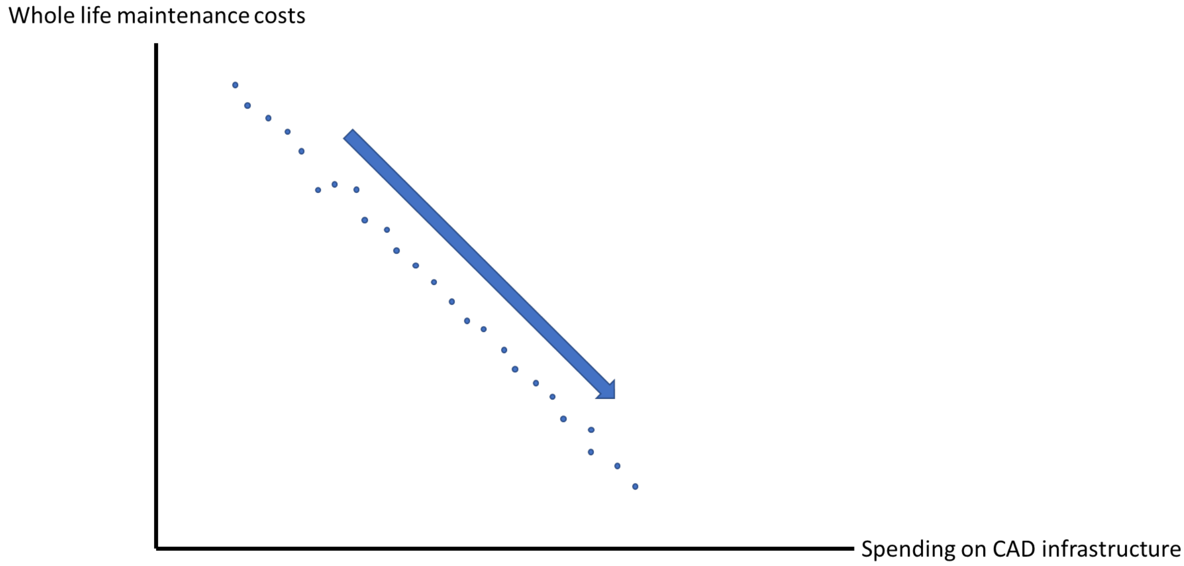

Figure *15* below points out, initial capital investment on CAD infrastructure might be justified if it lowers the overall wholelife cost schedules. The key metric is Present Value, which discounts costs in future years for like-with-like comparisons. As CAD investment and maintenance spending occur in different years, NRAs need to compare values using this common basis. 2.7.1.4 describes this cost benefit model in more detail.

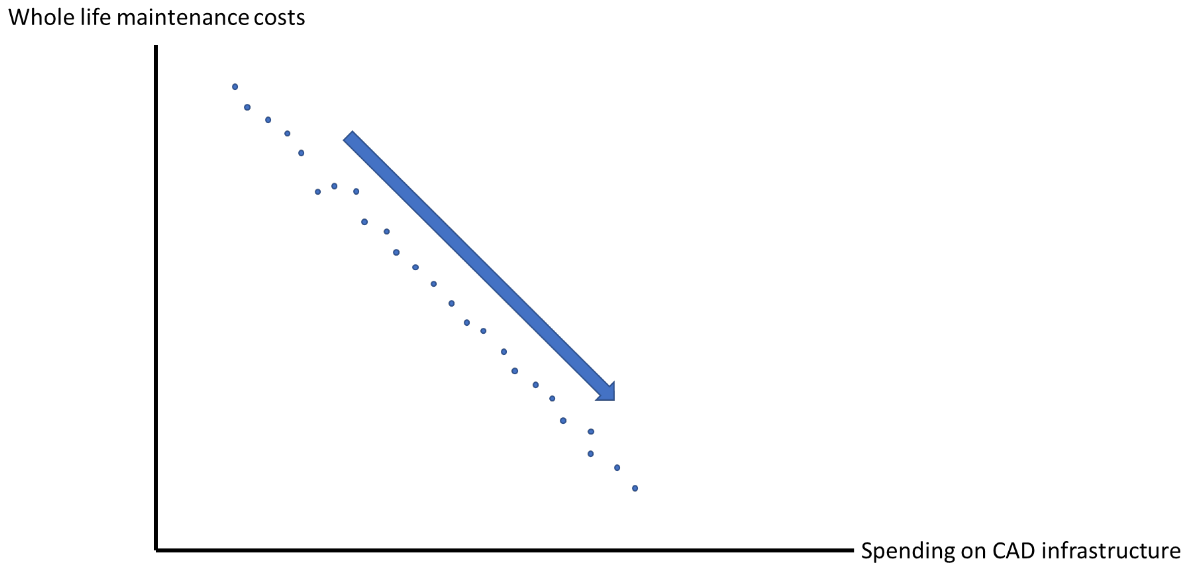

Figure 15: Potential trade-off between spending on CAD infrastructure and wholelife maintenance

7.1.1.1.1. Change in journey times and Value of Time (VoT)

Another direct impact that NRAs need to understand is the reliability of journeys. NRAs should assess whether a CAD scheme would contribute to a reduction of travel time. As CAD becomes well-developed, efficient traffic flow could lead to a reduction in journey time, driven by a reduction in traffic congestion and increased flow rate. However, improved traffic flow can also attract further demand. Therefore, simulations and transport modelling would be required. Next, NRAs need to understand how the economic value of the journey time savings. Several European countries have principles and norms that have to be followed in order to do this evaluation in a coherent and consistent way across different transport infrastructure projects, such as roads and rail. According to the UK's Web Technical Appraisal Guidance (WebTAG) unit A1.3 on transport appraisal, journey time should be categorised as "commute", "business" and "other" since these have different economic values of travel time. The guidance recommends that a revealed preference approach is used in estimating the willingness-to-pay for faster journeys. This means collecting the current demand for different services (or journey paths) and estimating choice models that translate the current modal choice behaviour. By means of a trade-off between the importance of time and cost on those choices, it is possible to find the willingness to pay to reduce journey time for those categories of trip motives, as well as for different modes of transport.

As public transport may be undervalued compared to private cars, public transport may be assigned a correction factor (2 for example, doubling its importance in modelling). when calculating the value of time to account for the bigger social benefits of public transport in terms of reduced externalities, such as emissions. In WebTAG data book, A1.3.1, the range of the market price of value of time is £5 to £29 per hour in 2010 prices using 2010 values. For the Netherlands, this value of travel time for a commuter trip by car is typically 10 euros/hour in the last few years.

Environmental impact

The Inrix global scorecard of congestion reports that congestion was responsible for losses of €72.7bn, €7.5bn and €2.8bn in the United States, United Kingdom and Germany respectively in 2019 (Inrix, 2020). One way to address increased demand is to increase physical infrastructure capacity. However, road construction and maintenance is associated with significant adverse journey time (Couture et al., 2018; Fernald, 1999) and environmental (Moretti et al., 2018) impacts.

Changes in traffic management can lead to changes in carbon emissions. Instead of improving existing journeys, technological upgrades may merely lead to more journeys. Consequently, there is potential value in technologies that can cost-effectively increase efficient utilization of the existing road network without needing to build additional roads. NRAs need to estimate how well the proposed technology might impact the traffic flow and hence the emissions.

We have approached this methodology with the perspective that NRAs may be able to increase network capacity by providing dedicated infrastructure for CAD. However, NRAs must also be mindful of the effects this may have on the wider transport system. The concept of induced demand in road transport is well known (e.g., Goodwin, 1996; Litman & Colman, 2001; Hymel et al., 2010) whereby increases in highway capacity attract new traffic, potentially causing greater congestion at other bottlenecks in the road network. Furthermore, facilitating private CAD for highway journeys may increase vehicle miles travelled and reduce the likelihood that travellers seek more sustainable options to complete the same journey (Soteropoulos, Berger & Ciari, 2019). Adler et al. (2019) has suggested path dependency in AV infrastructure investment decisions. It is therefore vital that NRAs undertake detailed modelling to ensure such effects are understood and mitigated in order to achieve the desired outcomes. Such modelling would require taking a wide range of factors and a range of recent research into account. From a road capacity consideration there is literature that suggests novel insights and methods to capture the impact of vehicle automation. Notable studies include Chen et al. (2017), Makridis et al. (2019) and Ma et al. (2021). Other aspects include induced demand modelling by Hymel et al. (2010), the impact on traffic management by Diakaki et al. (2015) and wider aspects of the transport system such as mode alternatives and land zoning.

In-vehicle productivity

There have been studies into the in-journey time which can be partly or fully used in a productive way with connected and autonomous driving. It is possible that some travellers are able to undertake productive activity inside an automated vehicle. In public transport projects, particularly rail projects, it is suggested that working tables, charging facilities and high-speed Wi-Fi can support productive time during journeys. This means work but can also mean valuable leisure time.

