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DiREC

Digital Road for evolving Connected & Automated Driving

Final Report

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Digital Road for Evolving Connected and Automated Driving

Final Report

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Executive Summary

The 2020 CEDR Research Call on *the Impact of CAD on Safe Smart Roads* had as its aim to "*prepare the national road authorities on future challenges of connectivity, digitalization and automation to get to an autonomously well-managed traffic flow." CEDR cautioned that " If NRAs do not act proactively, the vehicle manufacturers will determine the automation of traffic flow alone, the NRAs will fall behind and huge investment will be needed to safeguard NRAs' objectives. NRAs' goals and roles in the Cooperative, Connected and Automated Mobility of the future must be clear…NRAs need to determine and act before other parties decide in our place where we need to invest.".*

The Digital Road for Evolving Connected and Automated Driving (DiREC) project set out to develop a toolkit for NRAs to use in their assessment and development of their capabilities as digital road operators. This toolkit, referred to as the CAV Readiness Framework (CRF), focuses on five key areas of provision that are central to the development of connected and automated driving capabilities. Those areas being:

- Physical infrastructure
- Digital infrastructure
- Communications infrastructure
- Standards and regulation
- Operational support

DiREC focused on technologies, services and regulatory infrastructure for which NRAs might either have direct responsibility or at least significant influence. Development led by vehicle manufacturers or the regulations governing them were considered to be outside the scope of influence of the NRAs, for the moment at least. Instead, attention was given to those technologies and services that are likely to be generically useful to most or all future CAD solutions. We identified that there is still a considerable diversity of approaches amongst the developers of automated vehicles, with no single technical strategy yet close to being dominant. We also found that while SAE level 3 Automated Lane Keep Assist systems are now commercially available and legal in Europe, level 4 systems, in which operation without the possibility of fallback to a human operator is foreseen, remain some way away from either commercial or legal feasibility in Europe.

DiREC conducted a review of literature and held a series of meetings and workshops with NRAs, vehicle Original Equipment Manufacturers (OEMs), telecoms and other service providers. The purpose of this review was to determine the attitudes of NRAs towards Connected and Autonomous Driving (CAD), and the levels and types of support that they are willing to provide. This review and engagement identified many differences of opinion among NRAs on how and even whether they should support CAD. These differences were the result of many factors, including lack of engagement between NRAs and OEMs and hence lack of understanding of needs, NRAs' lack of visibility on the rate and extent of technological progress in vehicle systems and communications technologies, NRAs' lack of involvement in development of national and regional regulations, and uncertainty regarding the uptake of CAD at all its different levels. In general, many NRAs feel underequipped to understanding current technologies and future direction.

This lack of a clear vision for CAD amongst NRAs is perhaps reflective of the seismic shift that automation may require them to make in the way they are organised and operate. Currently the NRAs are responsible only for the provision and operation of physical assets, supported to some extent by digital resources which focus on the maintenance of the assets themselves or supporting users in travelling safely and efficiently by detecting and warning drivers of hazards or congestion. The exchange of information between the NRA and the travelling public is minimal, almost exclusively unidirectional, from the NRA to the user, simplistic, and largely incidental to the safe conduct of any individual journey. NRAs require only the most simplistic understanding of the vehicles using their networks, largely restricting their interests to the masses and dimensions of those vehicles and historically haver not sought to exercise any influence over the detailed design of those vehicles through regulation. Vehicles on the network are entirely under the control of their drivers who carry the legal responsibility for operating those vehicles safely and within limits of speed, mass, usage etc. However, a future in which automated vehicles are commonplace may see the role of NRAs moving closer to that of air traffic controllers; taking responsibility for the routing of individual vehicles and ensuring they avoid collisions and other hazards and may require NRAs to have a much more active role in the safe conduct of journeys made by individual vehicles. These responsibilities may include the bi-directional exchange of considerable volumes of highly detailed data which may be vital to the safe operation of the vehicle. This shift will require NRAs to considerably develop their digital capabilities and engage with the communications industry in ways which have never previously been necessary. However, at present 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.

As a result of this review process, DiREC developed a vision to empower NRAs with the tools and techniques to make measurable assessments of their investment decisions that will drive the adoption of CAVs on the road network. The associated mission was to deliver a CAV-Readiness Framework (CRF) for NRAs that supports current and future requirements of the network. Hence DiREC developed the CRF. The CRF can help NRAs to define the ways in which they wish to support CAD, specifically through assistance to the provision of Cooperative Intelligent Transport Systems (C-ITS) services. C-ITS services and use cases are well-defined at a conceptual level, although their implementation and standardisation are still evolving. NRAs can support the implementation and evolution of C-ITS services through a mix of physical, digital and communications infrastructure, operations, and inputs to standards development. The CRF allows NRAs to articulate the type and extent of support they wish to provide. It helps NRAs to prioritise that support through identification and analysis of costs and benefits. It also helps NRAs to develop roadmaps to enable them to plan for that support.

DiREC produced a CRF tool and has demonstrated how the CRF could be applied in practice by an NRA. The CRF tool is a prototype. We recommend application of the tool by NRAs to test its usefulness and applicability to help them develop roadmaps to support individual C-ITS services. The CRF also has the scope to evolve as C-ITS services evolve. Both the CRF and the tool can be developed in the long term to help NRAs articulate and shape their future investments in C-ITS services and hence in CAD.

Abbreviations

Abbreviation	Definition
ASAM	Association for Standardisation of Automation and Measuring Systems
CAD	Connected and Automated Driving
CAV	Connected and Autonomous Vehicle
CBA	Cost Benefit Analysis
CEDR	Conference of European Directors of Roads
C-ITS	Cooperative Intelligent Transport Systems
CRF	CAV-Readiness Framework
DENM	Decentralized Environmental Notification Message
DiREC	Digital Road for evolving Connected and Automated Driving
ETSI	European Telecommunications Standards Institute
GLOSA	Green Light Optimised Speed Advisory
GNSS	Global Navigation Satellite System
HCM	Highway Capacity Manual
HLN	Hazardous Location Notification
InterCor	Interoperable Corridors deploying Cooperative Intelligent Transport Systems
ISAD	Infrastructure Support Levels for Automated Driving
ITS	Intelligent Transport System
IVI	In-Vehicle Information
IVS	In-Vehicle Signage
LoS	Level of Service
MEC	Multiaccess Edge Computing
NRA	National Road Authority
ODD	Operational Design Domain
OEM	Original Equipment Manufacturer
PKI	Public Key Infrastructure
PVD	Probe Vehicle Data
RWW	Road Works Warning
RWW-LC	RWW Lane Closure
RWW-RC	RWW Road Closure
RWW-M	RWW Mobile
RWW-WM	RWW Winter Maintenance
SAE	Society of Automotive Engineers
TMA	Truck Mounted Attenuator
TRB	Transportation Research Board
WP	Work Package

Glossary

Term	Meaning
C-ITS	Cooperative Intelligent Transport Systems. Refers to transport systems, where the cooperation between two or more ITS sub-systems (personal, vehicle, roadside and central) enables an ITS service to offer higher quality or an enhanced level of service, compared to the same ITS service provided by only one of the ITS sub-systems.
C-ROADS	The platform of harmonised C-ITS deployment in Europe, 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.
CAV Readiness Framework	Defines the needs of CAD in terms of the physical and digital infrastructure, services, and operational policies and procedures that NRAs could provide to support CAD.
DATEX II	DATEX II or DATEX 2 is a data exchange standard for exchanging traffic information between traffic management centres, traffic service providers, traffic operators and media partners. It contains for example traffic incidents, current road works and other special traffic-related events.
HD Mapping	High Definition mapping is highly accurate mapping used in various applications including positioning, driver-assistance and smart mobility applications which can be used to support autonomous driving.
ISAD Infrastructure Support Levels for Automated Driving	The ISAD levels were developed under the Inframix project. They categorise the digital information support given by physical and digital infrastructure to CAD.
Road Works Warning (RWW)	An example of a C-ITS service. In the Road Works Warning service, warnings are provided to road users about road works, which can be mobile or static, short-term or long-term. Road works cover all types of operations undertaken by the road operator including operations involving road operator vehicles.
SAE Levels of Automation	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. It 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.

1 Introduction

Whilst Connected and Automated Driving (CAD) will bring new choices and capability to users of the road network, it is an area of technology which is likely to bring disruption and change to the design and operation of road network infrastructure. Most forms of CAD require some level of infrastructure support for their safe operation. Additional infrastructure and services to support CAD would have the potential to improve safety even further, and to bring other benefits such as increased capacity or reduced congestion. However, conventional road infrastructure is already costly, amounting to around 1-2% of GDP for OECD countries, and accommodating the needs of new CAD technologies may increase these costs. But the infrastructure requirements from OEMs are not always clear, and it is difficult for NRAs to predict and plan the future levels of support needed for CAD, given the rapidly evolving technology and uncertain projections of future CAD demand. There is a need for better dialogue between NRAs, OEMs and service providers to articulate those requirements and to define a roadmap and responsibilities for achieving safer and smarter roads through CAD.

In 2020 the CEDR Transnational Research Programme (funded by Belgium (Flanders), Denmark, Ireland, Israel, Netherlands, Norway, Sweden, Switzerland and the United Kingdom) published its call on the Impact of CAD on Safe Smart Roads. The aim of this research programme was to prepare national road authorities for the future challenges of connectivity, digitalization and automation, to achieve autonomously, well-managed, traffic flow. The call looked to address three sub-topics: A - Digital Infrastructure; B - Connectivity; and C – Traffic Management. The DiREC (**Di**gital **R**oad for **E**volving **C**onnected and Automated Driving) project proposed to address sub-topics A and B.

DiREC proposed to establish a CAV-Readiness Framework (CRF) to support dialogue between NRAs, OEMs and service providers, based on a Level of Service approach. The CRF would define the needs of CAD in terms of physical and digital infrastructure, services, and operational policies and procedures that NRAs could provide to support them. The CRF would consider a wide range of components that influence the ability of the NRA to become a digital road operator, including machine readability of physical infrastructure, digital services, connectivity, and aspects such as governance of the infrastructure and services, and legal and regulatory requirements.

