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Final Programme Report

CEDR Call 2020 Impact of CAD on Safe Smart Roads

DiREC | TM4CAD

May 2024

Call 2020 Impact of CAD on Safe Smart Roads Final Programme Report
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This Report is an output from the CEDR Transnational Road Research Programme Call 2020: Impact of CAD on Safe Smart Roads. The research was funded by the CEDR members of Belgium – Flanders, Ireland, Netherlands, Norway, Sweden, the United Kingdom, as well as by Israel.

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Executive Summary

The CEDR Transnational Road Research Call 2020 Impact of CAD on Safe Smart Roads funded two projects, with the aim to prepare the national road authorities on future challenges of connectivity, digitalization and automation to get to an autonomously well-managed traffic flow:

- DiREC – DIgital Road for Evolving Connected and Automated Driving,
- TM4CAD – Traffic Management for Connected and Automated Driving

Both projects started in September 2021, but finished a half year apart from each other, TM4CAD in March 2023 and DiREC in August 2023. The project's results, open questions and next steps for implementation are summarized in this report.

DiREC established a CAV-Readiness Framework (CRF) to support dialogue between NRAs, OEMs and service providers, based on a Level of Service approach. The CRF defines 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 considers 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.

The CRF helps 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). 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.

TM4CAD explored the role of infrastructure systems across various Infrastructure Support for Automated Driving (ISAD) levels in creating ODD awareness for CAD systems. The starting point was various categories of distributed ODD attribute information and defined acquisition principles of the information based on exchange between the stakeholders, ultimately to enable CAD systems to be aware of their ODD in real-time. TM4CAD has demonstrated the basic mechanisms of ODD management via two real-world use cases, which build on the premise of interaction between traffic management systems and CAD vehicles. This provides NRAs insight into methods to inform CAD systems about the kinds of support they can provide for CAD operations on European roads.

The TM4CAD project has introduced the DOVA concept as a mechanism to enable early deployment of Connected Automated Driving (CAD) by providing infrastructure support to the CAD system to aid its capability for ODD awareness. ODD definition and awareness are key to the safe operation of the CAD systems. Various ODD attributes and the potential for infrastructure support for real-time information gathering for each of the ODD attributes were discussed, as well as time criticality of updating each ODD attribute value, which depends on its rate of change. Depending on the level of infrastructure support and the level of CAD on-board sensing, various kinds of information relevant to the ODD can be supplied as part of a DOVA framework. The DOVA framework enables the ADS to benefit from off-board sensing and information

infrastructure to become aware of ODD attribute values which it may not be able to measure or sense directly using on-board sensors.

Both projects have delivered a framework for NRAs to address future challenges of connected and automated mobility. The CAV-Readiness Framework (CRF) by DiREC and the Distributed ODD attribute Value Awareness (DOVA) framework by TM4CAD. A logical next step would be to apply them in practice, preferably in close liaison and cooperation with the European automated vehicle industry stakeholders. This is also how most of the open questions should be addressed in further research, projects and collaborations.

A final conference was organized on 20-21 November 2023. This conference allowed the project consortia to present their results to the Programme Executive Board as well as to each other and some invited stakeholders and provided an opportunity to further discuss the results and their implications for NRAs. The final conference was an interesting event with lively discussion in an open and constructive manner. The importance and relevance of road operators to become digital road operators and prepare themselves on future challenges of connectivity, digitalization and automation was stressed. Although being an ambitious NRA would mean higher costs and investments in the short term, it is probably a wise decision in the long run as costs and resources can be saved by becoming digital NRAs. It would be interesting to see if NRAs are willing to invest those savings into facilitating CAVs.

The presence of OEM representatives at the final conference was very valuable and their contribution to the dialogue along with their perspectives helped identify certain issues and open questions and it reiterated the importance of multi-stakeholder collaboration to deal with future challenges of connectivity, digitalization and automation.

Abbreviation	Definition
ADS	Automated Driving System
AIM	Asset Information Modelling
ALKS	Automated Lane Keeping System
AV	Automated Vehicle
ASAM	Association for Standardisation of Automation and Measuring Systems
AVG	Automated Vehicle Guidance
BIM	Building Information Modelling
BSI	British Standards Institution
C2C-CC	Car-to-Car Communication Consortium
CAD	Connected and Automated Driving
CAM	Cooperative Awareness Message
CAV	Connected Automated Vehicle
CCAM	Cooperative Connected Automated Mobility
CBA	Cost Benefit Analysis
CEDR	Conference of European Directors of Roads
CEN	European Committee for Standardization
C-ITS	Cooperative Intelligent Transport Systems
CPM	Collective Perception Message
CRF	CAV Readiness Framework
C-V2X	Cellular Vehicle-to-Everything (communication)
DENM	Decentralized Environmental Notification Message
DG	Directorate General
DOVA	Distributed ODD attribute Value Awareness
DiREC	Digital Road for evolving Connected and Automated Driving
DOM	Dynamic ODD Management
DoRN	Description of Research Needs
DSRC	Dedicated Short Range Communication
EIP	EU ITS Platform
ETSI	European Telecommunications Standards Institute
GDPR	General Data Protection Regulation
GLOSA	Green Light Optimised Speed Advisory
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HCM	Highway Capacity Manual
HLN	Hazardous Location Notification
HMI	Human Machine Interface
I2V	Infrastructure-to-Vehicle (communication)
ICT	Information and Communication Technology
InterCor	Interoperable Corridors deploying Cooperative Intelligent Transport Systems
ISAD	Infrastructure Support for Automated Driving
ISO	International Standardisation Organisation
ITS	Intelligent Transport Systems
IVI	In-Vehicle Information
IVIM	In-Vehicle Information message
IVS	In-Vehicle Signage
L3	Level 3 (driving automation)
L4	Level 4 (driving automation)
LoS	Level of Service
LTE	Long Term Evolution
M2M	Machine-to-Machine
MAPEM	MAP Extended Message
MCDM	Multimedia Content Dissemination Message

MCM	Manoeuvre Coordination Message
MEC	Multiaccess Edge Computing
MRC	Minimal Risk Condition
MRM	Minimal Risk Manoeuvre
NRA	National Road Authority
ODD	Operational Design Domain
OEM	Original Equipment Manufacturer
PAS	Publicly Available Specification
PKI	Public Key Infrastructure
PVD	Probe Vehicle Data
RLT	Road and Lane Topology
RQ	Research Question
RSI	Road Side Infrastructure
RSU	Road Side Unit
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
SPATEM	Signal Phase and Timing Extended Message
TM4CAD	Traffic Management for Connected and Automated Driving
TMA	Truck Mounted Attenuator
TMC	Traffic Management Centre
ToC	Transfer of Control
TOD	Target Operational Domain
TRB	Transportation Research Board
TRP	Transnational Research Programme
TTI	Traffic and Traveller Information
UN	United Nations
V2I	Vehicle-to-Infrastructure (communication)
V2X	Vehicle-to-Everything (communication)
VRU	Vulnerable Road User
WIM	Weigh in Motion
WP	Work-package

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1 Introduction

1.1 background

The CEDR Transnational Research Programme was launched by the Conference of European Directors of Roads (CEDR). CEDR is the Road Directors' platform for cooperation and promotion of improvements to the road system and its infrastructure, as an integral part of a sustainable transport system in Europe. Its members represent their respective National Road Authorities or equivalents and provide support and advice on decisions concerning the road transport system that are taken at national or international level. CEDR is an organisation which brings together the road directors of 27 European countries. The aim of CEDR is to contribute to the development of road engineering as part of an integrated transport system under the social, economic, and environmental aspects of sustainability and to promote co-operation between the National Road Administrations.