For vehicle automation there is still uncertainty regarding how the value of travel time will change. Research by Correia et al. (2019) used stated preference surveys in the Netherlands to assess the value of travel time changes between conventional private cars and automated private cars prepared for leisure and prepared for work (separately). The results showed that, in a future where private cars can be used productively, the value of travel time savings are only the result of the difference between the experience of working in a normal workplace and working in a car (for the car prepared for work) and the difference between having leisure in our normal leisure locations and having leisure in a car (for a car prepared for leisure).

That signifies that if the car enables a perfect performance of these activities the cost of travel time would be zero. There would be no opportunity cost for being inside a car which can contribute to keeping people more time in vehicles and eventually exacerbate traffic congestion (Yap et al., 2016). In the same study, it was possible to understand that people, at least in the Netherlands, may see themselves working in a car (derived from their type of work) but they do not see how they would perform their normal leisure activities inside a car.

NRAs need to conduct assessments of the value of in-vehicle productivity in an era of CAD. Models will have to take the different value-of-time categories and multiply by the corresponding numbers of existing travellers who would benefit. If induced demand and congestion lead to passengers spending more time in the vehicle there will be a journey time disbenefit. NRAs should aggregate the in-vehicle productivity benefits and any congestion disbenefit. These need to be expressed in Present Value terms.

7.2.4 Construction of a systematic Cost Benefit model (step 4)

Having considered the above, NRAs should be able to construct a Cost Benefit model which accounts for the above factors. The cost benefit model requires NRAs to input benefit and cost estimates per year for an agreed appraisal period (usually 30 years) for each option. Table 14 shows one example of how this could be formatted, as well as the potential trends of each benefit and cost category. However, NRAs need to adapt the format to their individual circumstances.

Having laid out the nominal benefit and cost estimates, NRAs should sum up the nominal totals for each appraisal year. These totals are then adjusted for inflation and discounting. Inflation refers to the general increases of price levels, which make comparisons between different years difficult. By "rebasing" to a common year, NRAs can ensure like-for-like comparisons. Discounting refers to the calculation of a present equivalent for a schedule of benefit and cost estimates in the future. Rebasing and discounting allow Benefit Cost Ratio and Net Present Value to be generated within the cost benefit model for each option.

Table 14: Cost Benefit Analysis Summary Table

Benefit	2022	2023	2024	2025	2026	2027	…	2050	2051
Safety	From reduced collisions and saved KSIs, likely increasing benefits as adoption increases								
Maintenance	Potential benefits to maintenance which may change over time as (e.g.) data provision commences								
Journey time	Likely fluctuates across years as demand dynamically responds to changing flows								
Environment	Likely increases over time with fluctuation, as demand and advances in alternatively fuelled vehicles interact.								
Nominal total	Summing up nominal benefits in respective years								
Rebased to 2022	Apply GDP deflator to ensure common basis for comparison								
Present value in 2022	Discounted using pre-defined rates								
Cost	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**…**	**2050**	**2051**
Construction	Initially high outlay with a likely decreasing cost schedule								
Maintenance (Digital)	Digital maintenance costs depending on ownership and efficiency forecasts for networks								
Maintenance (physical)	Costs of maintaining the new infrastructure								
Environment	If increasing demand outstrips carbon emissions reduction improvements								
Nominal total	Summing up nominal costs in respective years								

Rebased to 2022	Apply GDP deflator to ensure common basis for comparison
Present value in 2022	Discounted using pre-defined rates
Resulting Metrics	
Benefit Cost Ratio	Present Value Benefit / Present Value Cost
Net Present Value	Present Value Benefit – Present Cost

7.2.5 Communicating wider impacts (step 5)

In addition to the core impacts quantified above, NRAs are encouraged to communicate wider impacts. Infrastructure spending often encourages the private sector to invest in software and hardware solutions. These can provide safer transport environments. Connected driving, for instance, requires sensors to be installed on the roadside before communication packages can be installed in vehicles. Many OEMs fear that private investment in equipping vehicles to engage in connected driving will not be matched in time for such products to appeal to the mass market.

Therefore, if NRAs and central governments can pre-commit to infrastructure development, OEMs would be encouraged to create and implement solutions which may not have been developed as a standalone technology, potentially improving road safety. Clearly, there is a trade-off between initial capital investment and later maintenance of existing safety infrastructure. Figure 16 presents the potential trade-off. On the horizontal axis, extending to the right means higher levels of public capital spending. Establishing new infrastructure technology is associated with lower road casualties, higher traffic flow and new business opportunities. All these point to higher levels of economic output. Likewise, successful transformation from existing to new technologies related to connected and autonomous driving, in the long term, will mean lower levels of spending required on existing infrastructure. Of course, there are risks such that new business models might not materialise. This is especially the case if new technologies do not turn out to be profitable or taken up by the market.

In that case, the outcome can move towards the bottom right quadrant of the graph, where NRAs might have incurred significant investment, but other economies dominate the new technology environment. On the contrary, governments would most welcome moving to the top right quadrant of the diagram. Here the new business opportunities turn out to be successful and the relevant sectors within the economy thrive on the development. Governments then incur lower levels of maintenance expenditure, while economic output increases. While it is recognised that these are difficult to quantify, NRAs can articulate the potential directions of these outputs and communicate to central government departments for consideration.

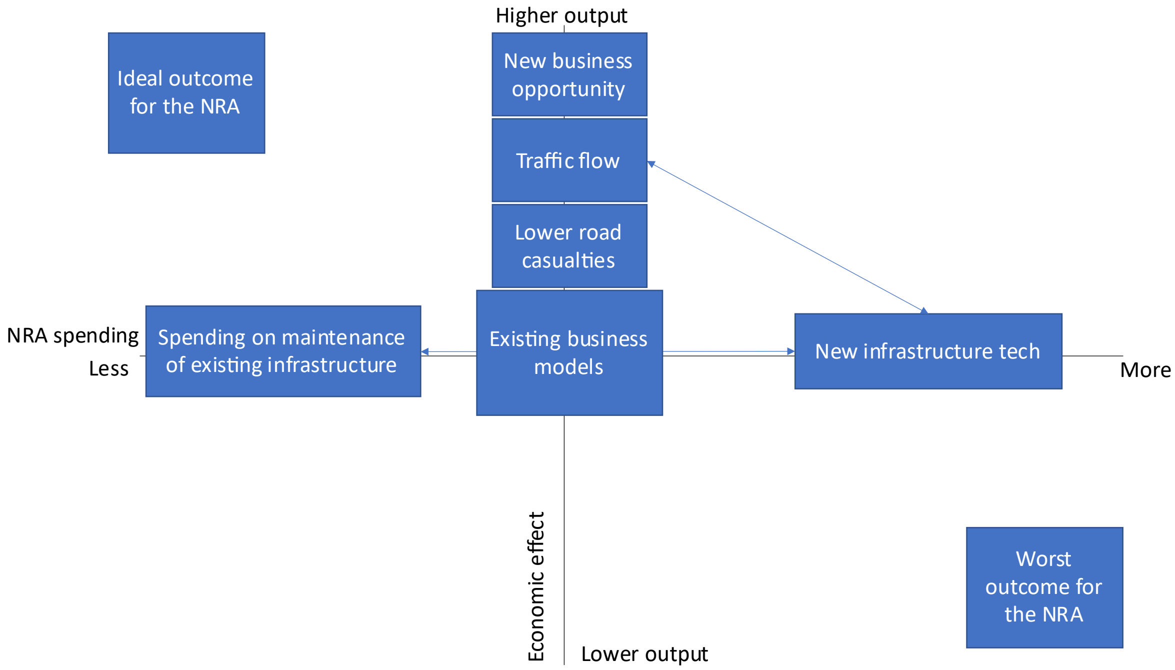

Figure 16: Trade-off between output and infrastructure spending

Creation of new industries

It is conceivable that the creation of new industries will, first and foremost, affect the transport industry. These can include setting up new control rooms that respond to video analytics of traffic. On the manufacturing side, there will be a need for new technologies such as software development for video analytics. However, there are further impacts. For example, the charging of electric vehicles is already creating new players in the commercial sector. Real estate developers that have the capacity to charge vehicles are more likely to attract footfall. This is encouraging developers to invest in these facilities to attract shoppers. More generally, areas investing in these new technologies can drive traffic into specific areas for tourism and industry. The second-order impacts from such innovation requires scenario planning from NRAs.

Decline of old sectors

Just as new sectors emerge, certain existing sectors will inevitably experience decline. For instance, when vehicles become fully automated, we can expect the vast majority of taxi and bus drivers in many areas to find their services no longer required. Depending on whether their skills can be transferred to the new industry or operation, some workers from previous industries might not be able to transition into other roles. Furthermore, the economic consequences of such decline vary from region to region. Tech-driven, university towns may be less affected than historic towns which depend on tourism. These would have to be qualitatively and strategically evaluated based on where the proposals concern.