DiREC also proposed that the CRF would include indicators that could be applied to measure the extent to which a road network is able to support CAD. These indicators could, for example, assess the machine-readability of infrastructure, the extent and quality of digital infrastructure, and the types of service available. The CRF would also include tools and methodologies to conduct cost-benefit analyses to help plan and develop different types and levels of service the infrastructure could provide to support CAD. These tools and methodologies would 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 could provide, including digital mapping, localisation, navigation and other services around traffic management. Other tools will measure organisational and network maturity levels against the CRF.

The purpose of this final report is to provide a summary of the DiREC project and its deliverables.

2 Overview of DiREC

2.1 Objectives

DiREC aimed to deliver the following objectives:

- A common vision of the requirements for CAV-ready, machine-readable and navigable infrastructure.
- A CAV-Readiness Framework (CRF) to define different CAV scenarios and the different infrastructure and services that support them, using a service level approach.
- A clear vision for, and definition of, digital twins among NRAs, including how they can be designed and implemented to support CAD.
- A review of the legal and regulatory aspects across Europe to enable coordinated and productive progress to support CAD.
- Practical service level assessment tools to help NRAs measure their progress towards CAV readiness.
- A methodology for conducting cost-benefit analysis to help NRAs plan and develop strategies and projects in support of CAD, supported by case studies.
- A roadmap for NRAs that identifies the benchmarks and the steps that could be taken to achieve defined levels of service in the short, medium, and long term.
- Recommendations for future governance of the CAV-Ready Framework.

2.2 Approach

DiREC conducted through a series of Work Packages and Tasks to address the two topics of the CEDR call, which led to the development of the CRF as described in Figure 1. The Work Packages were:

- WP0 Project Management
- WP1 Stakeholder Management
- WP2 Review and Evaluation
- WP3 Framework Development
- WP4 Case Studies and Roadmap
- WP5 Dissemination

Figure 1. DiREC Work Packages and the CRF

2.3 Deliverables

Table 1 shows the key deliverables under the project. This Final Project Report (D0.4) summarises the main research outcomes from DiREC's technical work packages as presented in the remainder of this report. These deliverables can be found at https://direcproject.com.

Table 1. DiREC deliverables

Work Package	Description	Deliverable No	Title
WP0	Project Management	D0.4	Final Project Report
WP2	Review and Evaluation	D2	Summary Report for Review and Evaluation
WP3	Framework Development	D3	CAV-Readiness Framework (CRF) tool
WP4	Case Studies and Roadmap	D4	CRF Roadmap

3 Stakeholder Management

WP1 Stakeholder Management was designed to ensure that key stakeholder groups were identified and coordinated for consultation across work packages in the project. Stakeholders were categorized into four main groups, namely National Road Authorities (NRAs) and Operators, Original Equipment Manufacturers (OEMs), Telecommunication service providers, and Other service providers, which include 3rd party data providers, mobile app providers, data standard organisations, and road user groups. A number of experts were selected and interviewed from each category. The following gives a brief summary of the main findings of the stakeholder engagement within each stakeholder category.

3.1 National Road Authorities (NRAs) and Operators

NRAs expressed a lot of uncertainty about the future uptake of CAD and future travel demand. This impacts budgeting and planning and causes uncertainty over the extent to which NRAs should support CAD, and the type of support that they should consider. Uptake of CAD is likely to be driven by legislation. Once the legislation is in place, then trust and acceptability are likely to increase, and peoples' behaviours will likely change quickly. Future projections of CAV usage on the network will impact the business case for NRA support to CAD. It is also important to understand that NRAs are funded by the taxpayer. Hence investment should be inclusive and seen to benefit all road users. One particular example was that of NRA focus on traffic management and controlling speeds on the network as a whole - to improve safety and efficiency for all.

A need was identified for a more common approach across NRAs, 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. For example, there are often many potential technological solutions to the same problem. It requires coordination and cooperation to establish the best and most cost-effective solutions in any one situation or use case (and it is even a challenge to define who the actors are and what their responsibilities in a particular C-ITS application). Further engagement and understanding is needed for NRAs to articulate their objectives, strategies, identify roles and responsibilities, and to plan and budget to support CAD. The 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 their objectives, and to define and plan what those levels of support might be.

It is clear from discussions with NRAs and from review of literature that there are many different NRA attitudes across Europe, and many potential solutions to the same problem depending on those attitudes and approaches. For example, one country might be willing to invest heavily in standardisation and maintenance of physical road signs, whereas other NRAs might consider that it is up to the OEMs to recognise existing signs, while others might say that rather than improving physical signs they will invest in making digital sign information available to CAVs.

A further example is platooning on bridges. Some NRAs have an attitude that as long as they make information on load capacity of their bridges available, and if the load capacity of a bridge is not sufficient to support platooning, then the trucks should increase the distance in the platoon. Therefore they are not looking to design of infrastructure to accommodate platooning, rather they are looking at C-ITS and traffic management solutions. The same arguments can apply to almost all physical, digital and communications infrastructure and services found of the network.

3.2 Original Equipment Manufacturers (OEMs)

The consultation identified that OEMs consider the key requirements for the successful deployment of automation in their vehicles to be:

- The sensors and cameras provided by their tier 1 suppliers
- The ADS software developed by themselves, or by companies with whom they closely collaborate
- The existence of appropriate Legal frameworks and safety standardisation.

OEMs did not express any concerns over the collaboration required between them and their tier 1 suppliers. The only improvement required are improvements in performance of the sensors as well as a desires for gradual reduction in prices, both of which are expected to happen. OEMs also see no collaboration barrier for ADS software development. However, the performance of this software needs to improve significantly to make next-level CAD a reality.

With respect to legal frameworks, OEMs consider CAD legislation in Europe to be lagging the technology developments. A comprehensive functioning legal basis for CAD is not in sight at the moment, which is a major challenge to large-scale success of consumer CAD.

3.3 Telecommunication service providers

The findings of the engagement with the key Stakeholders in this category included:

1. The need for defined Use cases to help drive wider adoption and market investment.
2. Importance of distinguishing between Connected Vehicles and Automated Vehicles - as they have potentially different requirements and are at different stages of evolution. The use of ADAS and other systems to support Connected Vehicles is not the same as Automated Vehicles all being Connected Vehicles, and vice-versa.
3. Development of commercially driven pilots that enable the market to support development programmes against their roadmaps.
4. Articulation of the business case needed to support the various use cases, and an overall engagement and collaboration of key stakeholders linked to the value of ongoing investment in emerging technologies and service delivery.
5. Understanding the importance of a digital backbone to support physical infrastructure investment.
6. Creating a framework and supporting body, linked to those already established, to help bring together the various actors across the ecosystem to share knowledge and roadmaps for deployment.
7. Challenges to the adoption of different technologies need to be addressed and NRAs must be empowered to procure the best choices linked to their required Use cases.
8. Consolidation of technical choices linked to ITSG5 and 5G, and linking use cases to the technologies best suited to their delivery.

3.4 Other service providers

The interviews with other service providers obtained the views of further members of the CAD ecosystem on the role of technology and Road Administrations on the ability to implement CAD. The interviews identified a range of challenges related to the deployment of connected and automated driving and its supporting technologies. However, it was of particular note that stakeholders had differing opinions on the way existing roads should be adapted to allow highly automated vehicles to operate. For example: the use of separate dedicated CAD lanes vs the ability to operate CAD on all lanes; the deployment of different types of communication (ITS-G5), and whether it should be in response to a need (i.e. once there are a lot of CADs on the network) or to stimulate the need (i.e. once it is in place then CAD use would grow); and whether deploying technology on the network should be undertaken by NRAs (e.g. to support location services) or not.

Based on the results of the interviews, several services were identified which stakeholders considered as potential services that could be provided by the road operator (or service providers collaborating with the road operator) to automated vehicles:

- Dedicated lanes for automated vehicles
- Digital maps for navigation purposes (allowing the automated vehicle to navigate)
- The detection of GNSS jamming in roadside environment
- Road condition information (to support calculation of vehicle ODD)
- Information on traffic rules and signs
- Locations with exceptions to traffic rules and signs (e.g. road works sites where lane markings may be missing or incorrect, traffic signs and traffic rules may be overridden with instructions by a traffic control officer or temporary traffic arrangements not shown in digital maps)
- Vehicle sensor calibration services in the roadside environment.

4 Review and Evaluation

WP2: Review and Evaluation produced a series of summary reviews and evaluations for different aspects of the CAV Readiness Framework, based primarily on literature review and engagement with NRAs, OEMs, telecoms and other service providers. The following summarises some of the key findings of that work (the heading numbers (e.g. T2.1) refer to the DiREC task number).

4.1 Infrastructure Design and Operation (T2.1)

4.1.1 Physical Infrastructure

The physical infrastructure requirements of roads will differ for different CAVs, and for different use cases for CAD. Most research has concluded that it is not practical to implement changes to physical road design to support vehicles with different SAE levels of automation (SAE, 2014). Where there are sections, carriageways or lanes that can be dedicated to vehicles with particular SAE levels, then certain physical design changes could be considered. It has been suggested that, on those roads where there is a mix of traffic (non-automated and automated), 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 this.

However, 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 CAD.

4.1.2 Digital Infrastructure

There are many ways in which digital infrastructure components can support CAD.

The INFRAMIX project established the important Infrastructure Support Levels for Automated Driving (ISAD) (INFRAMIX, 2020). They categorise the digital information support given by physical and digital infrastructure to CAD. This classification scheme helps prepare road infrastructure to support the coexistence of conventional and automated vehicles on road networks.

Satellite positioning support is key to automation. High accuracy positioning needs infrastructure support such as land stations, and dedicated sources are 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 (High-Definition) Mapping is seen as important to provide both static and dynamic information in a high-precision environment for use in positioning, driver assistance, and smart mobility applications.

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 CAD. 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 vehicles or barriers), coverage of blackspots or HD maps for locations with insufficient lighting such as tunnels.

However, NRAs feel underequipped with regard to understanding current technologies and future direction. It is clear that there will be different requirements and different priorities within the strategic road networks of each country. Many NRAs are only now beginning to understand, define and plan what those levels of support might be.