The participating NRAs in the CEDR Call 2020 "Impact of CAD on Safe Smart Roads" are Belgium – Flanders, Ireland, Israel, Netherlands, Norway, Sweden, and the United Kingdom. As in previous collaborative research programmes, the participating members have established a Programme Executive Board (PEB) made up of experts in the topics to be covered.

This Transnational Research Programme pools research funding from CEDR members to fund transnational research projects on topics of shared interest to European road authorities and forms a continuation of previous programmes organised under the ERA-NET ROAD brand. "ERA-NET ROAD – Coordination and implementation of Road Research in Europe" was a Coordination and Support Action funded by the 7th Framework Programme of the European Commission which concluded in December 2011. The goal of ERA-NET ROAD (ENR) was to develop a platform for international cooperation and collaboration in research areas of common interest. This included the production of an "ENR-toolkit" for carrying out transnational research and trials of the various procedures developed through a series of projects and programmes funded directly by European Road Administrations.

Content wise, the Call 2020 on Impact of CAD on Safe Smart Roads has built on the findings of its predecessor Call 2017 on Automation with the projects MANTRA, DIRIZON and STAPLE (Ulrich et al 2021) as the results of this call provide the research ground for the Call 2020 on the Impact of CAD on safe smart roads which was opened in November 2020.

1.2 General information on the programme

The Project Executive Board (PEB) of the CEDR initiated Programme entitled "Impact of CAD on Safe Smart Roads" started two research projects in 2021.

The aim of this research programme was to prepare the national road authorities on future challenges of connectivity, digitalization and automation to get to an autonomously well-managed traffic flow. CEDR is convinced 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. Exchange of data, digital twins and the digital road operator are now hot topics in the European Commission. NRAs need to determine and act before other parties decide in our place where we need to invest.

The two projects funded within this call were:

- DiREC – DIgital Road for Evolving Connected and Automated Driving
- TM4CAD – Traffic Management for Connected and Automated Driving

1.3 Methodology

The writers of this report represent the DiREC and TM4CAD projects. The perspective of each project was initially provided in a succinct manner individually, from which overall conclusions were drawn which bring together the overarching results and recommendations of this report which are focused on the programme goals.

Table 1. Work allocation

Task	Project Input		Validation, compilation & overall results
	DiREC	TM4CAD	
General information about the programme	-	-	MAPtm
Executive summaries	TRL	MAPtm	TRL, MAPtm
Outcomes, highlights and remarks of the final conference	TRL	MAPtm	MAPtm
Recommendations for implementation steps and applicability of the projects	TRL	MAPtm	MAPtm
Overall conclusions and recommendations for the national road administrations	TRL	MAPtm	MAPtm
Open questions	TRL	MAPtm	MAPtm

As part of the preparation of this report a conference was held in Brussels in November 2023 in which both projects presented the results and conclusions of their studies. The summaries on the outcomes of the plenary discussions during the final conference are summarized in this report.

2 Project descriptions

2.1 DiREC

Duration: September 2021 – August 2023
Budget: €601,827.72
Coordinator: TRL (United Kingdom)
Partners: TU Delft (Netherlands), VTT (Finland), ARUP (Ireland), VTI (Sweden) and FEHRL (Belgium).
Website: https://direc.project.cedr.eu/

2.1.1 Project overview

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.

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.

2.1.2 Main Results

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.

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 for 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.

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 desire 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.

Telecommunication service providers

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

- The need for defined use cases to help drive wider adoption and market investment.
- Importance of distinguishing between Connected Vehicles and Automated Vehicles - as they have potentially different requirements and are at different stages of evolution.
- Development of commercially driven pilots that enable the market to support development programmes against their roadmaps.
- 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.
- Understanding the importance of a digital backbone to support physical infrastructure investment.
- 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.
- 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.
- Consolidation of technical choices linked to ITSG5 and 5G, and linking use cases to the technologies best suited to their delivery.

Other service providers

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.

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.

Infrastructure Design and Operation

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.

Digital Infrastructure
Satellite positioning support is key to automation. High accuracy positioning needs infrastructure support such as ground 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.

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.

Infrastructure Connectivity

There is no common agreement on the communications technologies of choice for the 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).

Data Exchange

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.
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.

Digital Twins

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.

Legal and Regulatory

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.

Impact of Emergent Technologies

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.

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.

Costs and Benefits

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.

Vision and Mission for the CAV Readiness Framework (CRF)

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.

CAV readiness framework

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 1):

- 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.

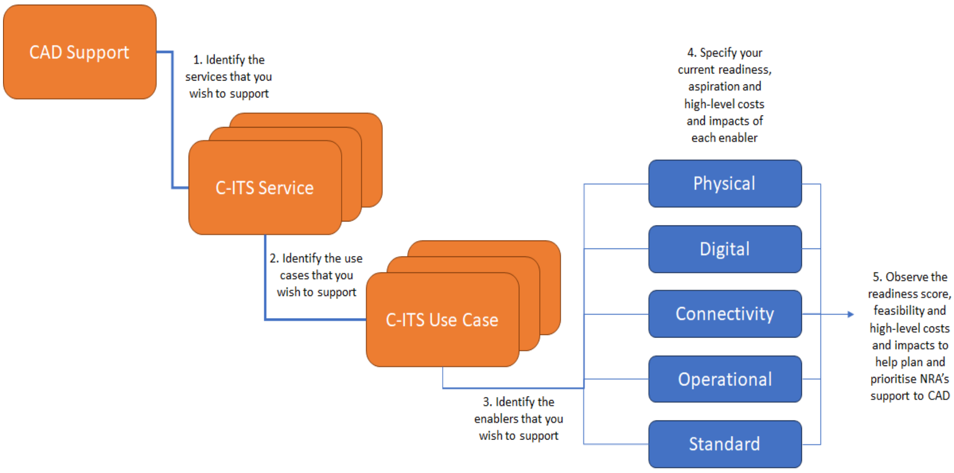

Figure 1: Overview of the CRF

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'.