Transition to new technologies

Even though Figure 16 considers the potential trade-off between output and investment, it presents the end state of the projected proposal. There will be a transition period before reaching the terminal state of any proposed development. For instance, safety requirements on vehicles have in many cases been applied to newly registered vehicles. This is due to the high cost of retrospective installation and difficulty in enforcement. Similarly, unless there is an overriding imperative for older technologies to be replaced, they will co-exist with new technologies for some years. During this transition period, NRA will still be expected to maintain existing assets, such as periodically repainting lanes. There may be technological proposals which would negate such ongoing costs. But National Road Authorities need to show that these have been thought through before making a judgement on the operating and maintenance costs of existing infrastructure.

Conclusion

This chapter has outlined a cost benefit methodology for National Roads Authorities to appraise proposed schemes related to Connected and Autonomous Driving. As with other investment proposals, National Roads Authorities should assess the value for money of such schemes. The cost benefit methodology starts with recognising the organisation's core objectives. If proposed schemes fulfil the objectives, the authorities should then develop a clear and robust set of assumptions, such as projected uptake of a certain technology. The third step is to identify intended impacts. The main ones include improvements in safety, maintenance, journey times and emissions. Modellers should quantify these impacts using relevant published values, such as the economic value of a prevented road fatality.

These quantified impacts should culminate in the main outputs of this methodology. They are Net Present Value and Benefit Cost Ratio, which compare the value for money among options against a baseline of business as usual. The production of these metrics involves discounting and rebasing to ensure that costs and benefits in different years are treated on a comparable basis. Finally, it is recognised that new technologies often have wider impacts on the economy and society. These could lead to the development of new sectors and a uncertain transition period. Acknowledging the difficulty in modelling such impacts precisely, National Roads Authorities should articulate possible trajectories and qualitatively communicate these impacts.

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8 Vision and Mission

DiREC Mission

The DiREC project's mission is to deliver a CAV Ready Framework for National Road Authorities (NRAs) that supports current and future requirements of the network.

This Framework will act as a key tool for NRAs to understand the role they play and the actions needed to facilitate safe and secure CAV deployments. The tool and associated methodologies will provide guidance for NRAs not only to plan infrastructure projects, but also to develop a long-term strategy for their networks in terms of the types of infrastructure and services they will provide, including digital mapping, localisation, navigation and other services around traffic management.

In short, DiREC will create a tool that will enable NRAs to:

1. **Assess** the level of maturity currently being provided in key areas associated with CAV across the Physical and Digital Infrastructure domains.
2. **Define** the NRA's current Service Level capability associated with key enablers for CAV
3. **Identify** paths for NRAs to increase or improve current Service Levels
4. **Engage** all the stakeholders in the CAV ecosystem, NRAs and OEMs, to work together for improved customer services
5. **Clarify** Key Performance Indicators and Business case requirement

Appendix 1.1: SAE Levels

The SAE J3016, “Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles” are widely used in defining the levels of driving automation. **Error! Reference source not found.** describes the features and levels of support for drivers and for automated driving.

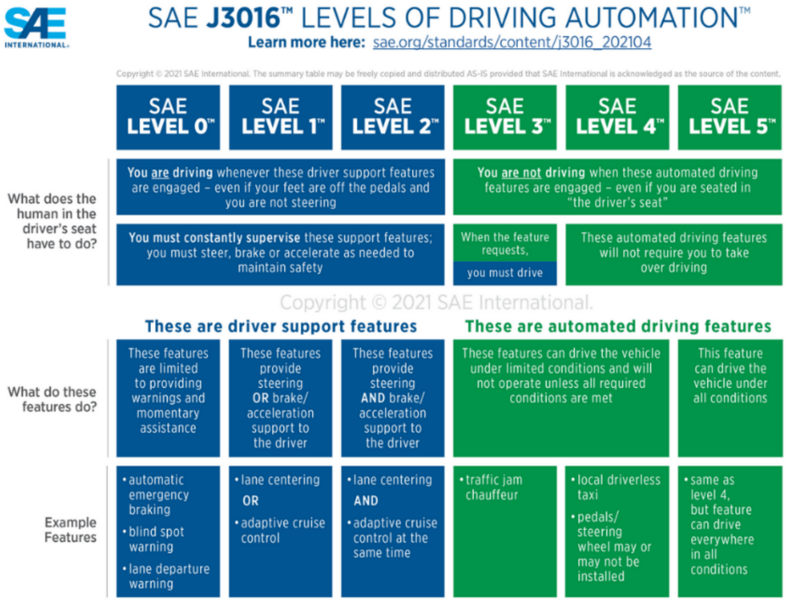


Figure 17 SAE J3016 Levels of Driving Automation

Appendix 1.2: ISAD Levels

The INFRAMIX project established an important classification scheme for infrastructure support to automated driving (INFRAMIX, 2020). Infrastructure support levels are meant to describe road or **highway sections** rather than whole road networks reflecting typical infrastructure deployments. This classification scheme helps prepare road infrastructure to support the coexistence of conventional and automated vehicles on road networks. See **Error! Reference source not found.**.

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

Figure 18 Infrastructure Support Levels for Automated Driving (ISAD)

Appendix 1.3: CAV Readiness Framework

This is the outline framework that DiREC is working towards, addressing eight core subject areas that NRAs must consider in the delivery and management of connected infrastructure to support CAD.

Appendix 1.4: PIARC Special Project Smart Road Classification

(Garcia et al, 2021) proposed a classification of the Level Of Service for Automated Driving (LOSAD). LOSAD is categorized into five levels, from A to E. It is determined as a function of how ready the road infrastructure is to support automated driving. The most important parameter to define the LOSAD of a road segment is the distribution of their Operational Road Sections. An Operational Road Section (ORS) can be defined as a section that fully supports automation for all driving automation systems with explicit ODDs.

Figure 19 shows the concept, indicating the input factors from the different layers and the interaction with other classification systems including ISAD, road typology and user classifications. Connectivity and automation create new kinds of user interactions. Traffic volume and composition are another group of factors that affect the infrastructure management.

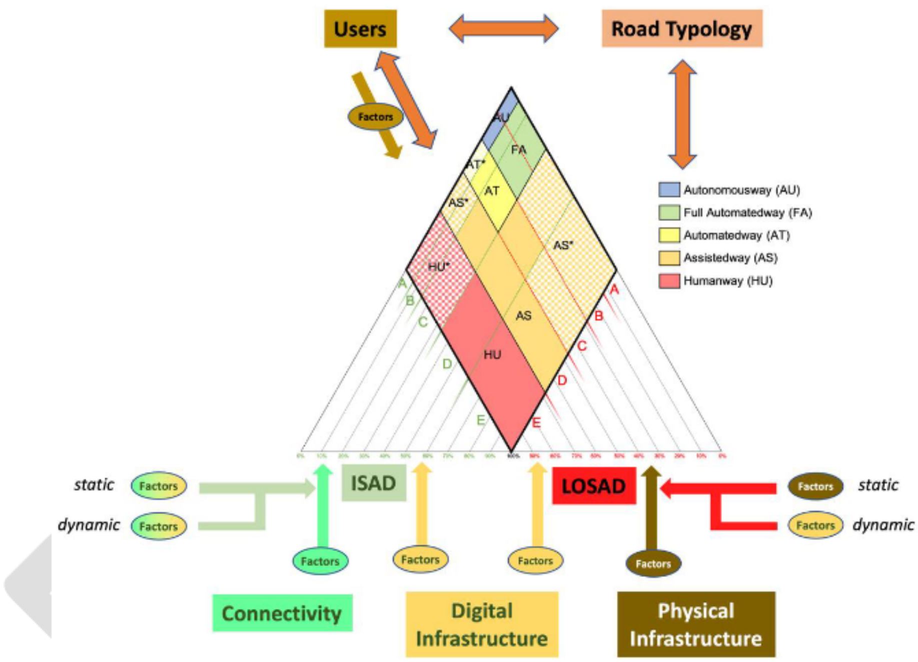


Figure 19 Smart Road Classification

Appendix 1.5: Infrastructure Support Level Classification

The Finnish Transport Infrastructure Agency's proposed a classification of digital infrastructure components for different ISAD levels (Finnish Transport Infrastructure Agency, 2021). This classification was proposed for the Finnish motorway network, and is not necessarily valid for other motorway networks.

Table 16 shows the proposed physical infrastructure classification. Table 16 shows the proposed classification for digital infrastructure components. Other tables are available for proposed classifications of environmental conditions and traffic management services.