4.1.3 Operations and Services

It is clear that 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). Uptake of CAD will have implications for traffic volumes and traffic speeds, and there may be both opportunities and implications for NRAs regarding the traffic management of these vehicles. The various digital infrastructure components (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 NRAs in the next decade to operations and services for digital and communications infrastructure, including data centre maintenance; software updates; cloud security; and data privacy.

4.2 Infrastructure Connectivity (T2.2)

There is no common agreement on the communications technologies of choice for delivery of CAD. In a multi-party ecosystem the business case - and the cost versus reward across the different actors - is not sufficiently clear. Therefore, there is lack of clarity on the business cases for where to invest. However, progress is being made. C-ITS deployments have taken place, albeit in limited areas, and there have been various 5G and ITS-G5 connectivity trials in Europe and elsewhere (including 5G-MOBIX, 5G-DRIVE, 5G-LOGINNOV, 5G-ROUTES to name but a few).

What is clear is that the technologies themselves can provide capability in the delivery of a range of services. The choice of 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 ITS-G5, 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, along with engagement with the various key actors, OEMS, telcos to underpin a delivery model that protects investment decisions and delivers customer satisfaction.

4.3 Data Exchange (T2.3)

DiREC has identified four main classes in the CAD data ecosystem: 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).

There are various standards within C-ITS relating to the exchange of this data, including traffic safety data exchange standards, real-time traffic data exchange standards, and HD map data exchange standards. DiREC has highlighted the importance, benefits, challenges, and future direction of the exchange of these data between different CAV stakeholders, and has provided a systematic overview of the issues involved, including those associated with real-time and non-real-time exchange of data, distinct categories of existing and developing standards for data exchange within C-ITS, data exchange models and formats, and the challenges related to exchanging each category of data.

There are particular challenges associated with data exchange for HD maps, including HD map content and standards, quality control and minimum data quality requirements, defining a universal mapping format, size of map data files, mapping traffic laws and regulations, improving navigation information integrity, collaborative mapping, scalability (i.e., building maps at the national or international scale), update and maintenance, business models, monetization and production cost, and preserving privacy.

4.4 Digital Twins (T2.4)

This activity explored the concept of Digital Twins of physical assets, and how these can be utilised to benefit CAD. Significant research, development and pilots of Digital Twins are ongoing in road authorities and by OEMs. There are some commonalities in terms of the types of information that might be included in a Digital Twin which could be relevant to CAD, including static data (road geometry, asset type, locations of signs, etc.) and dynamic data (road conditions, speed limits, incidents). However, there is no overarching standard or framework for Digital Twins for NRAs to support CAD. DiREC has also identified legal implications, as Digital twins are complex and can create challenges of data ownership, causation and liability. There are questions around data use rights, privacy, and potential exposure from a cybersecurity perspective.

With regards to HD mapping, this should be one of the fundamental data layers in a Digital Twin. However, 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, and there is lack of interoperability between map suppliers. Furthermore, there seems to be little incentive for mapping companies to share their data.

Without a standardised approach to what Digital Twins are, it is difficult for NRAs to make decisions about the type, use and business value associated with their creation. NRAs have limited budget and ongoing day to day operation requirements that will take resource and capital requirements, and these may be taking priority over investment in digital transport requirements. However, it is expected that the work of CCAM and C-ROADS, and the EU's Mobility Strategy, will better define the needs for digital transport systems. These may highlight how NRAs should consider Digital Twins and develop meaningful case studies before widespread deployment.

4.5 Legal and Regulatory (T2.5)

Legal and regulatory aspects will affect (CAD) and the capability of road infrastructure to support it. DiREC has identified regulatory challenges, limitations and gaps and reviewed existing legal and regulatory frameworks relating to CAD, including examples of ongoing regulatory development. Policy and legislation are considered as one of four pillars and key enablers of CAV readiness, along with technology and innovation, infrastructure, and consumer acceptance. 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 CAD. As such, regulatory frameworks are also crucial for gaining legal certainty, a wider acceptance in society of CAD, support for innovation, and stability of investment in technology and infrastructure.

Interviews with stakeholders (in WP1) revealed that CAD legislation in Europe is lagging behind technology developments. A comprehensive functioning legal basis for CAD is not on sight, which is a major challenge in large-scale success of CAD. 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 change. Therefore, for a successful deployment of CAD, there is a need for favourable legislation and standards that clearly define responsibilities for each actor within the CAD ecosystem, e.g., NRAs, OEMs, Telco, 3rd service providers.

Even though stakeholders perceive that the CAD legislation in Europe is lagging behind technology developments, and that the lack of legislation and standardisation is a major challenge, the review highlighted that there is extensive regulatory activity taking place both internationally and in the European Union, which aim to address the challenges of CAD introduction and deployment. Important regulatory initiatives expected to be adopted soon include the draft amendment of UN Regulation no. 157 on Automated Lane Keeping Systems, and the draft EU ADS Regulation.

There are also country-specific initiatives. For example, Germany and the UK have taken a proactive approach and introduced regulatory initiatives. 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 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 2025. The UK initiative is also divided into two regulatory paths: one directed at a human user in the vehicle, and a second directed at remote operation. Both legal systems have elaborated and introduced new legal actors and concepts like Technical Supervisor, Authorised Self-Driving Entity, User-In-Charge, and No-User-in-Charge.

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 particularly important and urgent to address and resolve to facilitate CAD uptake. These include 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 the proposal or development stage. It is too early to assess if these initiatives will sufficiently address risks, increase data sharing and result in public acceptance.

4.6 Impact of Emergent Technologies (T2.5)

Automated vehicles have the capability to read and identify many elements of the road environment such as traffic signs and lane markings. DiREC has summarised the types of information which either increase the robustness of the operation of automated vehicles or cannot easily be obtained with in-vehicle sensors, such as information on situations with likely operational design domain (ODD) termination. These may include e.g. weather conditions (real-time and forecasted) or traffic incidents.

Emergent technologies also include the technologies that enable vehicles to better communicate/connect. DiREC categorised connectivity needs into groups:

- 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

DiREC considered the connectivity options for roadside units, and reviewed the costs of installation of ITS-G5 roadside units, and upgrading of roadside ITS systems to support ITS-G5 communications, in addition to annual operating expenses of RSUs. In summary, three connectivity options (1: ITS-G5 combined with LTE connectivity, 2: C-V2X combined with LTE connectivity and 3: 5G-V2X including connectivity via LTE and 5G) were described. The connectivity options were mapped to six deployment scenarios of automated driving and the connectivity needs.

Various connectivity requirements were also identified for different deployment options including automated shuttles, automated vehicles for local goods delivery, automated trucks, highly automated passenger cars, and passenger cars with automated driving in limited scenarios.

4.7 Costs and Benefits (T2.7)

DiREC has proposed a cost benefit methodology that NRAs could apply to appraise schemes for infrastructure investment that they may be considering to support CAD. As with other investment proposals, NRAs should assess the value for money of such schemes. The proposed cost benefit methodology starts with recognising the organisation's core objectives. If the proposed scheme fulfils 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 of the scheme. The main ones include improvements in safety, maintenance, journey times and emissions. Modellers should quantify these impacts using agreed published values, such as the economic value of a prevented road fatality.

The main outputs of the methodology 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. It is also recognised that new technologies often have wider impacts on the economy and society. These could lead to the development of new sectors and an uncertain transition period. Acknowledging the difficulty in modelling such impacts precisely, NRAs should articulate possible trajectories including level of acceptance by the public and the impacts of CAD on vehicle usage, and qualitatively communicate these impacts.

4.8 Vision and Mission for the CAV Readiness Framework (T2.8)

In the light of DiREC's intention to build upon the above reviews, and hence develop a CAV Readiness Framework, the project included a task to articulate the vision and mission that the project aimed to achieve in the development of the framework. The vision was articulated as:

> "*to empower National Road Authorities (NRAs) with the tools and techniques to make measurable assessments of their investment decisions that will drive the adoption of CAVs on the road network*"

The mission was defined as:

> "*to deliver a CAV-Readiness Framework for NRAs that supports current and future requirements of the network*".

Hence it was proposed that the CRF should provide a tool for NRAs to understand the role they play and the actions needed to facilitate safe and secure CAD deployment. The tool and associated methodologies should 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 to support CAD, including digital mapping, localisation, navigation and other services around traffic management.

5 CAV-Readiness Framework (CRF)

5.1 Development of the framework

DiREC structured the CRF around C-ITS Services and Use Cases as defined under the C-ROADS project. C-ROADS is a joint initiative of European Member States and road operators for testing and implementing C-ITS services, with a desire for cross-border harmonisation and interoperability.

Under C-ROADS, the deployment of C-ITS is seen as evolutionary, starting with less complex use cases ("Day-1 Services" encompassing messages about traffic jams, hazardous locations, road works and slow or stationary vehicles, as well as weather information and speed advice). "Day 2" and "Day 3+" services are being investigated in R&D projects. Hence the C-ITS Service and Use Case definitions (C-ROADS, 2022) provided a firm basis on which to implement the CRF, both now and in the future. The CRF thus becomes a framework which can be used by NRAs to help assess their aspirations and readiness to support CAD, and to implement individual C-ITS services and use cases. It does this by (see Figure 2):

- Defining the C-ITS services to be provided;
- Breaking those services down into use cases and enablers;
- Scoring the NRAs readiness, aspirations and high-level assessment of costs and impacts of each enabler to help plan and prioritise the NRA support for CAD.