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).
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.
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.

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.

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.

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.

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.

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, including 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).

Illustrative example

We provide, as an illustrative example, the design and implementation of an individual C-ITS service. Figure X 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 2 helps define the enablers to be considered in the implementation of the RWW service by the NRA.

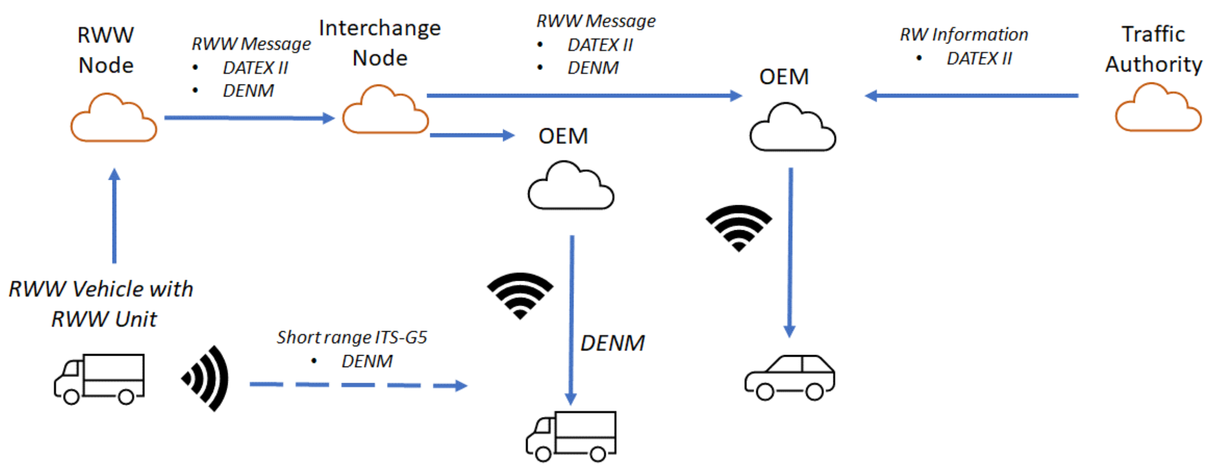

Figure 2: Flow of messages for Road Works Warning (RWW) implementation

In the CRF, each enabler is defined as a separate item. 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.

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 3). The 'spokes' of the radar diagram represent the categories of the enablers.

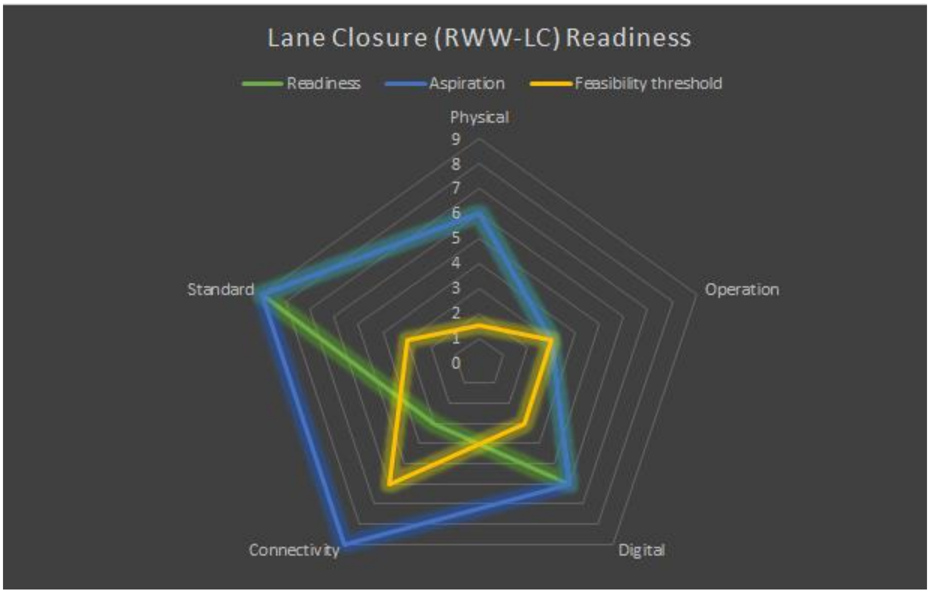

Figure 3: Readiness of a NRA to provide or deploy a specific use case

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 4. 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 the development or implementation of services.

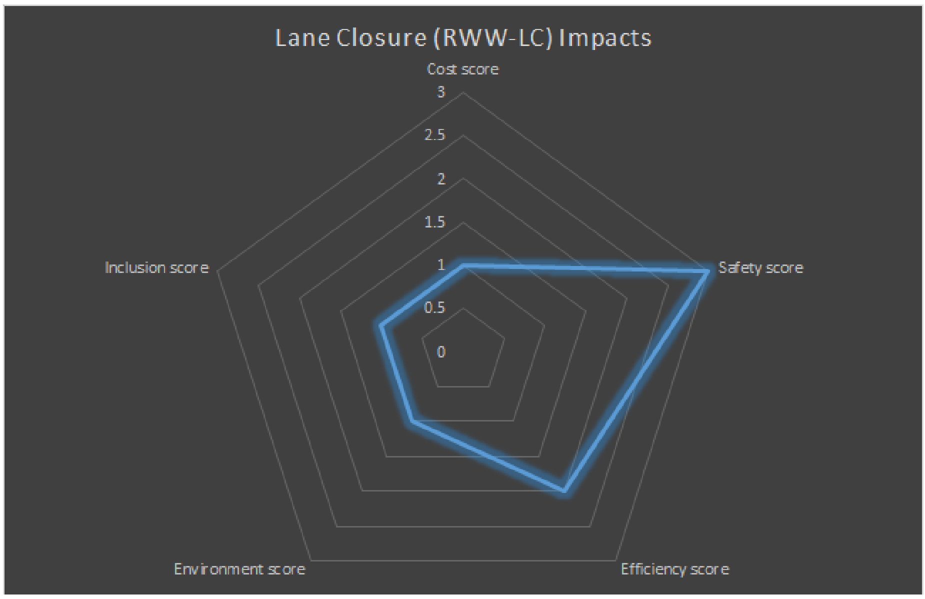

Figure 4: Impact of a C-ITS Use Case

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 5. 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.

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)	54%			
	Lane Closure (RWW-LC)	67%			
	Road Closure (RWW-RC)	65%			
	Road Works – Mobile (RWW-RM)	4%			
	Winter Maintenance (RWW-WM)	80%			

Figure 5: 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.

2.1.3 Recommendations

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). 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.