Table 15 Physical infrastructure classification for different ISAD Levels

	ATTRIBUTE	E: CONVEN-TIONAL (PHYSICAL) INFRA-STRUCTURE ONLY, NO AV SUPPORT	D: PHYSICAL INFRA-STRUCTURE ADAPTATIONS FOR AV	C: ENHANCED INFRA-STRUCTURE WRT MAINTE-NANCE	B: IMPROVED INFRA-STRUCTURE WRT MRM	A: IMPROVED INFRASTRUCTURE WRT POSITIONING AND SUPERVISION
DRIVABLE AREA LANE SPECIFI-CATION	Lane marking retro-reflectivity	According to national guidelines	min 100 mcd/lx/m² dry road	Same as level D	Same as level D	Same as level D
	Luminance contrast ratio	According to national guidelines	>2:1	Same as level D	>3:1	Same as level B
	Lane marking consistency	No contradictory markings	After road works e.g. repaving, new markings done without delay and temporary markings totally deleted	Same as level D	Same as level D	Same as level D
	Bearing capacity of lane	According to national guidelines, should be OK for also platoons	Sufficient for platoons of 3 trucks moving with headway of 15 m	Same as level D	Same as level D	Same as level D
DRIVEABLE AREA EDGE	Shoulder width	According to national guidelines	Outside >= 2000 mm Inside >= 1250 mm	Same as level D	Outside >= 3000 mm Inside >= 2000 mm	Same as level B
	Shoulder bearing capacity	According to national guidelines	Sufficient for platoons of 3 trucks moving slowly with gap of 15 m	Same as level D	Same as level D	Same as level D
	Widening or lay-by	None required	Every 50 km	Every link between major inter-sections	Same as level C	Every 500 m

	ATTRIBUTE	E: CONVEN-TIONAL (PHYSICAL) INFRA-STRUCTURE ONLY, NO AV SUPPORT	D: PHYSICAL INFRA-STRUCTURE ADAPTATIONS FOR AV	C: ENHANCED INFRA-STRUCTURE WRT MAINTE-NANCE	B: IMPROVED INFRA-STRUCTURE WRT MRM	A: IMPROVED INFRASTRUCTUR E WRT POSITIONING AND SUPERVISION
DRIVABLE AREA SURFACE	Drivable area induced road surface condition	Aim: No pot-holes nor major damages, rut depth <20 mm; corrective measures as instructed in prevailing road guide-lines	Same as level E	30% shortening of repairment contractor response times	Same as level C	70% shortening of contractor response times
FIXED ROAD STRUCTURES	Landmarks (specific structures beside carriage-way)	None required in addition to existing structures	Same as level E	Conspicuous and tall enough; at problematic spots/sectio ns with no usable landmarks	Equip with radar reflectors, where necessary	Equip with radio beacons, where necessary
TRAFFIC MANAGE-MENT	Construction site detour	Marking with temporary signs or utilising existing signs	Standardised markings that can be perceived correctly by AVs	Same as level D	Same as level D	Same as level D
	Road works	According to national guidelines	Markings and arrangement compatible to (pre)standards related to AVs. Location and physical arrangement in digital form in a standard accepted by HD map	Same as level D	Same as level D	Same as level D

Table 16 Digital Infrastructure component classification for different ISAD Levels

Infrastructure Attribute	Sub-attributes	ISAD E: Conventional (physical) infrastructure only, no AV support	ISAD D: Static digital information/map support	ISAD C: Dynamic digital information	ISAD B: Cooperative perception	ISAD A: Cooperative driving
Communication	Short-range V2I	Not required	Not required	Available at selected hot spots and corridors to convey critical information to AVs	Available at all hot spots	Available at all hot spots and critical road sections
	Medium and long-range V2I	Not required	Available	Available	Available	Available
	Medium and long-range V2I with low latency and wide bandwidth	Not required	Download and upload speed min 5 Mbit/s, latency <5 s, reliability min 90%	Download and upload speed min 15 Mbit/s, latency <500 ms, reliability min 95%	Download speed min 100 Mbit/s and upload speed min 25 Mbit/s, latency <20 ms, reliability min 99%	Download speed min 100 Mbit/s and upload speed min 100 Mbit/s, latency <10 ms, reliability min 99.99%
Satellite positioning	Land stations	Only local correction service (RTK) which requires conversion from local to global	Same as Level E	WGS84 correction service via satellite is available	The same as level C Decimetre level accuracy achievable with dual frequency receiver	WGS84 and IP network localisation assistance available, sub-decimal accuracy achievable together with dual frequency receiver plus navigational aid on problematic shadow road sections
	Positioning support in tunnels	Not required	Not required	Awareness, research; pilots; Satellite positioning support, connectivity	Geofencing for hazardous goods transport; provisions for two-way traffic during maintenance	Deployments in critical tunnels
HD Maps	Maps of road environment including landmarks for camera, radar, and ultrasound sensors	Not required	Digital map with static road signs (incl. accurate position of traffic signs and Variable Message Signs (VMS), dynamic update of static information (e.g roadworks, speed limits change due to long term roadworks)).	Same as level D plus HD maps (incl. Accurate position of signs, dynamic update of lane topology)	Same as level C Plus HD maps (cloud based digital maps incl. the accurate position of signs, dynamic update of lane topology, location of emergency stop zones)	Same as level B

Infrastructure Attribute	Sub-attributes	ISAD E: Conventional (physical) infrastructure only, no AV support	ISAD D: Static digital information/map support	ISAD C: Dynamic digital information	ISAD B: Cooperative perception	ISAD A: Cooperative driving
					Weather (High precision meteorological stations, inpavement sensors to detect moisture, temperature, strain)	
	Maps of road environment including landmarks for LiDAR sensors	Not required	Not required	Data from existing digital road maps of the road operators made available to service providers including map providers	Digitalisation of the selected road network in required content and quality, including landmarks for positioning support	Digitalisation of all public road networks
Information system (digital layer of the HD map)	Real-time event, roadworks, incidents and other disturbances	Not required	Not required	TMC provides information on incidents and events; Dynamic information on location etc. on stationary roadworks	More specific high-quality information on incident or event available (V2I); Real-time high-quality information available of stationary and mobile roadworks	Individual trajectory recommendation available;
	Digital traffic rules and regulations	Documentation available only in human readable form	Digitalisation of static rules and regulations according to standards (e.g. METR)	Provision of prevailing rules and regulations incl. VMS	Same as level C	Same as level C
	Geofencing information	Not required	Not required	Available	Available	Free from geofencing
	Availability of physical infrastructure	Documentation available only in human readable form	Digitalisation of physical infrastructure attributes (especially those related to ODD)	Dynamic updating of physical infrastructure based on changes due to damages, maintenance, building	Dynamic updating based also on CAV data	Same as level B
Traffic performance status on road network	Traffic status on network	Not required	Historic traffic performance status available, updated annually, EU EIP	Real-time information on traffic flows, EU EIP Enhanced (**)	EU EIP Enhanced (**) quality level for cooperative	EU EIP Advanced (**) quality level for cooperative services

Infrastructure Attribute	**Sub-attributes**	**ISAD E: Conventional (physical) infrastructure only, no AV support**	**ISAD D: Static digital information/map support**	**ISAD C: Dynamic digital information**	**ISAD B: Cooperative perception**	**ISAD A: Cooperative driving**
			Basic (*) level	level	services	
	Real time digital twin of the network managed including traffic flows	Not required	Not required	Automated update of digital infrastructure.	Same as level C	Same as level C
	ODD management	Documentation available only in human readable form	Digitalisation of static ODD attributes and their value	Digitalisation of dynamic ODD attributes and their value	Provision of basic ODD management based on data exchange between infrastructure and Avs	Provision of immediate ODD management based on data exchange between infrastructure and AVs
	Traffic management centre and processes	Documentation available only in human readable form	Digitalisation of existing TMPs	Digitalisation of TMP use in real time	Same as level C	Same as level C
Fleet supervision	Fleet monitoring and supervision centres	Not required	Not required	Research and limited pilots	Deployment and use for relevant vehicles	Deployment and use for relevant vehicles