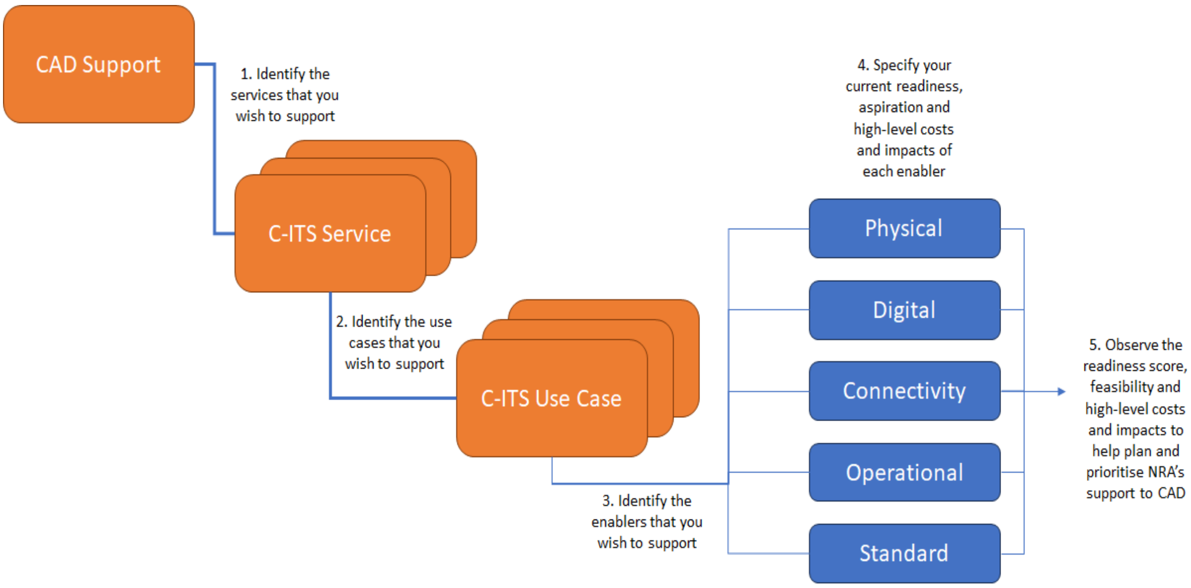

Figure 2. Overview of the CRF

In C-ITS terminology, a service is a clustering of use cases based on a common denominator, for example an objective such as awareness of road works. Services are also known as 'applications'. C-ITS services are currently identified as shown in Table 2.

Table 2. C-ITS Services

C-ITS Services
In-Vehicle Signage (IVS)
Hazardous Location Notification (HLN)
Road Works Warning (RWW)
Signalized Intersections (SI)
Automated Vehicle Guidance (AVG)
Probe Vehicle Data (PVD)

There is a one-to-many relationship between services and use cases. Take as an example the C-ITS Road Work Warning (RWW) service. C-ROADS currently identifies four use cases within that service: lane closure (RWW-LC), road closure (RWW-RC), road works – mobile (RWW-RM) and winter maintenance (RWW-WM). See Table 3.

Table 3. Use Cases for the RWW C-ITS Service

C-ITS Service	Use Cases
Road Work Warnings (RWW)	Lane closure (RWW - LC) Road closure (RWW - RC) Road works - Mobile (RWW - RM) Winter maintenance (RWW - WM)

In DiREC terms, and for the purposes of the CRF, each of these use cases can be described using a set of enablers. The 'enabler' is the lowest building block of the CRF tool. Some examples of enablers are shown in Table 4 along with their category which groups them under one of Physical, Operation, Digital, Connectivity, or Standard. The examples shown here are high-level examples for simplicity, more detailed examples are given in chapter 6.

Table 4. Sample enablers in the CRF tool

Enabler	Enabler Category
Roadside Units (RSUs)	Physical
DENM messaging (ETSI EN 302 637-3)	Digital
ETSI EN 302 637-3	Standard
C-ITS Mobile Roadside ITS G5 System Profile	Connectivity
Cameras	Physical
Response plan	Operation

The CRF defines, for each enabler:

- the *readiness* of the NRA to provide or deploy each enabler individually;
- the *aspiration* of the NRA to provide or deploy each enabler;
- the *feasibility threshold* for the service which defines the minimum level of support provided by the NRA to make implementation of this enabler feasible;
- high-level costs and impacts of each enabler.

The scores, costs and impacts of each of the above can be rolled up to the level of the use case, and the service, and indeed the total package of support for CAD, to help plan and prioritise NRA support for each enabler.

5.2 Level of Service Approach

The Level of Service (LoS) is a widely employed metric that quantifies the performance and quality of a provided service, utilizing a predetermined scale. In the transportation domain, road capacity (i.e., maximum throughput in a road section) is the most widely used indicator where the LoS is applied. In road capacity studies, the LoS definition is dependent upon the specific context and facility under examination, such as urban areas or motorways. In urban settings, the criteria typically employed for determining LoS include average travel speed, average travel time, frequency of stops, and delays. Conversely, on motorways, LoS is determined by factors such as vehicle density, traffic speed, and frequency of lane changes, as defined in the Highway Capacity Manual (HCM) (Transportation Research Board (TRB), 2016). Upon specifying the context, the chosen criteria are applied, and threshold requirements are established to categorize the performance and quality under the appropriate LoS. The LoS scale can range from binary levels (e.g., acceptable or unacceptable) to more nuanced scales. For instance, the HCM employs a six-point scale (A = very good; B = good; C = acceptable; D = bad; E = very bad; F = system breakdown).

However, for C-ITS services (i.e., information provision) the aim is to provide information that is, among other things, accurate and timely to CAVs so they can react accordingly to events on the road network. The CRF aims to illustrate the progress of (NRAs) towards becoming a digital authority, meaning that the NRAs should provide information (data provision) to CAVs that are precise, accurate, and timely. As such, we can define three distinct LoS categories:

1. Basic: Minimum acceptable performance/quality
2. Enhanced: Not optimal but sufficient performance/quality
3. Advanced: Ideal or best performance/quality

Additionally, a fourth level of service can be considered, for services that are already available. In this case, the LoS metric may be utilized by NRAs to assess the performance and quality of existing services.

5.2.1 Requirements

The CRF LoS is a quality and performance evaluation metric based on a set of enablers with predefined requirements. Transportation facilities may be classified based on road environment, such as urban, rural, or motorway. These different environments may impose unique demands due to the traffic they accommodate. However, our goal in the CRF was to develop a generic LoS tool that could be applied to any road environment, to any use case or technology. The definition should therefore be generic, applicable to all cases, and technology agnostic. Example LoS for the three proposed levels (basic, enhanced, and advanced) are given in Table 5.

The LoS is intended to evaluate the performance of the C-ITS service and needs to reflect the integrity and urgency of critical information provision, e.g., accuracy and latency. According to (Lubrich, Geissler, Öörni, & Ryström, 2022), the most important quality values are the minimum ones, as the basic requirements to realise an information provision service. If the quality is below this basic level, the benefits would be negligible.

5.2.2 LoS in the CRF

The application of LoS in the CRF should aim to determine the performance of the information provision, based on the enablers chosen in the CRF for the particular use case. The LoS gives an indication of which enablers need to be upgraded/installed to go up in the LoS scale. In this way, the CRF can serve to further refine the costs and impacts of NRAs support for CAD. At present, the CRF LoS defines the basic requirements for a service (in terms of availability, latency, refreshment, locational accuracy, and error rate). If necessary, the CRF could be used to (for example) compare the same use cases representing a basic level of service and an advanced level of service, using different enablers with different costs and benefits. At present, the costs and benefits of the implementation of each use case are not well enough refined or sensitive enough to accommodate different levels of services. This is an area that needs further definition and research, as the CRF is applied by NRAs.

Table 5. Suggested LoS Requirements for C-ITS services

Criterion	Definition	Basic	Enhanced	Advanced
Availability	Average availability for all operating connected data senders, including the communication chain up to the data receiver.	95% (347 days/year)	99% (361 days/year)	99.5% (363 days/year)
Latency	Total time for communicating messages between A and B	95% of all messages <10 minutes	95% of all Messages <7 minutes	95% of all Messages <2 minutes
Refreshment	Time interval for refreshing / updating the status reports coming from a data sender.	<5 minutes	<3 minutes	<1 minutes
Location Accuracy	Confidence for the horizontal position accuracy of the reported location with respect to the actual location.	95% of all messages within tolerance circle <10 m	95% of all messages within Tolerance circle <1 m	95% of all messages within Tolerance circle <10 cm
Error rate	Percentage of messages with erroneous information, as reported by a data sender, with respect to the reality.	<15%	<10%	<1%

Source: (Lubrich, Geissler, Öörni, & Ryström, 2022)

5.3 CRF spreadsheet tool

DiREC produced a spreadsheet version of the CRF in order to demonstrate how the CRF could be applied in practice by an NRA. A spreadsheet was considered to be an appropriate tool to help explain and walk through the operation of the CRF in an easy and accessible way, and to enable rapid development as a prototype for a more formal and refined tool.

This spreadsheet is referred to as the 'CRF tool' below. It has been issued as deliverable D3 under the project, and can be found on the DiREC website at:

https://direcproject.com

The CRF tool is structured into separate tabs:

- Instructions for use of the tool, inlcuding colour coding of pages and fields to identify data inputs and outputs ;
- Definition of which C-ITS services and use cases are to be analysed
- Detailed analysis of a particular C-ITS service and use case to calculate the aspiration, readiness and feasibility of NRA support for that service and use case
- Side-by-side comparison of the analysis of multiple services and use cases
- Overall assessment of an NRA's readiness to implement an entire service

Also, embedded in the spreadsheet are approximately 100 enablers that were identified from various sources including the Nordic Way Evaluation Report (Nordic Way, 2020) and the InterCor (Interoperable Corridors deploying Cooperative Intelligent Transport Systems) project (Rijkswaterstaat, 2017).

Chapter 7 recommends development and 'productisation' of a tool to go hand in hand with any future expansion or evolution of the CRF itself. Such a product could use the prototype tool developed here as a starting point.

Some images in the following sections are taken from the use of the tool. Screenshots of the tool are given in Appendix 1 to this Final Report.

5.4 Illustrative example

We provide, as an illustrative example, the design and implementation of an individual C-ITS service. Figure 3 is derived from a Nordic Way Evaluation Report (Nordic Way, 2020) and describes the flow of messages from an implementation of a Road Works Warning (RWW) system. The service and warning message for Road Works Warning (RWW) was generated at the RWW unit mounted on a truck mounted attenuator (TMA) vehicle. The message was received by a roadside unit which transferred the RWW message in DENM and DATEX II format through an interchange node to the OEM cloud and then to the vehicle. The OEM cloud also received Roadwork information messages from the Traffic Authority in DATEX II format. Figure 3 helps define the enablers to be considered in the implementation of the RWW service by the NRA.