2.2 TM4CAD

Duration: September 2021 – March 2023
Budget: € 309.877,61
Coordinator: MAP traffic management (the Netherlands)
Partners: Traficon (Finland), Transport & Mobility Leuven (Belgium), Warwick University (United Kingdom), Steven Shladover (independent consultant) and Keio University (Japan).
Website: https://tm4cad.project.cedr.eu/

2.2.1 Project overview

The TM4CAD project explored the role of infrastructure systems across various Infrastructure Support for Automated Driving (ISAD) levels in creating ODD awareness for CAD systems. The starting point was various categories of distributed ODD attribute information and defined acquisition principles of the information based on exchange between the stakeholders, ultimately to enable CAD systems to be aware of their ODD in real-time. TM4CAD has demonstrated the basic mechanisms of ODD management via two real-world use cases, which build on the premise of interaction between traffic management systems and CAD vehicles. This provides NRAs insight into methods to inform CAD systems about the kinds of support they can provide for CAD operations on European roads.

To gain a complete understanding of traffic management for CAD, the TM4CAD project has:

- Identified the full range of ODD attributes for consideration, based on experience from working on ODD issues in standardization activities and in other related research projects;
- Integrated the different perspectives of the CAD vehicle system developers and the national road authorities and operators to focus on the overlapping areas;
- Introduced the concept of ODD attribute awareness and the role of infrastructure in it;
- Developed recommendations based on the technical constraints of the ODD-relevant information that can be perceived and exchanged in real time by the NRAs and the sensing systems of the CAD-equipped vehicles;
- Provided insights on how to support CAD operation and ODD management, and how ISAD should be refined for traffic management use, and
- Detailed how traffic management systems and CAD vehicles can best interact to improve traffic operations.

2.2.2 Main Results

The main results of the TM4CAD project are described in the following sections.

DOVA

The TM4CAD project has introduced the DOVA concept as a mechanism to enable early deployment of Connected Automated Driving (CAD) by providing infrastructure support to the CAD system to aid its capability for Operational Design Domain (ODD) awareness. ODD definition and awareness are key to the safe operation of the CAD systems. Various ODD attributes and the potential for infrastructure support for real-time information gathering for each of the ODD attributes were discussed, as well as time criticality of updating each ODD attribute value, which depends on its rate of change. Depending on the level of infrastructure support and the level of CAD on-board sensing, various kinds of information relevant to the ODD can be supplied as part of a DOVA framework.

The DOVA framework enables the ADS to benefit from off-board sensing and information infrastructure to become aware of ODD attribute values which it may not be able to measure or sense directly using on-board sensors. For example, a CAD system will not be able to detect foggy conditions more than a couple of hundred meters ahead on its path, nor will it be able to distinguish how badly they degrade visibility. It could, however, receive this information from an existing roadside weather station or a new special-purpose visibility sensor located in fog-prone locations, which can provide this information through over the air communication directly with the CAD system or indirectly through a cloud-based repository. This would enable the CAD system to have awareness of this current operating condition and compare it with its ODD visibility constraints to determine how it should respond.

ODD attribute awareness via the DOVA framework is one factor influencing the safe operation of the CAD systems. Other factors influencing CAD safety assurance and automation driveability, visualized in Figure 6, include:

1) Technological and behavioural competencies of the CAD system
2) Driving behaviour of the CAD system
3) Rules of the Road

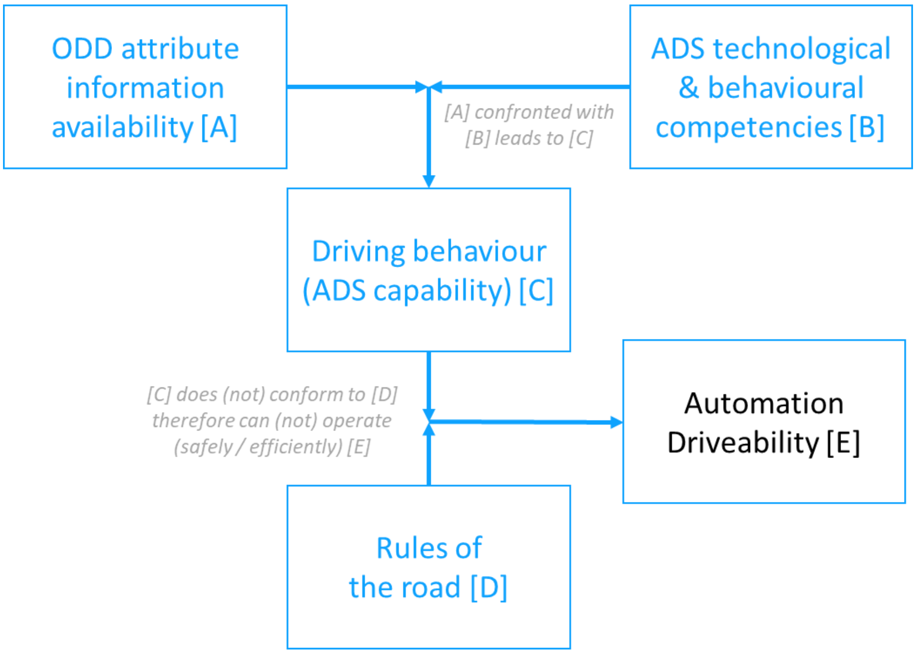

Figure 6: Relationships among ODD awareness, ADS capabilities, rules of road and safety assurance

It is important to note that while the DOVA framework enables provision of ODD attribute information, it doesn't guarantee safe operation of CAD systems. ODD attribute information via the DOVA framework enables the CAD system to identify its technological capability to operate in a given environment, enabling it to determine the vehicle's ability to comply with the rules of the road and to avoid conflicts with other road users. In other words, an ADS with access to the necessary attribute information, should be able to decide driving behaviour that can be considered safe and efficient, and therefore be able to operate in the particular local condition.

In order to implement the DOVA framework, the NRAs and commercial entities will be required to invest in the infrastructure to enable the gathering and sharing of the information on various ODD attributes. The selection of ODD attributes' information and the time criticality of the information, i.e., update urgency, will have an impact on the infrastructure investment decisions due to cost and effectiveness considerations.

As ODD awareness is key to the safety of CAD systems, DOVA is also essential for safety of CAD systems, especially for CAD systems with limited on-board sensing capability, to enable the CAD systems to be aware if it is approaching its ODD boundaries and perform an appropriate manoeuvre (transition of control or a minimal risk manoeuvre). How the DOVA framework can aid with the automated driving systems' technological capabilities and its driving behaviour while ensuring it complies with the rules of the road during deployment has been described.

The technological sophistication of each CAD system will determine its ODD limitations and the behavioural competencies that it can perform within each ODD. There is an inherent dependency between the behavioural competency and the ODD attributes. ODD attribute information allows the CAD system to select which behavioural competencies it is able to execute in a particular ODD, within the design limitations initially set for the design of the CAD system.