Appendix 1.6: Summary Table

Type	Infrastructure	Sub-attributes	Comment	Impact to road operators	Applicable Levels	Future Opportunity and Risk
Physical Infrastructure	Road Design & Layout	Road geometry and configuration	Road layout, geometry, intersections could be designed differently for CAVs in future, depending on different use cases.	▪ Type: long-term impact for planning, design, operation, and maintenance ▪ Complexity: High (physical, digital and operation). ▪ High investment requirements for building new roads and renovating existing roads.	▪ SAE Level 4-5 ▪ ISAD Level A	↑ In the short-to-medium term it may be useful to simplify intersections in terms of interaction between CAVs. Less complex road junctions / intersections may lead to reduction of road accidents (Austroads, 2017). ↑ In the longer term, greater coordination between vehicles may allow intersections to become more compact (Austroads, 2017) – improved efficiency and cost saving ↑ The width of lanes could be reduced, as Lane Keeping Systems will guarantee that the vehicle will maintain an optimal central position (SLAIN, D7.2: Other initiatives to meet the needs of automated cars, 2020).
		Special road sections for CAVs	Additional efforts may be required to support CAVs at critical roadway sections (e.g tunnel, bridge, toll plazas, etc)	▪ Type: long-term impact for planning, design, and maintenance ▪ Complexity: High (physical, digital and operation) ▪ High investment requirements for building new roads or adapting existing roads.	▪ SAE Level 4-5 ▪ ISAD Level A	● While AVs offer opportunities to rethink aspects of road design (e.g. horizontal and vertical curvature, lane widths, intersections), it is not practical to implement changes as long as there is mixed traffic with a mix of vehicles of different SAE levels. However, where there are sections, carriageways or lanes dedicated to a particular SAE level of vehicle, then certain design changes might be considered. ● Many modifications to road design may be meaningful only in the case of SAE Level 5 vehicles. (Belgian Road Research Centre, 2020). ↓ Design standards need to be explored further to determine the impact of platooning. Current bridge design standards make assumptions about the number of vehicles likely to be on the bridge at any one time (Austroads, 2017). Limited wandering (lateral movement of truck tires) can have negative influence on fatigue life. Fixed path platooning can significantly increase the construction-maintenance cost of the pavement (Hassan et al, 2020). ↓ Tunnels are very relevant to CAV and require further research into detection and perception of tunnels under adverse weather and lighting conditions as well as sensor and GPS capabilities. (SLAIN, D7.2: Other initiatives to meet the needs of automated cars, 2020)
		Dedicaded lanes / seperations	Dedicated lane (permanent or temporary) for CAV	▪ Type: long-term impact for planning, design, and maintenance ▪ Complexity: High impact to road operators – rethink their way of managing fleet or traffic flows ▪ High investment requirements – plan the transition of mixed traffic and traffic separation, complex and a long-term effort	▪ SAE Level 4-5 ▪ ISAD Level A - D	↑ Special use highways may be required to accommodate certain types of AV traffic such as platoons of heavy vehicles. ↑ Alternative approach road certification, which is to provide some guidance or framework, outlining where certain AV use cases should or should not operate. (Austroads, 2017) ↓ Design standards need to be explored further to determine the impact of platooning (Austroads, 2017)
		Pavement of road	Road materials and skid resistance impact to CAV	▪ Type: long-term impact for research, planning, and maintenance ▪ Complexity: High, as need research and road operations, adapting maintenance policies ▪ Medium investment requirements for new materials or new way of road design or maintenance	▪ SAE Levels 2-5 ▪ ISAD Level A - C	↓ Because CAVs will run consistently in the same lane positions there will be greater wear and tear in the wheel tracks, and that either the road area beneath the tracks will need to be strengthened, or maintenance repairs will need to be more frequent (Lamb, 2015) ↓ Reasonable levels of skid resistance are required where there are road users who are susceptible to varying levels of skid resistance. Motorcycles, bicycles, and pedestrians are affected by dramatic changes in skid resistance of surfaces. ↑ CAVs can adjust vehicle speed more predictively through V2V and V2I communications to avoid sharp braking thus reducing the stopping distance design standard (Dunford et al., 2014). ↑ The failure to estimate friction on the carriageway is identified as a significant cause of roadway departure crashes for CAVs and further research is needed for safe CAV operation
		Bearing capacity	Different part of roads (lanes, shoulders, bridges)	▪ Type: long-term impact and requirements for research, policy planning, and maintenance ▪ Complexity: High (physical, digital, and operations to adapt maintenance policies) ▪ High investment requirements for new design and way of management for roads	▪ SAE 4-5 ▪ ISAD level A	↑ Rethink every part of the road to improve road capacity and efficiency by utilising the advantages of CAVs (automated harbour area is an example) ↓ This may raise requirements for additional road functions (e.g., lanes, shoulders, bridges) ↑ Road efficiency and bearing capacity can be greatly improved based on the new design of roads – e.g. platooning operations

Type	Infrastructure	Sub-attributes	Comment	Impact to road operators	Applicable Levels	Future Opportunity and Risk
	Speed Range	Static speed limit	CAVs are perceived to adapt the speed of the vehicle based on the road design characteristics	▪ Time: Long-term (research, policy, planning, design) ▪ Complexity: Medium (physical, digital, communications, and operations to adapt ODD policies) ▪ Investment: Medium	▪ SAE Levels 3 – 5 ▪ ISAD Level A - C	↑ Potential opportunity for road safety - CAVs can also adapt the speed of the vehicle based on the road design characteristics – reduced adoption of speed limits or maintenance cost ↑ Developing increased efficiency of traffic flow as speed can be changed in group, based on the requirements of local traffic situation.
		Dynamic speed limit	It is possible to use direct control of the connected vehicles to adjust vehicle speeds towards the new traffic situation.	▪ Type: Long-term (research, policy, planning, design) ▪ Complexity: High (physical, digital, communications, and operations to better road efficiency) ▪ Investment: High	▪ SAE Levels 2 – 5 ▪ ISAD Level A - C	↑ There is potential to improve traffic performance when variable speed control is applied to CAV
	Shoulder or Kerb	Wide shoulder	Provision of safe harbour areas is a key priority area for CAVs. Hard shoulders provide a continuous strip of hardstanding for vehicles to stop in an emergency; they can be converted into a running lane, or safe harbour areas, or 'Dynamic Hard Shoulder Running'	▪ Type: Long-term (research, policy, planning, design) ▪ Complexity: High (physical, digital, and operations to better road management) ▪ Investment: Medium	▪ SAE Levels 2 – 5 ▪ ISAD Level A - C	↑ Shoulders might be used as safe harbour areas for CAVs – this provides additional benefits for existing shoulders but needs wider renovation. ↑ High speed dual and single carriageway roads currently have no requirement for safe harbour areas to be provided ↑ Develop more potential application for wider shoulders
		Passenger pick-up/drop off areas	The development of automated valet parking is vital to the commercialisation of Level 4/5 CAVs in cities	▪ Type: Long-term (research, policy, planning, design) ▪ Long-term – need to revaluate the bearing capacity for support CAV, and CAV-related requirements ▪ Medium investment requirements	▪ SAE Levels 2 – 5 ▪ ISAD Level A - C	↑ Necessary for automated shuttles and robotaxis ↑ CAVs will drop off passengers, how they park between trips to recharge, access storage, or be serviced, and blend the relationship between on and off-street parking to support Mobility-as-a-Service (MaaS) operators.
		Lay-bys or parking areas	Necessary for automated shuttles and robotaxis	▪ Type: long-term impact and requirements for research, policy ▪ Complexity: Medium (physical, digital, and operations to adapt maintenance policies) ▪ Medium investment requirements for new design and way of management for roads	▪ SAE Levels 2 – 5 ▪ ISAD Level A - C	↑ The introduction of automated valet parking could help cities, urban areas, traffic and highways planners to ensure empty CAVs do not contribute to traffic and congestion. ↑ Drop-offs and pick-ups for CAV journeys are likely to be on-street and close to points of interest
	Road Markings	Lane markings	Road markings of sufficient retro-reflectivity in different conditions	▪ Type: medium impact (research, design) ▪ Naked highway may not need lanes as virtual lanes can be applied ▪ Complexity: Medium (physical, digital, and operations) ▪ High investment requirements for road management and maintenance	▪ SAE Levels 2 – 5 ▪ ISAD Level A - C	↓ A number of AV manufacturers note problems with recognising existing signs and lines, so that greater consideration of machine readability is required when designing signs and lines. ↓ Proximity of the line to materials such as concrete shoulder and concrete s afety barriers which have similar properties to lines from a machine learnin g perspective made these harder for CAV systems to identify them ↑ Innovative design may be necessary to ensure lane markings are maintained at a high standard. ↓ Road markings need sufficient retro-reflectivity in different conditions – it means poor conditions cause problems. ↓ Higher maintenance requirement may Increase operational cost for road markings
		Visibility	Road markings need better maintenance Static physical landmarks possibly equipped by sensor	▪ Type: medium impact and requirements for research ▪ Naked highway may not need lanes as virtual lanes can be applied ▪ Complexity: Medium (physical, digital, and operations)	▪ SAE Levels 2 – 5 ▪ ISAD Level A - C	↑ Recognition of overlapping and inconsistent road markings, quality of marki ngs, and recognition during adverse weather conditions and at different times of day. ↑ Intelligent electronic devices are integrated into the next generation of road markings. Two types of sensors are used in RMUs: a magnetic sensor and a high-performance accelerometer. These sensors can be used to measure and estimate properties of road surfaces, vehicles, and traffic