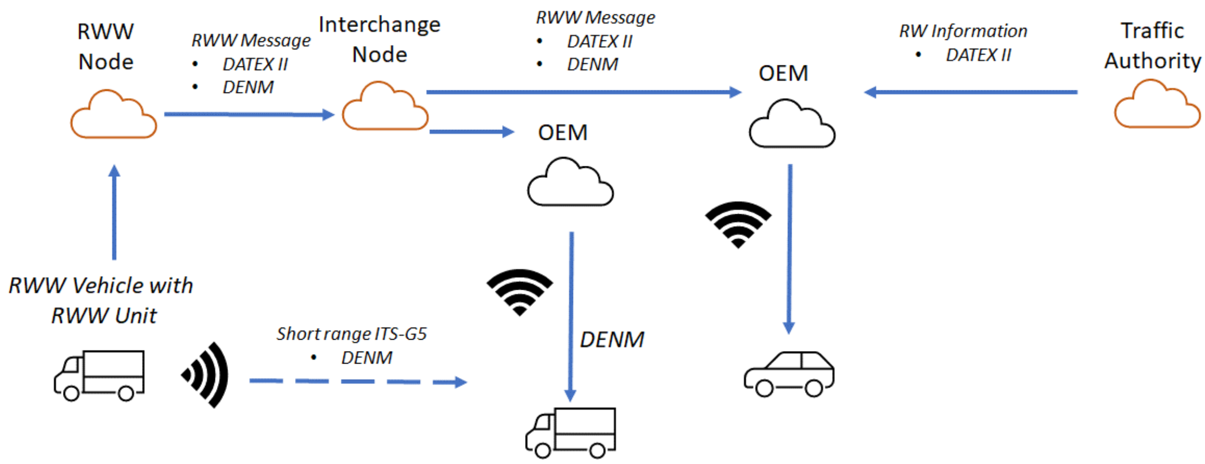

Figure 3. Flow of messages for Road Works Warning (RWW) implementation

In the CRF, each enabler is defined as a separate item. See Figure 4. Each enabler is given an importance weighting (Low, Medium, High) within its use case. The readiness score is calculated as the multiplication of the importance of the enabler with the stated readiness of the NRA to provide or deploy it (also Low / Medium / High) to give a Readiness Score. In the example, Roadside Units are given an importance of High (3) and a Readiness of High (3), to give an overall Readiness Score of 9. The overall Readiness Score for the use case is the average of the readiness scores of each enabler, in this case, 6.0.

Enabler	Category	Importance	Readiness	Readiness score	Aspiration	Aspiration score	Feasibility threshold	Treshold score	Feasible
Roadside Units (RSUs)	Physical	High	High	9	High	9	Low	3	1
DENM messaging (ETSI EN 302 637-3)	Digital	High	High	9	High	9	Medium	6	1
ETSI EN 302 637-3	Standard	High	High	9	High	9	Low	3	1
C-ITS Mobile Roadside ITS G5 System Profile	Connectivity	High	Low	3	High	9	Medium	6	0
Cameras	Physical	High	Low	3	Low	3	None	0	1
Response plan	Operation	High	Low	3	Low	3	Low	3	1

Figure 4. Measurement of the readiness of a NRA to provide or deploy enablers for a given use case

In addition to the readiness score, the framework also adds the concepts of the *aspiration* of the roads authority to provide or deploy each enabler, and the *feasibility threshold* for the service which defines the minimum level of support provided by the NRA to make implementation of this use case feasible. The Aspiration and Feasibility Threshold are given Low / Medium / High scores. A Feasibility calculation in the CRF helps to identify the enablers which the NRA needs to concentrate on in order to provide or deploy this use case. In this example, the NRA's low readiness to deploy C-ITS Mobile Roadside ITS G5 systems means that the provision of the overall use case is not feasible.

Within the CRF tool the average readiness, aspiration, and feasibility threshold of all enablers under the use case are shown diagrammatically (see Figure 5). The 'spokes' of the radar diagram represent the categories of the enablers.

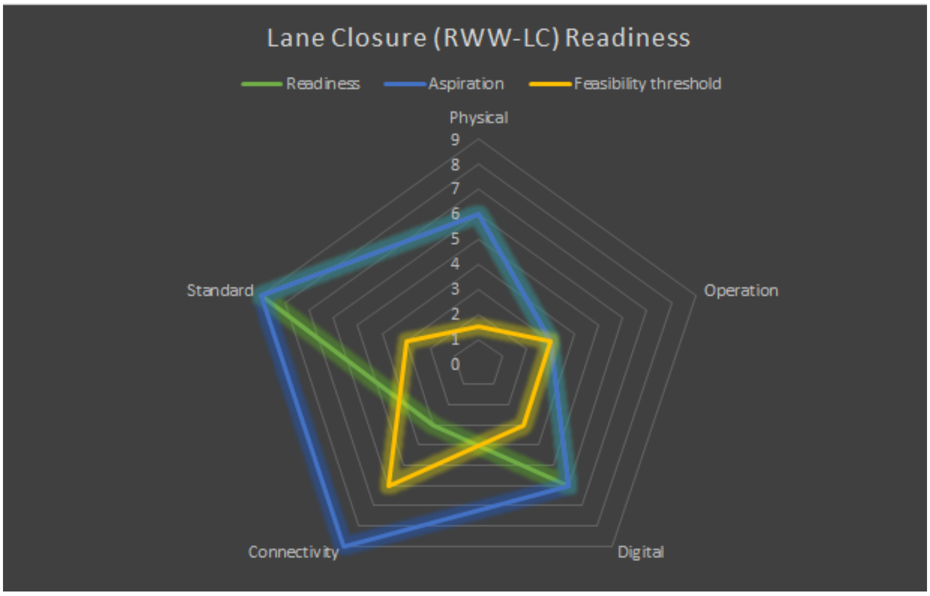

Figure 5. Readiness of a NRA to provide or deploy a specific use case

The framework also allows the NRA to define the impact of deploying each use case, in terms of five key impact factors (cost, safety, efficiency, environment, and inclusion). See Figure 6. Each of these impact factors is defined in terms of Low (1) / Medium (2) / High (3) scores. This graphically illustrates the relative costs and benefits of each use case or each service, and can be used by the NRA to help prioritise development or implementation of services.

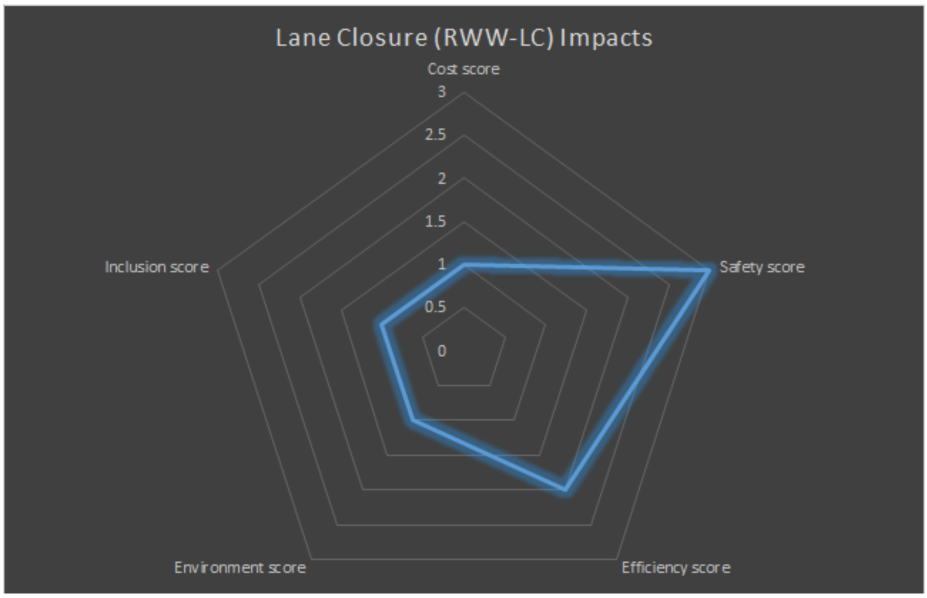

Figure 6. Impact of a C-ITS Use Case

Expanding this concept up, hence scoring each of the use cases for the service, provides an assessment of an NRA's readiness to implement the entire service. See Figure 7. Should the NRA wish to support the deployment of the entire RWW service across its network, then the outputs of the CRF help it identify those use cases and enablers which it should prioritise.

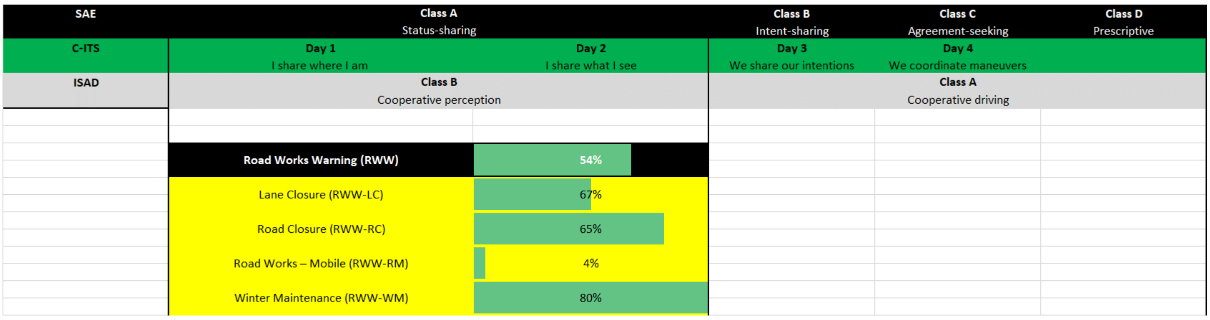

Figure 7. Measurement of the NRA's readiness to implement a C-ITS service

This example is simplified in the way in which high-level enablers have been defined, in order to explain and visualise the workings of the framework.

The CRF tool (Deliverable D3) contains a more realistic example using a case study of lower-level enablers.