Examples of ways in which infrastructure support can compensate for limitations in the capabilities of the in-vehicle ADS technologies include:

- Roadside sensors and V2X communications alerting vehicles about locations of traffic jams or obstructed lanes, relieving them of the need for very long-range sensing to be able to detect these hazards in high-speed motorway driving (and enabling them to achieve better safety by providing more time to respond to detected hazards);
- Roadside sensors and V2X communications providing information about occluded hazards in locations with poor sightlines, extending the ODD for CAD systems into areas that would otherwise be technically infeasible;
- V2X communications of traffic control information (such as signal phase and timing, variable speed limits or advisories) relieving the CAD systems of the technological burden of detecting these by video image processing under adverse visibility conditions (poor lighting or weather);
- V2X communications of traffic control information (signal phase and timing, variable speed limits or advisories) providing unambiguous knowledge of these important commands, so that the CAD systems can respond to them more quickly and confidently than they would otherwise;
- High-precision digital maps and GNSS localisation with differential corrections enabling the CAD system to accurately track its lane position without needing to rely on high-performance onboard video image processing or laser scanner technology (or being able to operate under adverse visibility conditions that would be disabling for lower-cost sensors).

Information exchange between traffic management centres and automated vehicles – information needs, quality and governance

Safe, efficient, and clean automated driving, requires connectivity and exchange of information between automated vehicles and the infrastructure (traffic management centres (TMCs), road network and physical, digital, and operational infrastructure). It is essential that both the automated vehicles and TMCs receive the relevant information in time and with the quality and service levels needed. Crucial properties of the information exchange including the content, timing, quality, and governance of the information have been detailed by TM4CAD.

The coherent sequence and cause-and-effect connections among various elements reveal that Operational Design Domain (ODD) attributes exhibit a real-time condition, necessitating some form of sensing before the attribute information becomes accessible, as shown in Figure 7.

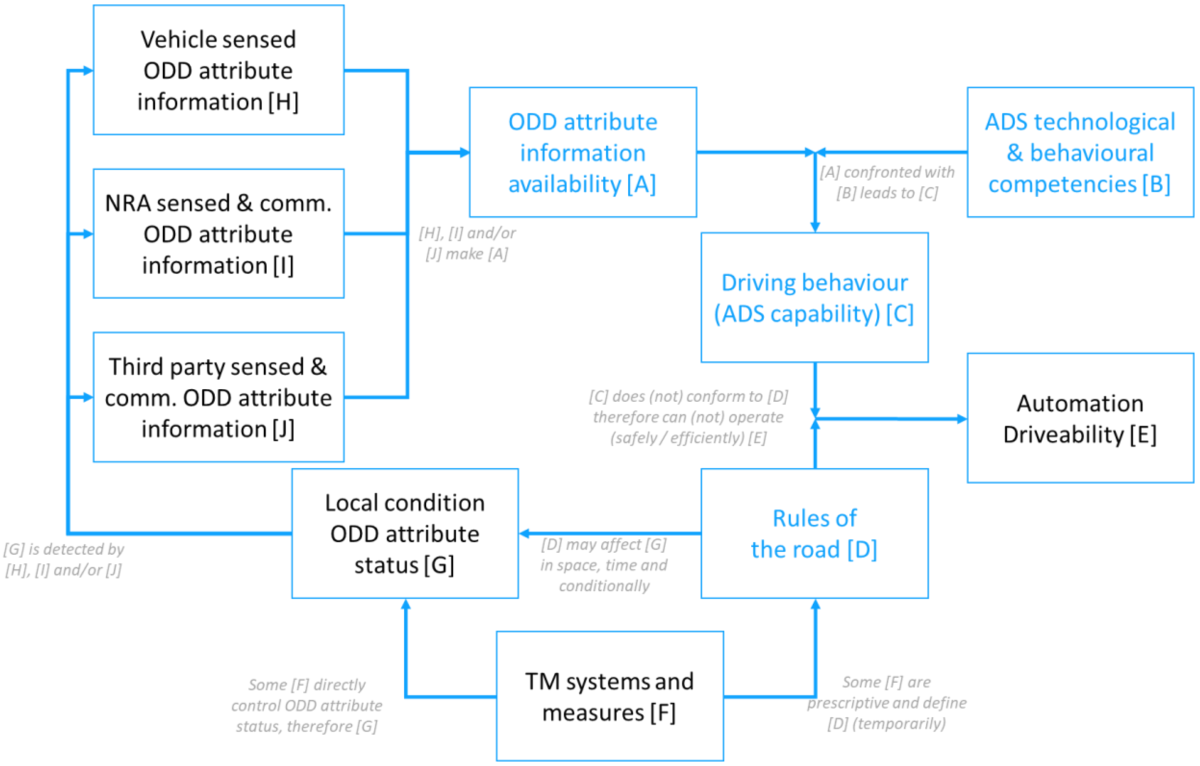

Figure 7: Distributed ODD attribute Value Awareness framework

The information needs of three actors (automated driving system developers/OEMs, traffic managers, and road works/maintenance operators) in three scenarios (traffic jam dissolving, adverse weather area, and road works zone) of SAE Level 3/4 vehicles on highways and motorways have been detailed for each actor and scenario utilising the Distributed ODD attribute Value Awareness (DOVA) framework developed by TM4CAD and its ODD or local condition attributes. The information attributes can be prioritised based on their importance to the various stakeholders as well as safety criticality. These priorities were validated via an online survey and workshop organised for vehicle manufacturers and a workshop for CEDR members. In all, seven physical infrastructure, eight digital infrastructure support, sixteen ambient environmental conditions, and nine operational roadway condition related local condition attributes were regarded as high-priority ones for providing ODD attribute value awareness.
TM4CAD described the quality indicators for the DOVA framework and its data contents and provides recommendations for quality recommendations in the future when the L3/L4 vehicles

have a considerable share in the traffic flow on highways. The quality requirements are higher than today, especially with regard to the location accuracy and timeliness-related quality indicators. The higher requirements can be reached, however, by the connected and automated vehicles providing the related data to the DOVA framework operator. Likely methods to be used for quality assessment and assurance are also described.

Methods, processes and standards for the exchange of the data within the DOVA framework to reach a feasible practical solution for harmonised data exchange are described. The issues in the governance of the DOVA are discussed in the light of the contextual background and the recent experiences from European actions with regard to road safety related data and national access points. The management and hosting of the DOVA framework are addressed specifically. The most promising solution is likely a neutral third party, trusted by all stakeholders and mandated to act as an information and data collection and clearing house. This could take the form a public-private partnership, in which the government also commits itself to providing information and data according to pre-agreed upon specifications.

Implementation aspects of Distributed ODD attribute Value Awareness

A practice-oriented perspective, based on the Distributed ODD attribute Value Awareness (DOVA) concept is provided, taking into account the context of NRAs, and made more concrete and tangible for specific situations. The DOVA framework enables the ADS to benefit from off-board sensing infrastructure and data sources to become aware of ODD attribute values which it may not be able to measure or sense by itself. Typically, the earlier the information is available, the more options are possible for the ADS to respond (operational, tactical, strategic).