Type	Infrastructure	Sub-attributes	Comment	Impact to road operators	Applicable Levels	Future Opportunity and Risk
			reflectors or radio beacons or similar to support accurate positioning	High investment requirements for road management and maintenance		situations. These devices facilitate safe and efficient interaction between drivers and the road infrastructure (Birk, Osipov, & Eliasson, 2009). ↓ Requirements will include clear road markings, appropriate and consistent signage on the network and communication to users regarding what vehicles can operate on that roadways.
	Traffic signs	Visibility / machine readability	Greater consideration of machine readability is required when designing road signs	▪ Type: short- to medium-term impact for design ▪ Better design may be required for ensure lane markings are maintained at a high standard	▪ SAE Levels 2 – 5 ▪ ISAD Level A - C	↓ For signs, many CAV manufacturers note issues with visibility, recognisability, positioning, and consistency. ↑ Some issues could be addressed by the adoption of harmonised regulation and standardisation of sign types, symbols used, shapes, heights, locations, and orientations. ↓ Improved maintenance and design standards can generate significant network-wide safety and performance gains (SLAIN, D7.1: Quality of horizontal and vertical signs, 2020). ↑ Adaptive traffic signal control systems (ATSC) can adjust traffic lights to CAV to maximize the intersection ↓ To ensure consistency in signing, a comprehensive and systematic traffic signs asset inventory system is essential. ↓ Greater consideration of machine readability is required when designing road signs
	Road Furniture	Safety barriers	Safety barrier may play a more important role to constrain run-off vehicle crashes	▪ Type: medium impact and requirements for research ▪ Complexity: Medium (physical, digital, and operations) ▪ High investment requirements for road management and maintenance	▪ SAE Levels 2 – 5 ▪ ISAD Level A - C	↓ Median barriers and side guard rails mitigate the negative consequences of lane and road departures. However CAV systems may have difficulty identifying smaller objects. (SLAIN, D7.2: Other initiatives to meet the needs of automated cars, 2020).
		Gantries for road signs	Indicating right to use or prohibiti on of use by highly automated vehic les		▪ SAE Levels 2 – 5 ▪ ISAD Level A - C	↑ Gantries can facilitate separation of CAVs from other vehicles ↑ Gantries can provide landmarks to facilitate accurate positioning of CAVs
		Gates and barriers	Access for dedicated CAV lanes, roads, or areas		▪ SAE Levels 2 – 5 ▪ ISAD Level A - C	
		Road lighting	Various opportunities and constraints related to use road lighting by CAVs, and maintenance of that lighting by road operators	▪ Type: long term impact and requirements for research ▪ Complexity: Medium (physical, digital, and operations) ▪ Investment: High	▪ SAE Levels 2 – 5 ▪ ISAD Level A - C	↓ Improved street lighting may be required (through better illumination or more closely spaced signs) to support CAVs. (Shaldover & Bishop, 2015) ↑ Improved street lighting will be generally beneficial to road safety through reductions in crashes and injuries. (SLAIN, D7.2: Other initiatives to meet the needs of automated cars, 2020). ↑ Lighting poles can operate as landmarks for positioning, and are a feature for potential inclusion in HD maps. (Finnish Transport Infrastructure Agency, 2021). ↑ CAV and road-side lighting may communicate to support and enhance CAV's vehicle vision. ↓ ODD related requirements for highway autopilot (L4) in 2018 require lighting during darkness. (Traficom, 2019)
Digital Infrastructure	Roadside	Short-range V2I Communication	Communication at hot-spots and road sections	▪ Time: Long-term (research, planning and installation) ▪ Complexity: Medium (physical, digital, communications, and operations to different user cases) ▪ Investment: High	▪ SAE Levels 2 – 5 ▪ ISAD Level A - C	↑ Zenzic's UK Connected and Automated Mobility Roadmap to 2030 (Zenzic, 2020) suggests that digital signage should be sufficiently evolved by 2027 to enable local authorities to be able to reduce their investment in road-side infrastructure and potentially start to remove some pieces of infrastructure.

Type	Infrastructure	Sub-attributes	Comment	Impact to road operators	Applicable Levels	Future Opportunity and Risk
	Communication and Signals	Medium and long-range V2I	Communications over road networks and corridors	▪ Time: Long-term (research, policy, planning, design) ▪ Complexity: High (physical, digital, communications, and operations to better road efficiency) ▪ Investment: High	▪ SAE Levels 2 – 5 ▪ ISAD Level A - C	↑ The interoperability of cellular C-ITS (cooperative ITS) services both for passenger and freight traffic, piloting continuous services offering a similar user experience ↑ The research literature is clear that communication is the most important aspect of CAV capability, and thus the most important asset class, because it is associated with all forms of connectivity, the big data management requirements of connectivity, and cyber security. Communications are where new development is most needed. (RAC Foundation, 2017) ↑ In Finland, the government has published a digital infrastructure strategy. Within that, CAVs are expected to be terminal requiring real-time information, and act as floating 'sensors' collecting and communication information. Reliable and high-quality networks are therefore a must. Privacy and cybersecurity are also seen as important aspects. (Ministry of Transport and Communications, Finland, 2018). ↑ Some existing sensors on the road infrastructure could potentially be used to provide crucial information to CAVs about the environment around a vehicle if on-board sensors cannot detect it. Rebsamen et al. (Rebsamen, et al., pp. 1-5)
		Medium and long-range V2I	Communications facilitating remote supervision of vehicles (with very high requirements for low latency and wide bandwidth)	▪ Time: Long-term (research, policy, planning, design) ▪ Complexity: High (physical, digital, communications, and operations to better road efficiency) ▪ Investment: High		
		Vehicle to Vehicle Communication		▪ Time: Long-term (research, policy, planning, design) ▪ Complexity: High (physical, digital, communications, and operations to better road efficiency) ▪ Investment: High		with the help of vehicular cloud, the communication, storage, intelligence, and learning capabilities will allow the vehicles to anticipate the customers' intentions
	Satellite Positioning and Localisation	Land stations	▪ Improving accuracy of positioning in challenging areas by providing correction data ▪ Need certain level of communication support	▪ Time: Long-term (research, policy, planning, design) ▪ Complexity: High (physical, digital, communications, and operations to better road efficiency) ▪ Investment: High		↑ Deployment of RTK or similar along networks and in tunnels
		Positioning support in tunnels / Challenging environment	GPS repeaters or other solutions to provide accurate positioning in tunnels	▪ Time: Long-term (research, policy, planning, design) ▪ Complexity: High (physical, digital, communications, and operations to better road efficiency) ▪ Investment: High		
	HD Maps	Maps of road environment	Maps of road environment including landmarks for camera, radar, and ultrasound sensors	▪ Time: Long-term (research, policy, planning, design) ▪ Complexity: High (physical, digital, communications, and operations to better road efficiency) ▪ Investment: High		↑ Mandates to roads authorities to provide up-to-date content of HD Maps, covering static information, dynamic information and high-precision data. ↑ Pilots on continuous update of HD Maps based on feedback from CAV sensing systems, to keep effort on maintenance of HD Maps to reasonable cost ↓ In future, digital maps need to be more highly detailed (e.g., 3D lane geometry), highly accurate (e.g., sub-meter absolute, decimetre-level relative), and richly attributed (e.g., lane-level attributes, position landmark, dynamic lane topologies etc). ↓ Cybersecurity issues. Needs to be explored with AV-related stakeholders. ↓ Legal implications of errors or untimely information in HD Maps.
		High accuracy road environment	Maps of road environment including landmarks for LiDAR sensors	▪ Time: Long-term (research, policy, planning, design) ▪ Complexity: High (physical, digital, communications, and operations to better road efficiency) ▪ Investment: High		
		Road database for digital map	CAVs require digital maps to help with navigation, planning,	▪ Time: Long-term (research, policy, planning, design)		