6 Case Studies and Roadmap

6.1 Identify NRAs for Case Study (T4.1)

Task 4.1 aimed to identify NRAs for two case studies - the first to demonstrate how the CRF can be used to produce a tailored roadmap for the NRA for planning of their support to CAD; and the second to demonstrate how cost-benefit analysis can be applied using the CRF to refine and prioritise planning of support to CAD.

However, it proved difficult to identify NRAs (from the earlier stakeholder engagement workshops) that were in a position to assist in the application of the CRF. The first phase of C-ROADS piloting had come to an end in 2021, and there has been relatively little literature published on the results of the pilots in terms of whether anticipated costs and benefits were realised, and whether the result of the pilots could be used to plan further rollout of services. Also, the technical knowledge associated with owning and operating C-ITS services often lies with subcontracted parties, not the NRA, and it is very difficult to identify and engage with individuals several years after the completion of a pilot. Also, the granularity of cost data is dispersed across multiple contracting entities, which makes it challenging to get cost information to aggregate and analyze for a cost-benefit analysis of C-ITS service ownership and operation.

Further discussions were held with stakeholders, but it became clear that no NRAs closely engaged with the project were actively planning a strategy to support CAD. Therefore, the approach taken in the Case Studies was to demonstrate how the CRF could be used by "any" NRA to help plan their future support for CAD, based on general information derived from the consultation across NRAs that had already taken place in the project.

6.2 Case Study 1 – Tailored Roadmap using the CRF (T4.2)

The Roadmap (Deliverable D4) considers how the CRF can be used by any NRA to plan its support for implementation of a particular C-ITS service, in this case a Road Works Warning (RWW) service. It sets out a series of questions to help an NRA identify its aspirations and readiness with regards to Standards, Operation, Digital, Connectivity, and Physical support, as well as the minimum thresholds needed to deliver change. It describes two scenarios: a "gold-plated" scenario in which an example might NRA aspire to provide support across all of these areas and where this example NRA is ready and capable of providing such support; and a "base" scenario in which an example NRA also aspires to provide support across all areas, but that NRA does not yet have the capacity or readiness to provide such support.

NRA aspirations are identified in terms of leading questions that a strategic planner in an NRA should ask themselves to assess their organisation's appetite to support CAD. These include:

- Political – is there a political will to undertake change and how does that manifest itself within the organisation.
- Policy – is there policy direction in place that supports the investment of public funds to support the CRF's impacts around CAVs. This is borne out in the need to ensure alignment of the decision maker's priorities with the impacts of the services being provided.
- Strategy – Does the NRA have a strategy for support to CAVs that links to the policy and how is that integrated with the spend profile of the organisation.

NRA readiness is assessed in terms of:

- Where does CAD stand in terms of priority for investment ?
- Is there a budget line item in place and an associated business case developed to justify the investment ?
- How is the organisation geared up to exploit the increased information opportunities from CAD?

The feasibility of meeting the NRA's aspirations within a given timescale is also assessed in terms of:

- Development of standards across all areas (technology, communications, data)
- Regional and national regulatory efforts
- OEM direction
- Uptake of CAD by the public, which to a large extent is influenced by the above

The interventions by the NRA, based on a review of the various questions outlined above, must be considered against the impacts as outlined in the CRF. These should be considered in terms of general support to CAD, and in terms of the particular C-ITS service being considered. Thus, the likely impacts of such support must be clearly articulated and researched if necessary. The Impacts described in the CRF include:

- Safety – how can safety be improved through and built upon ?
- Efficiency – Is there a prime impact in terms of network efficiency, and how does this deliver services to the travelling public ?
- Environment – Can the solutions contribute to a positive and sustainable environment and how is this achieved?
- Inclusion – Is the service inclusive ? And if not, how are the impacts assessed and can other measures be identified to make it inclusive.
- Cost – The work undertaken by DiREC in the benefits versus costs need to be considered also as part of the deployment plan.

This case study went on to set out the different types of interventions that could be considered by an NRA, and to provide a set of detailed questions that the NRA planner should ask when developing their roadmap for future support to CAD. These interventions are broken down into the categories and sub-categories summarised in Table 6. A final roadmap to be produced by an NRA should answer at least those questions, and develop a series of activities and timelines to address the issues identified. Deliverable D4 lists the questions in detail, it can be found on the DiREC website at https://direcproject.com.

Table 6. Components of a roadmap for an NRA

Intervention Category	Sub-Category
Physical	Strategic Policy Technical Asset Management Data Security Integration Skills
Digital	Strategic Operations Technical Standards Data
Operations	Accountability Timeliness Performance
Connectivity	Performance Market Business Case

6.3 Case Study 2 – Cost Benefit Analysis (T4.3)

6.3.1 Selecting an example technology

Most CAD technologies are in their infancy and not fully field tested. Due to lack of testing and mass production, many technologies involved have uncertain costs (purchase and maintenance) and uncertain benefits (e.g. travel time, safety, convenience). Furthermore, at this stage of the technological readiness level of CAD, it remains uncertain what technologies will be provided from the vehicles themselves versus road infrastructure. In the light of this, and with the aim to provide a guideline for various potential technologies and a heterogeneous set of NRA rules, this case study provides an example of how one CAD technology**, lane closure warning**, could be assessed in a Cost Benefit Analysis (CBA framework).

Lane closures for maintenance, or due to road incidents, are a frequent occurrence that require substantial efforts in terms of signalling, personnel and infrastructure. In urban areas with high traffic volumes in particular, flexibility in lane use has proven beneficial in recent years. However, incursion into roadworks is a significant issue – National Highways (England) observes >100 such incidents each year with consequent risk to roadworkers and road users. This figure is likely to be a conservative estimate due to under-reporting of incidents. The biggest cost to road users is in the form of collision cost and travel time loss. These costs can amount to 1-2% of GDP lost for Western countries (Adler, Peer, & Sinozic, 2019).

Lane closures can be both planned (in the case of maintenance) and unplanned (in the case of a collision). For the benefits analysis we assume that CAD technologies (and even precursor connected vehicle technology) are able to warn the majority of road users about both types of lane closures.

6.3.2 Costs and benefits

As indicated in the introduction to this WP, the granularity of cost data is dispersed across multiple contracting entities. This makes it extremely challenging to get cost information to aggregate and analyze for a cost-benefit analysis of C-ITS service ownership and operation. For now, the CRF tool records a rough estimate of costs of each enabler in terms of High / Medium / Low, although clearly a more detailed assessment of costs would be preferred. A recommendation is included at the end of this report regarding better tracking and monitoring of costs of implementing C-ITS services. The CRF does, however, enable identification of whether the same enabler can be used to deploy or support multiple C-ITS use cases and services, and hence spread the costs over those multiple services.

In terms of benefits, the main benefits will accrue in terms of road incident (including crash) reduction and journey time optimisation. Road incident reductions will result from factors such a reduced likelihood of lane closure resulting in incidents, as well as the associated cost reductions from road congestion and health and material costs. It is a well-established fact that unforeseen road circumstances and road congestion itself increase the likelihood of further incidents (such as multiple rear end crashes on highways in foggy conditions or crashes with road maintenance teams). Furthermore, lane closure information can improve journey time reliability through better predictive routing apps such as TomTom, Here, Google Maps, Apple Maps and Waze.

Assumptions of the analysis:

- Lane closure information can be provided to road users through in-vehicle technology (either onboard equipment or portable device)
- Aftermarket installation and use of mobile Apps leads to a near-omnipresent application of lane closure warnings to road users. That is equivalent to a medium to high readiness level of technology on the end user side and on the side of the road authorities.
- All estimates must be adjusted by each NRA according to country and context specifications.
- Communication to road users is App or vehicle based and these costs are private cost, which are marginal since most modern smartphones and connected vehicle systems offer these capabilities.
- Supportive regulations increase the market penetration of lane closure warnings to 85%+ of road users, especially focused in dense urban areas and high frequency users (e.g. professional drivers).
- NRA lane closure information due to regular maintenance is included in its planning activities and therefore at zero additional cost.
- An NRA can communicate lane closure position and timing of lane closures to users of roadside information through data uploads on publicly available platforms and that road information providers can readily incorporate such warnings into their roadside announcements and vehicle routing.

1-2% of GDP is lost due to road incidents and traffic congestion. For example, the economic cost of crashes of 1.6% GDP for USA in 2019[1]; the economic cost of congestion as 0.4% GDP for USA in 2018[2].

The potential benefit of lane closure communication is then about 2% of GDP, which is then multiplied by the percentage reduction in incidents and traffic congestion that the lane closure warning system achieves. For simplicity, assuming that the lane closure warning system affects x% of travel time losses and the same x% of incident cost, the cost of such a system would need to be smaller than (<) x% x 2% GDP of the country or region in question. Assumptions and cost should be verified empirically before deciding on a specific action.

For high CAD market saturation levels, the potential annual benefits of the technologies should be compared with total annual investments. In that case, the potential benefits of safety and travel time improvement are enormous and would almost certainly recommend NRA support for CAD use. The biggest risk and cost risk of CAD is increased road use without road externality pricing, such as congestion cost, and traffic pollution, for which costs are also enormous (see WHO findings on traffic pollution). Similarly, long run reductions in urban density and agglomeration benefits that are possible side[3]-effects from CAD use can theoretically substantially diminish gains from CAD. To avoid these countervailing effects that diminish welfare gains, it is essential to coordinate knowledge sharing and strategies across urban planning, transport, economic and environmental ministries over the coming decades.

[1] https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/813403
[2] https://www.weforum.org/agenda/2019/03/traffic-congestion-cost-the-us-economy-nearly-87-billion-in-2018/
[3] https://www.who.int/activities/estimating-the-morbidity-from-air-pollution-and-its-economic-costs
And older OECD data:
https://www.oecd.org/env/the-cost-of-air-pollution-9789264210448-en.htm

7 Conclusions and Recommendations

7.1 Using the CRF to develop a roadmap for an NRA

The CRF provides a framework to help NRAs understand their current readiness to provide or deploy C-ITS services and to understand potential investment decisions and link them to an overall strategic approach to deployment and delivery of a range of services. In addition to measuring the readiness of the NRA to support individual services and use cases, it also adds the concepts of the *aspiration* of the NRA to provide or deploy each enabler, and helps identify a *feasibility threshold* for the service which defines the minimum level of support provided by the NRA to make implementation of this use case feasible.