Current ADS immaturity causes a lot of uncertainty for road authorities as they cannot decide with confidence what is the best way to anticipate ADS development and deployment to preserve operational safety and efficiency on their road network. Typically, the actual competencies of ADS in the operating environment are not entirely known and ADS capabilities are regularly overestimated or underestimated based on assumptions that are derived from the scarce information that is publicly available. At the same time, many different situations can occur on open roads and in variable traffic and weather conditions, in particular when these roads are dynamically managed by the road operator (e.g. lane, speed and tunnel management). It is natural that NRAs are concerned about the introduction of ADS that execute the complete dynamic driving task. The most constructive and perhaps only way forward is to create a dialogue between road authorities, automation system developers and regulators.

To following principles will help to better understand the basic principles of ADS system deployment and the role of different actors in the DOVA framework:

- Traffic management systems will not actively manage the tactical or operational decision making of ADS, i.e. activate and de-activate automation, instead its added value to ADS and thereby traffic safety lies in improving the situational awareness of ADS and providing strategic guidance;
- The driving rules and expected driving behaviour must be defined in regulations such as the Vehicle General Safety Regulation and UN Regulations;
- Information beyond the line-of-sight of vehicle sensors is relevant for timely anticipation of the downstream conditions. This is where NRAs support ADS the most today, by providing information in advance.

A decision-making flow diagram was developed to support NRAs in the conversation with automation system developers and regulators, and to break down any use case assessment in smaller elements (Figure 8).

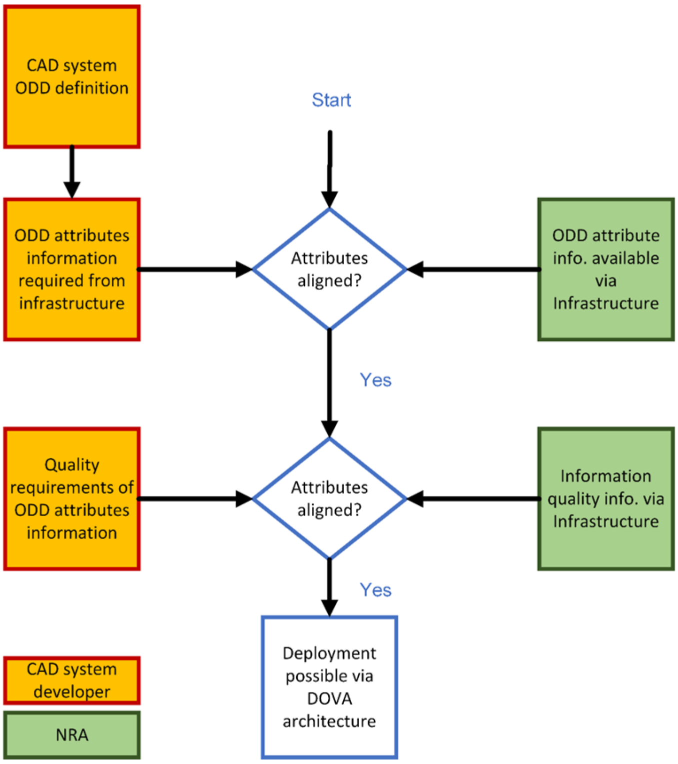

Figure 8: Logic flow for decision making process for implementing DOVA

Four use cases were selected and elaborated: (1) adverse weather conditions, (2) road works, (3) traffic jam and (4) tunnels, each in turn divided into multiple scenarios. Due to the structured way the use case scenarios were described their commonality is visible. Roughly in each scenario an ADS receives in-advance information about a local condition further down the road. As the ADS is informed about the local condition and the (detailed) characteristics of the condition, the ADS assesses the situation. Consequently, it can, in a timely manner, transfer the dynamic driving task to the driver in case of Level 3 ADS (and thereby decrease the risk of minimal risk manoeuvre in case the driver does not respond) or avoid the need for a transfer of control entirely. In case of Level 4, the ADS is able to avoid the minimal risk manoeuvre or to achieve a safer minimal risk condition.

For example, in a combination of use case 1 and 3, due to limitations of the range of in-vehicle sensors, in-advance information about adverse weather and traffic jam may enable an ADS to better cope with downstream local conditions. Especially poor visibility due to weather combined with traffic jams is important. It is also relevant to provide in-advance information when the vehicle/ADS will drive out of a traffic jam or adverse weather zone, so that ADS can act appropriately. For the case of ALKS the basic aspects related to this use case scenario are illustrated in Figure 9.

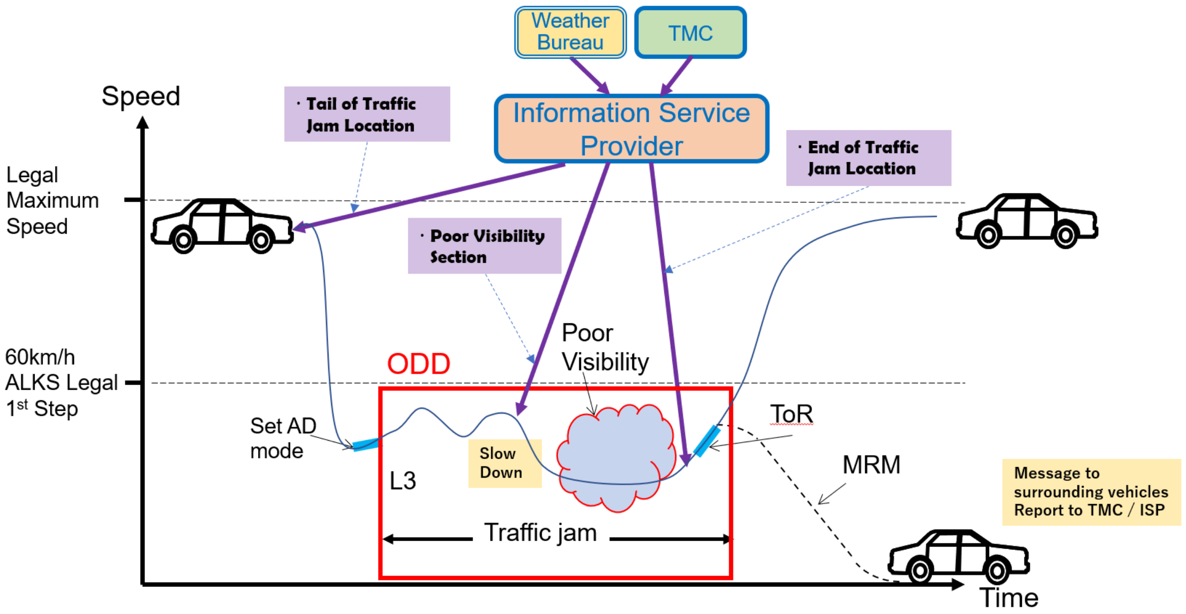

Figure 9: Illustration of ADS in traffic jam and adverse weather area (courtesy of H. Kawashima)

2.2.3 Recommendations

The ultimate motivation for NRAs and government bodies to support the development and introduction of CAD systems on roads is the potential societal benefit from these technologies. However, in order for society to reap the benefits of CAD systems, it is essential that all stakeholders in the CAD ecosystem work towards building societal trust and acceptance of the CAD technologies. Safety plays a key role in the development of trust in a system.