Type	Infrastructure	Sub-attributes	Comment	Impact to road operators	Applicable Levels	Future Opportunity and Risk
			localisation, and comfort. These digital maps are highly detailed	▪ Complexity: High (physical, digital, communications, and operations to better road efficiency) ▪ Investment: High		
	Information System (To CAV/Road Users)	Real-time event, roadworks, incident & other disturbances	Roadworks, incident, and other disturbances	▪ Time: Long-term (research, policy, planning, design) ▪ Complexity: High (physical, digital, communications, and operations to better road efficiency) ▪ Investment: High		↑ Implementation of work zone protection can reduce major safety hazards to workers. ↑ Digital twins for road transport systems including ODD and ISAD information can provide high quality information for automated vehicles ↓ There are currently significantly different approaches to definition of roadworks data and provision of data to CAVS. Roadworks are planned events and information should be able to be provided in real time. Information should include physical changes to road layouts. There is a need for consistency of approach across projects and jurisdictions. (Austroads, 2017). ↓ Regarding communication of positioning of automated maintenance vehicles, project MANTRA concluded that it should be available to either both automated and non-automated vehicles or neither, rather than being given to automated vehicles only because non-automated vehicles may not be able to merge into a lane due to large speed differences. (MANTRA, Impacts of automation functions on NRA policy targets, 2020).
		Digital traffic rules and regulations	Providing permanent and temporary rules of operation	▪ Time: Long-term (research, policy, planning, design) ▪ Complexity: High (physical, digital, communications, and operations to better road efficiency) ▪ Investment: High		↑ METR (Management for Electronic Traffic Regulations) is ongoing and managed under CEN/TC 278 Intelligent Transport Systems. Standardisation has already started, with pilot deployments. ↑ Development, standardisation and deployment of Trusted Electronic Regulations Access Points (TERAP). (MANTRA, 2020).
		Geofencing information	Informing of access to specific roads, networks, and areas and/or right of use of specific automated driving use cases	▪ Time: Long-term (research, policy, planning, design) ▪ Complexity: High (physical, digital, communications, and operations to better road efficiency) ▪ Investment: High		↑ Multiple use cases for geofencing, e.g. for hazardous goods transport, maintenance vehicles, incident management, roadworks, ODD. Possible incorporation in Digital Twins.
		Availability of physical infrastructure	Real-time information on the availability and usability of the physical infrastructure required for the ODD	▪ Time: Long-term (research, policy, planning, design) ▪ Complexity: High (physical, digital, communications, and operations to better road efficiency) ▪ Investment: High		
	Traffic Network Management	Traffic status on network	Provides the transport system real-time status information to the HD Map	▪ Time: Long-term (research, policy, planning, design) ▪ Complexity: High (physical, digital, communications, and operations to better road efficiency) ▪ Investment: High		
		Real time digital twin of the network managed including traffic flows	Enables simulation, modelling and testing of difference traffic management measures in order to select optimal measures for vehicle flows including CAVs	▪ Time: Long-term (research, policy, planning, design) ▪ Complexity: High (physical, digital, communications, and operations to better road efficiency) ▪ Investment: High		↑ Integration of key CAV concepts (ODD, ISAD) in digital twin and information provision through HD mapping. ↑ Implementation of real-time simulation models to model traffic flows under various scenarios. ↑ Implementation of geofencing in digital twins. ↓ Cybersecurity issues
		ODD management	Management of factors affecting the ODDs of vehicles using the roads			↑ Research, agreements and MOUs with OEMs, ADS providers and fleet operators for management of ODDs. ↑ It is likely that the ODDs for the highly automated vehicles (SAE Level 4) will be quite constrained, and the first use cases deployed will be automated shuttles and robot taxis, with a safety operator in the vehicle.
		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	Many organisations will need to operate remote centres to manage their CAV fleets.	▪ Time: Short-to-medium term ▪ Complexity: High (legal, physical communications, operations and services) ▪ Investment: Medium		↓ Regulations for remote supervision and control of vehicles; ↓ Legal framework needed to operate and manage fleet supervision centres. ↓ Secure communications channels for remote supervision ↓ NRAs to determine which parts of their network on which they can operate remote fleets.
Operations and Service	Incident & Event Management	CAV may adopt behaviours that are considered cautious or risk averse.	CAVs allow various opportunities for detecting, managing and preventing incidents	▪ Type: short-to-medium term operations ▪ Complexity: Medium (digital and operation). ▪ Investment: Medium	▪ All SAE levels ▪ All ISAD levels	↑ Standardised marking and provision of data at incident sites at EU level (MANTRA, 2020) ↑ Project PRIMA proposed a concept of pro-active incident management and incident prevention, in which CAVs plays a key role in detecting and reporting incidents (Weekley, Cornwell, & Nitsche, 2017). V2X can play an important role here without expensive physical infrastructure. ↑ Sensors on CAVs can also detect incident clearance and communicate that information to other road users (Kulmala, et al., 2020). ↑ Automation of incident warning and rerouting services (e.g. for over-wide vehicles) ↑ CAV response to emergency vehicles ↑ Use of safety trailers at incident sites to safeguard clearance ↑ Legal harmonisation to enable sharing of safety critical data
	Crisis Management		Events that are more serious in nature than incidents are referred to as crisis or emergency events. There are various risks and opportunities beyond those for regular incidents.	▪ Type: short-to-medium term operations ▪ Complexity: Medium (digital and operation). ▪ Investment: Medium	▪ All SAE levels ▪ All ISAD levels	↑ Driverless and self-driving vehicles could have a role in evacuation and rescue. ↓ Communications infrastructure may be damaged during a crisis. ↓ Communications networks might not function at all during a disaster such as a terrorist attack or a natural catastrophe. ↑ (MANTRA, Road map for developing road operator core business utilising connectivty and automation, 2020)
	Road Maintenance		Road operation and maintenance automation can increase safety of operational workers as well as road users, improve traffic flow and minimize operational costs.	▪ Type: short-to-medium term operations ▪ Complexity: Medium (digital and operation). ▪ Investment: Medium	▪ All SAE levels ▪ ISAD levels A - C	↓ CAD might greatly affect requirements and service levels for road signs and markings, including removal of old road markings, resulting in significant increases in costs for NRAs. ↓ Similarly, ODD for Level 4 CAVs requires lighting during darkness. ↑ Harmonised management of road works sites is needed to provide information on locations, timing, changes to road layouts. ↑ Establishment of work zone protections ↑ Legal framework for driverless maintenance vehicles for easy road maintenance tasks such as condition inspections, lane markings or grass cutting ↑ Vehicles can provide road condition data through V2I communications to the road operator to provide major improvements to predictive

Type	Infrastructure	Sub-attributes	Comment	Impact to road operators	Applicable Levels	Future Opportunity and Risk
						maintenance. (MANTRA, Impacts of automation functions on NRA policy targets, 2020). ↓ Legal frameworks will need to be developed for driverless maintenance vehicles.
	Winter Maintenance	Weather has an impact on road safety, operation and efficiency	Winter maintenance provides several opportunities and risks beyond those for road maintenance.	▪ Type: short-to-medium term operations ▪ Complexity: Medium (digital and operation). ▪ Investment: Medium	▪ All SAE levels ▪ ISAD levels A - C	↑ Legal framework for automated winter maintenance vehicles. These could significantly reduce the workload of winter maintenance staff, and result in a smoother traffic flow with faster operation speed. ↑ Vehicles can provide road condition data through V2I communications to the road operator to provide major improvements to predictive maintenance. (MANTRA, Impacts of automation functions on NRA policy targets, 2020). ↑ There is significant potential to develop enhanced road maintenance decision-support systems. ↓ Visibility of road markings and traffic signs in adverse weather conditions is an issue for CAV systems.
	Traffic Information Services					▪ Standard AV-suitable communications protocols with Traffic Management Centres, fleet managers, service providers and automated vehicles.
	Traffic Enforcement		Digitalisation, connectivity, automated driving and cooperative traffic management will allow evolution of new enforcement systems. Geofencing is a fundamental component of enforcement.	▪ Type: short-to-medium term operations ▪ Complexity: Medium (digital and operation). ▪ Investment: Medium		↑ Development of remote enforcement infrastructure is possible using data from CAVs on their speed, weight, environmental category, etc. through V2I. ↑ Overrides of intelligent speed adaptation systems could be a target for enforcement.
	Road User Charging					↑ Marking of toll plazas for highly automated vehicles. ↑ Inclusion of road user charges into HD Maps.

Appendix 1.7: Autonomous Vehicles Readiness Index

The Autonomous Vehicles Readiness Index has been developed by KPMG been applied to 30 countries and jurisdictions based on 28 different measures under 4 pillars - policy and legislation, technology and innovation, infrastructure and consumer acceptance. (KPMG, 2020)

Policy and Legislation Pillar

AV Regulations
Government-funded AV Pilots
AV-focused agency
Future orientation of government
Efficiency of legal system in challenging regulations
Government readiness for change
Data-sharing environment

Technology and Innovation Pillar

Industry partnerships
AV technology firm headquarters
AV-related patents
Industry investments in AV
Availability of the latest technologies
Innovation capability
Cybersecurity
Assessment of cloud computing
AI and IoT
Market share of electric cars

Infrastructure Pillar

EV charging stations
4G coverage
Quality of roads
Technology infrastructure change readiness
Mobile connection speed
Broadband

Consumer Acceptance Pillar

Population living near test areas
Civil society technology use
Consumer ICT adoption
Digital skills Individual readiness
Online ride-hailing market penetration

Appendix 1.8: Classification of C-ITS services

SAE levels of cooperation

(SAE International, 2021) describes cooperation between two or more entities to support the performance of DDT with driving automation features engaged. Cooperative driving automation (CDA) classes, which may improve DDT performance and traffic operations, are defined as class A through D based on the level of cooperation. These classes are described below and depicted in Figure 20.