The CRF should allow the NRA to define the impact of deploying each use case or service, in terms of five key impact factors (cost, safety, efficiency, environment, and inclusion). As discussed under the Case Studies section, it proved very challenging to identify the actual costs of establishing C-ITS services across different contracting parties. The project therefore outlined key assumptions and considerations when calculating costs and benefits to NRAs of supporting CAD. The CRF can illustrate the relative costs and benefits of each use case or each service, and can be used by the NRA to help prioritise development or implementation of services, although clearly there is significant scope for improvement in this if accurate and more granular costing is available.

DiREC Deliverable D4 provides a set of detailed questions that an NRA planner should ask when developing a roadmap for future support to CAD, and illustrates the types of component that should be in such a roadmap.

7.2 Implementing and refining the CRF

C-ITS and CAD is a rapidly developing field and to reflect this the CRF itself should evolve to refine its features and capabilities to help NRAs plan and prioritise their support to CAD. Figure 8 outlines a timeline of sets of potential actions that could help to implement and further develop the capabilities of the CRF. These actions are further described below.

Figure 8. Action plan for implementation and development of the CRF

Actions 1 - Now

i) To support effective use of the CRF, NRAs should undertake a number of internal workshops and discussions to help articulate their position on the topics raised. Such workshops in themselves will help drive utilisation of the CRF within the organisation and within CEDR. Indeed, it is possible to use the CRF as the centrepiece of the debate in order to stimulate engagement and outcomes linked to the various questions raised when considering a roadmap for CAD deployment.

ii) Consolidate through internal discussions in the NRA, the list of enablers and the impacts associated with the various investment decisions. Each NRA will have different drivers and philosophies, so it is important that the NRA's utilise the CRF at a local level to help their investment decisions.

iii) Use the CRF to develop further services and use cases in order to align with the work underway at a European level, such as C-Roads, to then fully consolidate the CRF tool itself a link between European engagement direction and the needs of the local Road authorities.

Actions 2 - Soon

i) The CRF can be contextualised for every NRA. However, at present it requires a good understanding of the CRF spreadsheet tool itself and the impact one change has on various other parameters. The development of a visualisation platform and dashboard view of the CRF would allow for ease of adoption and development.

ii) Utilise existing asset management tools and Digital Twins in road operators to help consolidate the various equipment types, utilisation, impacts, and costs and benefits linked to the CRF and the deployment of CAD on the road network. This would also provide the basis for indicators to measure the extent to which a road network supports C-ITS services.

iii) Develop a database at a National and European level to help inform the various parameters linked to the CRF and the wider Mobility sector, as well as developing the granularity and functionality of the CRF.

iv) Discussion with the wider stakeholder community around the use and impacts of the various telecommunication options to help articulate the business case linked to the service deployment around these options.

v) Use the CRF against a current deployment to help assess areas of refinement, both for the project itself and variances needed possibly for the CRF to help manage activities at a local level.

Actions 3 - Later

The CRF is a powerful framework for investment decisions linked to Connected and Automated Driving. To further develop its capabilities, it is recommended that:

i) Create a European CRF approach to help consolidate investments linked to the European Directives and local modification to allow for national investment decisions to take place.

ii) Link ongoing Road Investment decisions to the utilisation of the CRF and help articulate the business cases of the wider road network in this way.

iii) Propose future CAD funded projects linked to the CRF to support consistent and transparent approaches to investment and underline engagement by the NRAs and the wider community.

8 References

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9 Appendices

Appendix 1 : CRF Spreadsheet – Examples

This appendix contains instructions, inputs and outputs for the CRF spreadsheet tool produced under Deliverable D3 in this project.

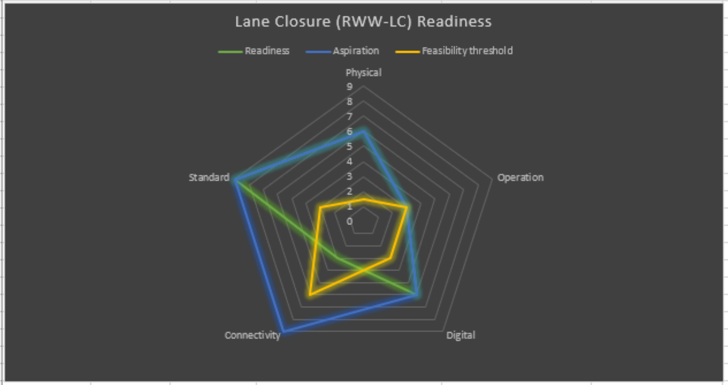
	Follow the steps in the given order and use relevant links to navigate CRF and observe its functionality. Each step represents input from NRA or input from CRF or output calculated by CRF.
	NRA Input
	CRF Input
	CRF Output
CRF step	Description
1	**Specify** all relevant C-ITS services and CAD use cases (relevant for the specific NRA who intends to use the CRF; here we have seleceted 3: HLN-SV, RWW-LC & SI-GLOSA)
2	For each use case (see examples and links in columns C:E):
2.1	**Specify** all (key) enablers by typing the enabler name in the first empty row of the enablers table (e.g., RSUs and cameras)
2.2	**Score** each enabler:
2.2.1	**Specify** importance of the enabler for the use case (choose from the dropdown menu, e.g., low, medium, high)
2.2.2	**Specify** current readiness (choose from the dropdown menu, e.g., low, medium, high) (this is the current state)
2.2.3	**Specify** feasibility threshold (choose from the dropdown menu, e.g., low, medium, high) (this is minimum level required for feasibility of the use case)
2.2.4	**Specify** aspiration (choose from the dropdown menu, e.g., low, medium, high) (this is the level that NRAs aspire (aim) to reach)
2.2.5	**Estimate** cost (choose from the dropdown menu, e.g., low, medium, high) (this is the cost of minimum feasible level)
2.3	**Score** use case:
2.3.1	**Estimate** (key) impacts of the use case (e.g., safety, efficiency, environmental impacts) (choose from the dropdown menu, e.g., low, medium, high)
2.3.2	**Observe** the cost of enabling the use case (for NRAs) (This is calculated by CRF)
2.3.3	**Observe** use case level scores per category of enablers (This is calculated by CRF)
2.3.4	**Observe** readiness, feasibility threshold, and aspiration per use case (aggregation of all enabler scores) (This is calculated by CRF)
3	**Observe** overall NRA readiness (based on the use cases considered) (This is calculated by CRF)
4	**Observe** the readiness level for each service (based on the aggregation of all use case scores) (This is calculated by CRF)
5	**Observe** the importance ranking for all enablers (based on contribution to all use cases) (This is calculated by CRF)

Figure 9. Instruction Page for the CRF Tool

Classification			Application			Infrastructure item information		Readiness								Cost	
ISAD	SAE	C-ITS	Service	Use case	Description	Enabler	Category	Importance	Readiness	Readiness score	Aspiration	Aspiration score	Feasibility threshold	Treshold score	Feasible	Cost	Cost value
Class B	Class A	Day 1	Road works warning (RWW)	Lane closure (RWW-LC)	Information service t	Roadside Units (RSUs)	Physical	High	High	9	High	9	Low	3	1	Low	1
Class B	Class A	Day 1	Road works warning (RWW)	Lane closure (RWW-LC)		DENM messaging (ETSI EN 302 637-3)	Digital	High	High	9	High	9	Medium	6	1	Low	1
Class B	Class A	Day 1	Road works warning (RWW)	Lane closure (RWW-LC)		ETSI EN 302 637-3	Standard	High	High	9	High	9	Low	3	1	Low	1
Class B	Class A	Day 1	Road works warning (RWW)	Lane closure (RWW-LC)		C-ITS Mobile Roadside ITS G5 System Profil	Connectivity	High	Low	3	High	9	Medium	6	0	Low	1
Class B	Class A	Day 1	Road works warning (RWW)	Lane closure (RWW-LC)		Cameras	Physical	High	Low	3	Low	3	None	0	1	Low	1
Class B	Class A	Day 2	Road works warning (RWW)	Lane closure (RWW-LC)		AID	Digital	High	Low	3	Low	3	None	0	1	Low	1
Class B	Class A	Day 1	Road works warning (RWW)	Lane closure (RWW-LC)		Response plan	Operation	High	Low	3	Low	3	Low	3	1	Low	1
						Type new enabler here											

Lane Closure (RWW-LC) Readiness					
Category	Readiness	Aspiration	Feasibility threshold	Cost	Feasible
Physical	6	6	1.5	1	1
Operation	3	3	3	1	1
Digital	6	6	3	2	1
Connectivity	3	9	6	1	0
Standard	9	9	3	1	1
Total	5.4	6.6	3.3	6	4

Lane Closure (RWW-LC) Impacts								
Safety	Efficency	Environmen	Inclusion	Cost score	Safety score	Efficiency sc	Environmen	Inclusion sco
High	Medium	Low	Low	1	3	2	1	1



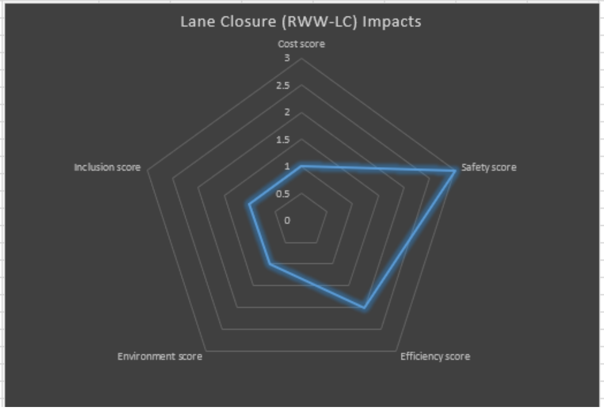


Figure 10. Sample worksheet for capture of the readiness, aspiration, feasibility and cost of RWW-LC readiness score and impacts for a single use case