For a dialogue between NRAs and automated vehicles developers the TM4CAD project provided a complete set of realistically implementable requirements from traffic management systems and road operators to CAD systems and automated vehicle manufacturers. This was done by means of on-going collection of requirements, first from a technical point of view (for traffic management and CAD systems), and then highlighting the roles that both the road operators and traffic management centres and vehicle manufacturers (and Tier-1 providers, ADS developers, AV fleet managers/operators) play in this respect.

Most of the requirements were given at a higher level, with extra inputs stemming from the MANTRA, EU EIP, and TransAID projects. In order to convey them to the relevant stakeholders, open stakeholder dialogues were held through workshops. It's recommended to publish the requirements in specific (standardisation) bodies on the one hand, and to establish a so-called codified highway code which has the ability to integrate all requirements in the long term.

In TM4CAD's workshop in November 2022, for an international audience including researchers, road operators, and vehicle manufacturers, the aim was to pave the way to a more unified and cooperative roadmap. Regarding the question "*Should NRAs set requirements on the desired behaviour of (partly) automated vehicles on where and how they should drive?*". The answer was nuanced: the desired behaviour of (partly) automated vehicles should be defined as a product of the interactions between the NRAs and the developers of the vehicle technology to produce a balance between technological feasibility and serving transportation system needs. In practice this entails much more interaction between NRAs and ADS developers. Prime examples of such discussion items in which it makes sense for NRAs to be engaged are the definition of an MRM, what constitutes an MRC, what behaviour is expected from an automated vehicle or ADS, and what are the consequences of any road code requirements and decisions taken by an ADS?

There currently exists a large gap of information between both parties in the spectrum: NRAs do need to understand how an ADS will react under certain conditions, and OEMs need to understand what is expected by the NRAs in order to finetune their ADS' behaviours. To facilitate this, a mutual exchange of information in an open dialogue is recommended. A vision for these requirements will typically be created from a perspective of vehicle safety. Safety for the vehicle, for the passenger, and for the environment (i.e., the other traffic participants). Based on a common understanding of the stakes involved, both NRAs and ADS developers should work together, and define what is realistically possible.

3 Outcomes of the final conference

A final conference was organised on November 20th – 21st, 2023. The first day as a hybrid meeting and the second day as a face-to-face meeting. The conference allowed the projects to report their results to both the Programme Executive Board as well as each other on the one hand and to provide the opportunity to discuss and further elaborate on overarching topics on the other. During the conference, discussion about the projects themselves, their highlights and the identification of open questions took place.

Participants were mainly CEDR members and project representatives but also included some members of public authorities, research institutions and OEM representatives.

The conference started with a welcome note from the chair of the PEB, Kristof Rombaut, highlighting the importance of the topic connected & automated driving for NRAs.

The projects presented their results and questions were collected in the chat during the presentation which were answered afterwards. The presentations covered the following topics with a strong emphasis on concrete project results and managerial recommendations, which are also reflected in the project descriptions of chapter 2 in this report:

- Short general project overview including consortium, objectives, work packages
- Main results of each work package
- Key project results and recommendations for deployment

The project results were overall satisfactory with no critical remarks or questions from the audience.

3.1 Highlights and remarks

The final conference turned out to be an interesting event with lively discussion in an open and constructive manner. The importance and relevance of road operators to become digital road operators and prepare themselves on future challenges of connectivity, digitalization and automation was stressed. Although being an ambitious NRA would mean higher costs and investments in the short term, it is probably a wise decision in the long run as costs and resources can be saved by becoming digital NRAs. It would be interesting to see if NRAs are willing to invest those savings into facilitating CAVs. Another saving that's associated by automating rides is journey time reduction. if you're not driving yourself, the value of time changes and this could also have implications for congestion management.

The presence of OEM representatives at the final conference was very valuable and their contribution to the dialogue along with their perspectives helped identify certain issues and open questions. One of the remarks was that deploying automated vehicles requires a long term effort and commitment, it is more of a marathon than a sprint, and it's a team effort due to the various stakeholders involved and the multidisciplinary nature of the associated challenges. The term evolution was used to illustrate that several years ago the position was often that OEMs needed clear road markings for CAVs, but now this is superseded, and OEMs speak of a "drive tube" that is defined by/for the vehicle.

Fragmentation of the ODD is a critical problem for OEMs, not only because of acceptability to customers (they will demand continuous and predictable use) but because it is one of the fundamental joint challenges to solve in order to make automation work. In the Horizon Europe flagship project Hi-Drive this is the narrative and so-called “defragmentation” of the ODD through various approaches, including infrastructure assisted solutions, the main goal. A generic dilemma on the correct approach is the something everywhere versus everything somewhere approach (or Tesla vs traditional vehicle manufacturers). It seems to be much better to do everything in a small area than bits and pieces across all areas. In the spirit of this philosophy, it is for instance also better to make commuting routes easier to navigate for CAVs than routes for going on holidays.

Vehicle manufacturers and ADS developers use data as a basis for automated vehicle operation only if they can trust the data to be correct, reliable and secure. This especially applies to externally sourced data as in the DOVA framework. To address this trust issue, it was discussed that OEMs and NRAs could interact via a neutral, mandated third party. It would work, but it will likely take time.

What is the business case for the stakeholders?

- A first group of stakeholders are the telecommunications operators, they get more data flowing through their systems
- This creates a new market
- Then there are digital service providers that add significant market value to the data
- Could NRAs consider themselves as commercial stakeholders

Various recurring dilemmas were discussed, for instance the mixed traffic challenge. For CAVs to blend in (given current human traffic behaviour) they sometimes would have to break the rules. But OEMs will never agree to program this or facilitate it if it explicitly means to go over the speed limit or otherwise deviate from the legal framework. It also sparks the debate on why these deviations from human operated vehicles is accepted and whether increased enforcement is necessary to close the gap.

Machine “understanding” of road regulation is critical, as one of the identified requirements for digital infrastructure, because an ADS needs to know at all times what is allowed and how it should behave, given a specific situation or context. But this can not be achieved by simply translating the current rules of the road as they are written with human drivers in mind and need a high level of contextual awareness.