Class A: status-sharing (here I am and here is what I see)

This class includes perception information about the traffic and the sending entity. An example of this type of cooperation is a C-ADS-equipped vehicle sharing its speed and the speed of the vehicle in front of it with the vehicle behind it.

Class B: intent-sharing (this is what I plan to do)

This class of cooperation includes sharing information about the planned future actions, for instance, a C-ADS-equipped vehicle sharing a planned lane change with nearby vehicles to facilitate safe and efficient traffic flow.

Class C: agreement-seeking (let's do this together)

This cooperation class includes a sequence of collaborative messages intended to influence DDT and local planning.

Class D: prescriptive cooperation (I will do as directed)

This cooperation class includes the direction of specific actions or tasks by a road authority to CDA vehicles. Examples this type of cooperation includes communicating a geofenced area that is temporarily closed due to an accident or an emergency vehicle directing C-ADS-equipped vehicle to cavate its lane.

		SAE Driving Automation Levels					
		No automation	Driving automation sytem		Automated driving system		
		Level 0	Level 1	Level 2	Level 3	Level 4	Level 5
CDA Cooperation Classes	**No cooperative automation**	(e.g., Signage, TCD)	Relies on driver to complete the DDT and to supervise feature performance in real-time		Relies on ADS to perform complete DDT under defined conditions (fallback condition performance varies between levels)		
	Class A: Status-sharing *Here I am and what I see*	(e.g., Brake Lights, Traffic Signal)	Limited cooperation: Human is driving and must supervise CDA features (and may intervene at any time), and sensing capabilities may be limited compared to C-		C-ADS has full authority to decide actions Improved C-ADS situational awareness beyond on-board sensing capabilities and increased awareness of C-ADS state by surrounding road users and road operators		
	Class B: Intent-sharing *This is what I plan to do*	(e.g., Turn Signal, Merge)	Limited cooperation (only longitudinal OR lateral intent that may be overridden by	Limited cooperation (both longitudinal AND lateral intent that may be overridden by	C-ADS has full authority to decide actions Improved C-ADS situational awareness through increased prediction reliability, and increased awareness of C-ADS plans by surrounding road users and road operators		
	Class C: Agreement-seeking *Let's do this together*	(e.g., Hand Signals, Merge)	N/A	N/A	C-ADS has full authority to decide actions Improved ability of C-ADS and transportation system to attain mutual goals by accepting or suggesting actions in coordination with surrounding road users and road operators		
	Class D: Prescriptive *I will do as directed*	(e.g., Hand Signals, Lane Assignment by Officials)	N/A	N/A	C-ADS has full authority to decide actions, except for very specific circumstances in which it is designed to accept and adhere to a prescriptive communication		

Figure 20 SAE cooperative driving automation classes (SAE International, 2021)

Other SAE C-ITS standardization documents

Apart from cooperation levels, SAE is currently attempting to provide unified V2X communication standards via two main categories of standardization documents, namely V2X communication message set dictionary under J2735 document (SAE International, 2020b) and systems engineering process guidance under J2945/X documents (SAE International, 2018, 2020a, 2020c, 2022), with more supplements under development (Gouse, 2021). Lists of main components of J2735 and J2945/X documents are provided below (CAD Knowledge Base, 2021; Gouse, 2021).

Table 17 Lists of main components of J2735 and J2945/X documents (CAD Knowledge Base, 2021; Gouse, 2021)

V2X communication message set dictionary (J2735):
• Defines Standardized Message Sets • Supports Interoperability • Defines Formats • Defines Basic Safety Message (BSM) • Defines Map Data (Map) Message • Defines Signal Phase and Timing Messages • Defines Personal Safety Messages for VRUs • Defines Traveller Information Messages (TIM).
Systems engineering process guidance (J2945/X):
• Provides System Engineering Guidance & Example • Defines Communication Protocol • Specifies Communication Performance Requirements • Defines Message Transmission Rate • Defines Channel usage

- Optional Data Usage
- Message Application Priorities.

Day X classification (EC)

Another classification of C-ITS services is the day 1 to day 4 classification suggested by the European Commission and commonly used by telecommunication researchers. Figure 21 shows the step by step progression from automated to connected and cooperative driving presented by (Vantomme, 2018). It includes four days, which could be interpreted as classes for C-ITS services. They are described in the following parts.

Day 1: I share what where I am

This class includes sharing location information. An example of this cooperation is a vehicle sharing its location with nearby vehicles for improved positioning.

Day 2: I share what I see

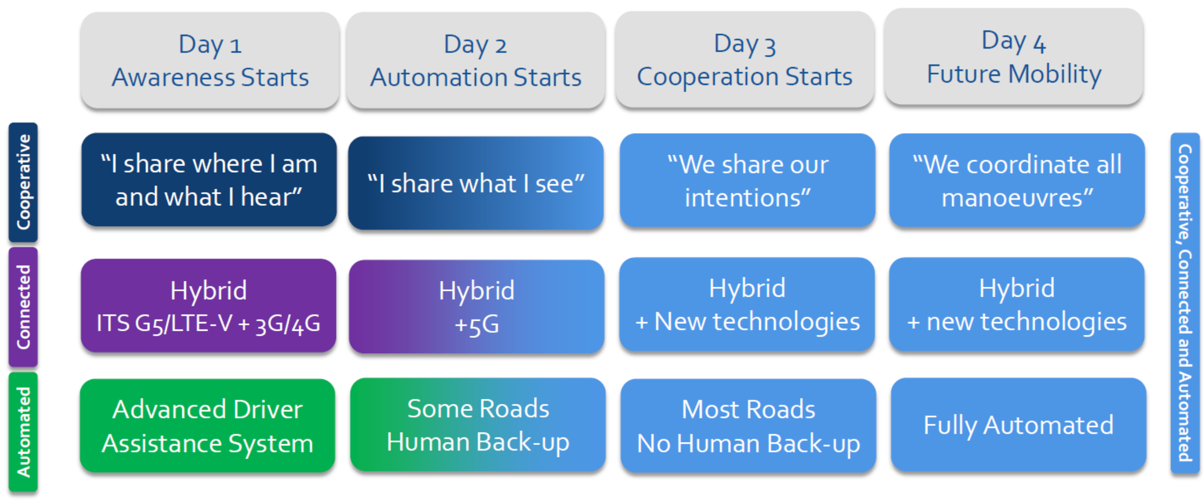
This type of cooperation includes sharing sensor data among vehicles. An example of this type of cooperation is a heavy vehicle sharing its camera feed with vehicles behind it to overcome the vision barrier and improve perception.

Day 3: We share our intentions

This type of cooperation includes sharing plans for future manoeuvres with other traffic participants. An example of this kind of cooperation is a vehicle sharing a lane-change plan with nearby vehicles.

Day 4: We coordinate all our manoeuvres

In this type of cooperation, vehicles use a sequence of cooperative messages to coordinate manoeuvres, such as cooperative merging.



Source: European Commission

Figure 21 Day 1 to day 4 road map for C-ITS deployment (Vantomme, 2018)

Other classifications and main use cases

Apart from the two common classifications discussed earlier, other classifications of C-ITS services have been proposed (Marilisa *et al.*, 2018; Botte *et al.*, 2019; Zhang *et al.*, 2021). Here, we would like to mention one interesting and useful classification of C-ITS services provided in (Maaloul *et al.*, 2021). This classification is based on the level of safety required for each service and can aid in prioritizing C-ITS messages based on safety criticality in dense vehicular environments, which will likely result in an overload of VANETs.

Comparison of different classifications

For clarity, we briefly compare SAE cooperation classification with Day X classification here. SAE class A (status-sharing) includes day 1 and day 2 applications; SAE class B (intent-sharing) corresponds to

day 3 applications; and SAE class C (agreement seeking) is comparable to day 4 applications. Moreover, according to SAE, class C is only foreseen for vehicles of level 3 automation or higher.
SAE class A and day 1-2 applications relate to ISAD class B (i.e., cooperative perception). SAE classes B, C and D as well as day 3 and day 4 applications are related to ISAD class C (i.e., cooperative driving). Table 18 Comparison of different classifications summarises the information discussed above.

Table 18 Comparison of different classifications

SAE	**Class A** Status-sharing		**Class B** Intent-sharing	**Class C** Agreement-seeking	**Class D** Prescriptive
Day X	**Day 1** I share where I am	**Day 2** I share what I see	**Day 3** We share our intentions	**Day 4** We coordinate maneuvers	X
ISAD	**Class B** Cooperative perception		**Class C** Cooperative driving		