	Overall Readiness		RWW-LC				HLN-SV				SI-GLOSA			
Category	**Overall Readiness**	**Overall Aspiration**	**RWW Importance**	**RWW Readiness**	**RWW Aspiration**	**RWW Feasibility**	**SV Importance**	**SV Readiness**	**SV Aspiration**	**SV Feasibility**	**GLOSA Importance**	**GLOSA Readiness**	**GLOSA Aspiration**	**GLOSA Feasibility**
Physical	5.5	7	1	6	6	1.5	1	6	9	7.5	1	4.5	6	4.5
Operation	3.7	6	1	3	3	3	1	6	9	6	1	2	6	4
Digital	6	6.5	1	6	6	3	1	6	9	6	1	6	4.5	6
Connectivity	4	9	1	3	9	6	1	6	9	3	1	3	9	3
Standard	7	9	1	9	9	3	1	9	9	3	1	3	9	6

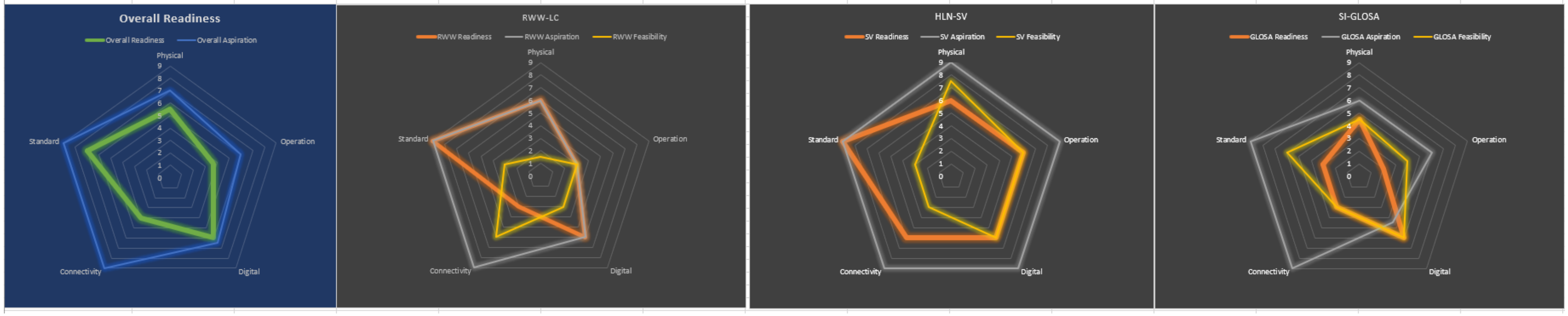


Figure 11. Sample worksheet that summarises the overall readiness of an NRA for multiple use cases

SAE	Class A Status-sharing		Class B Intent-sharing	Class C Agreement-seeking	Class D Prescriptive
C-ITS	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	
ISAD	Class B Cooperative perception			Class A Cooperative driving	
	Road Works Warning (RWW)	**52%**			
	Lane Closure (RWW-LC)	60%			
	Road Closure (RWW-RC)	65%			
	Road Works – Mobile (RWW-RM)	4%			
	Winter Maintenance (RWW-WM)	80%			
	Signalized Intersections (SI)	33%			
	Signal Phase and Timing Information (SI-SPTI)	23%			
	GLOSA (SI-GLOSA)	**34%**			
	Imminent Signal Violation Warning (SI-ISVW)	0%			
	Traffic Light Prioritization (SI-TLP)	13%			
	Emergency Vehicle Priority (SI-EVP)	95%			
	Automated vehicle guidance (AVG)	**45%**			
	SAE Level Guidance (AVG-SAELG)	0%			
	Platoon Support Information (AVG-PSI)	90%			
	Probe Vehicle Data (PVD)	**50%**			
	Vehicle Data Collection (PVD-VDC)	100%			
	Event Data Collection (PVD-EDC)	0%			

Figure 12. Sample Level of Service Summary for multiple C-ITS services

Embedded in this spreadsheet are approximately 100 enablers that were identified from various sources including the Nordic Way Evaluation Report *(Nordic Way, 2020)* and the InterCor (Interoperable Corridors deploying Cooperative Intelligent Transport Systems) project.

Enabler	Description	Category
Separate CAV carriageway		Physical
Video (Cameras)		Physical
Separate CAV lane		Physical
Additional refuge areas		Physical
Increased shoulder width		Physical
Shoulder strengthening		Physical
Road/bridge strengthening		Physical
Legacy (power supply)		Physical
Temporary Signs		Physical
Variable Messaging Signs		Physical
Temporary Road Markings		Physical
Radar		Physical
LiDAR		Physical
Ultrasonic sensors		Physical
Central ITS System (C-ITS-S)	Traffic Control Centre	Physical
Stationary Roadside Unit (R-ITS-S)	Stationary RSU	Physical
Mobile Roadside Unit (V-ITS-S)	Mobile RSU	Physical
Roadside beacons		Physical
Enhanced sign maintenance		Operation
Enhanced road marking maintenance		Operation
Enhanced emergency response		Operation
Equipped vehicles (trailer, patrols) – Mobile RSU - V-ITS-S		Operation
Response plan		Operation

Enabler	Description	Category
Traffic flow rules		Operation
3G cellular		Connectivity
4G cellular		Connectivity
5G cellular		Connectivity
5G MEC	Multi access edge computing	Connectivity
ITS G5 C-ITS		Connectivity
C-V2X C-ITS		Connectivity
Redundancy		Connectivity
Failure mechanism		Connectivity
Legacy (fiber optic)		Connectivity
ETSI CAM		Connectivity
ETSI MAPEM/SPaT		Connectivity
ETSI IVIM		Connectivity
ETSI SREM/SSEM		Connectivity
ETSI DENM (ground floor: safety info)		Connectivity
IVI (on top for rules & regulation info)		Connectivity
MAP (topological info)		Connectivity
Over-the-air functionalities		Connectivity
End-to-end encryption		Connectivity
Backend Cloud		Connectivity
Cloud from car industry		Connectivity
Cloud from road operator		Connectivity
Cloud from 3rd party provider		Connectivity
GNSS		Connectivity
HD map (on-board, accurate, precise, dynamic info, real-time)		Digital
Digital Platfrom (DT)		Digital

Enabler	Description	Category
ITS-AID	ITS Application Id	Digital
ETSI EN 302 665	Communications Architecture	Standard
ETSI TS 102 965	Application Object Identifier: Registration	Standard
ETSI TS 102 638	Basic Set of applications (BSA): Definitions	Standard
ETSI TS 101 539-1	V2X Applications; Part 1; Road Hazard Signaling (RHS) app. req. spec	Standard
ETSI TS 102 894-1	Facility layer structure; functional requirements and specifications	Standard
ETSI TS 102 637-1	Basic Set of Applications (BSA); Part 1: Functional Requirements	Standard
ETSI EN 302 637-2	Cooperative Awareness Basic Service (CAM)	Standard
ETSI EN 302 637-3	Decentralized Enviromental Notification Message (DENM)	Standard
ETSI TS 102 894-2	Common Data Dictionary (CDD)	Standard
ISO TR 20025	Probe Data Application and System requirements	Standard
ETSI EN 302 895	Vehicular Communications; BSA: Local Dynamic MAP-(LDM)	Standard
ISO TS 17419	ITS-AID (Application ID)	Standard
ISO TS 18750	Extended Infrastructure oriented Local Dynamic MAP-(LDM)	Standard
ETSI TS 102 890-2	Service Anouncement Message (SAM)	Standard
ISO TS 19321:2015	Dictionary of in-vehicle information (IVI) data structures	Standard
ETSI EN 302 636-1	GeoNetworking: Requirements	Standard
ETSI EN 302 636-2	GeoNetworking: Scenarios	Standard
ETSI EN 302 636-3	GeoNetworking: Network Architecture	Standard
ETSI EN 302 636-4-1	GeoNetworking: Media-Independent Functionality	Standard
ETSI TS 102 636-4-2	GeoNetworking: Media-Independent Functionality for ITS-G5	Standard
ETSI EN 302 636-5-1	GeoNetworking: Basic Transport Protocol	Standard
ETSI EN 302 931	Geographical Area Definition	Standard
ETSI EN 303 663	Access layer spec. for ITS operating in the 5 GHz frequency band (ITS-G5)	Standard
ETSI TS 102 687	Decentralized Congestion Control Mechanisms for ITS-G5 (DCC)	Standard
ETSI TS 102 724	Harmonized Channel Specifications for ITS-G5	Standard

Enabler	Description	Category
ETSI EN 302 571	Radiocommunications equipment operating in the 5 855 MHz to 5 925 MHz frequency band	Standard
ETSI TS 102 792	Mitigation techniques to avoid interference between CEN DSRC and ITS-G5	Standard
IEEE 802.11	Lower Layer specifications (ensuring ITS in 5.9 GHz)	Standard
ETSI TS 102 867	Stage 3 mapping for IEEE 1609.2	Standard
ETSI TS 102 940	ITS communications security architecture and security management	Standard
ETSI TS 102 941	Trust and Privacy Management	Standard
ETSI TS 102 942	Access control	Standard
ETSI TS 102 943	Confidentiality services	Standard
ETSI TS 103 097	Security header and certificate formats for ITS G5	Standard
ETSI TS 103 301	Facilities layer protocols and communication requirements for infrastructure services	Standard
C-ITS Message Profiles and Parameters	C-Roads C-ITS Message Profiles and Parameters	Standard
ETSI TS 103 175	Cross Layer DCC Management Entity for operation in the ITS G5A and ITS G5B medium	Standard
C-ITS Security Policy	C-Roads C-ITS Security Policy	Standard
C-ITS Certificate Policy	C-ITS Certificate Policy - Release from preparatory phase of C-ITS Delegated Regulation – March 2019	Standard
C-ITS Point of Contact (CPOC) protocol	C-ITS Point of Contact (CPOC) protocol	Standard
Basic Interface	C-Roads Basic Interface	Standard
ETSI TS 103 097	ITS Security - Security header and certificate formats	Standard
ETSI TS 102 941	ITS Security - Trust and Privacy Management	Standard
ETSI TS 103 600	ITS Testing - Interoperability test specifications for security	Standard
Datex II		Standard
Basic Transport Protocol BTP		Standard

Figure 13. Enablers identified in the CRF spreadsheet tool