In the discussion on transitions of control (ToCs) various takeover times were discussed. It is a certainty that ToCs will take place for L3 vehicles, given the fact that the ODD in practice is fragmented and CAVs will later or sooner encounter the ODD boundaries, whether it’s expected or unexpected. It was stated that in principle it was possible to engage in a non-driving task such as participating in a Teams meeting, as long as there’s a 10 second hand over time to the driver. Although often is stated that Level 3 specifies a 5-10 second ToC time, this is a design choice and not a standard (Koopman).

Related to this topic was the discussion on Minimal Risk Manoeuvres (MRMs) which are necessary in case a ToC is ultimately unanswered by drivers. The most common MRM is coming to a safe stop in such a situation, but this is something that NRAs would like to avoid on the highway or at least minimize. When possible, a vehicle that requires an MRM should be able to leave the highway or at least come to a stop on a hard shoulder rather than in its lane. It was also concluded that MRMs are highly context dependent and that the process of determining how to define them could greatly benefit from a multi stakeholder approach including NRAs, developers and human factors specialists.

On the topic of remote assistance and tele-operation, the room was divided. For most of the current deployments of CAVs around the world, remote monitoring and/or support is being used and it is regarded as a necessity. Perhaps over time, when CAV’s capabilities increase, such support may be minimized or even become obsolete, but for the foreseeable future it is certainly indispensable (Alkim et al, 2023). There is still a need for further research on higher operational speeds and resulting increased safety risks, investigating edge cases, and looking at the ODD from a system-to-system perspective beyond the scope of only the vehicle. Overall, remote support is expected to play a crucial role in achieving safe and comfortable highly automated transport services in mixed traffic. But for tele operations there are objections related to possible latency issues and also the question whether one tele driver for one tele-driven vehicle is a sensible proposition in terms of scaling up and work force issues.

As several participants, including the PEB chair had gained some experience with Waymo and Cruise self driving vehicles in SF, a presentation and some videos were shown. This lead to quite some discussion and controversy as it was argued that the Cruise deployment was an example of moving to fast with a big tech mentality. But it was also proposed that some shortcomings could be prevented with a better collaboration with road operators. For more info on the experience of 20 European experts, see this blog that was written in the context of the EU funded FAME project: https://www.connectedautomateddriving.eu/blog/seeing-is-believing-riding-with-cruise-and-waymo-in-san-francisco/

3.2 recommendations for implementation steps

CRF how do you practically use it, and what do you do with the results

Help define/describe MRMs

Pragmatic approach, try out DOVA in practice

Roadworks are an early target for better digital information

Further investigate the topic of digital twins and the role road operators can play here, link with DROIDS

Explore the trust issue: what if OEMs and NRAs would interact via a neutral, mandated third party? It would work, but it will take time…

How can CEDR/ACEA MOU help to set up constructive dialogue? By connecting projects, topics (like edge cases)

Traffic management is an essential enabler for highly automated vehicles to be part of a safe and efficient traffic system, where a certain level of support from and interaction with the infrastructure are necessary requirements for future traffic systems with automated vehicles (e.g., for improving the ODD or implementing traffic rules). In addition, traffic management should serve to address unanticipated negative effects of automated vehicles (e.g., impacts on traffic efficiency), which are otherwise expected to decrease the current road and network capacities, with potentially negative economic externalities. Finally, understanding and incorporating human factors in automated vehicles and traffic management design, regarding both strategies and responses, is essential in order to raise acceptability, ensure wider adoption of vehicle automation, and generate positive effects for society as a whole. To achieve all of the above, there is a need to seek more collaboration among stakeholders, e.g., involving vehicle manufacturers, road authorities, and researchers to better frame the problems and achieve better, more sustainable, solutions through multidisciplinary approaches. In particular, further research is needed on human factors, involving both the automated vehicle occupants and the interactions with other entities.

4 Applicability of the projects and recommendations for implementation

4.1 DiREC

4.1.1 Overall conclusions and recommendations for national road administrations

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). 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.

4.1.2 Open questions and next steps

For DiREC the following open questions remain:

- Can connected and automated vehicles deliver the societal benefits that have been promised for them, and in what timeframe?
- How can we build a stronger relationship between NRAs, vehicle regulators and OEMs to facilitate the implementation of technological solutions that require cooperation across disciplines?
- What are the NRAs ambitions for connected and automated vehicles?
- To what extent are NRAs willing to take on responsibility for safety critical digital infrastructure?

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.

Actions 1 - Now

- 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.

- 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.
- 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 as a link between European engagement direction and the needs of the local Road authorities.

Actions 2 - Soon

- 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.
- 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.
- 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.
- 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.
- 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 to:

- 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.
- 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.
- 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.

4.2 TM4CAD

4.2.1 Overall conclusions and recommendations for national road administrations

Decisions on infrastructure investment will need to be made in consultation with the CAD system developers or vehicle manufacturers in order to ensure that the correct and relevant level of infrastructure support to aid ODD awareness is being provided.

4.2.2 Open questions and next steps

From the final conference and various discussions within the CCAM ecosystem, the DOVA concept was highly appreciated and regarded as a useful mechanism to exchange externally sourced information from NRAs to CAVs. So, it seems logical to start using DOVA. However, a primary open issue is the basic one of trust. Vehicle manufacturers and ADS developers will use the data as a basis for automated vehicle operation only if they can trust the data to be correct, reliable and secure. Much work needs to be done to improve the quality of the data, the reliability of the data and its exchange as well as the cybersecurity of the DOVA-process to the level satisfying the liability-related requirements of the automated vehicle industry.

A generic issue is how to maintain and share the digital infrastructure of the road operator. The uses of the road operators' digital infrastructure including also the DOVA framework are numerous as are the sources and suppliers of the contents of the digital infrastructure.

Another key open issue is the governance of the DOVA and the data exchanged via it. An agreed governance model is a prerequisite for operating such a framework in practice.

Request to the CCAM platform to digitize the rules of the road. This is an important action and it's not currently being done. It entails more than translating the current set of rules that are designed for humans.

1. what is the necessary information? Right info at the right time at the right place
2. what is the right (appropriate or expected) behaviour given the context and correct "translation" of the rules of the road?

Aging infrastructure and digitization challenges

Complementing information from different sources

The work on open issues should commence in many cases in close liaison and cooperation with the automated vehicle industry stakeholders on the European level, e.g., in the scope of the Horizon Europe or CEF 2 programmes as well as on the policy level. These could lead to infrastructure-enabled solutions improving the continuity of or extending the Operational Design Domains (ODDs) with mechanisms such as extended perception and decision-making delegation, supporting the real time knowledge about conditions in the "electronic horizon", the centimetric accuracy of the positioning signal, and the ability of CCAM enabled vehicles (incl. collective awareness) to navigate through road works and incident sites.

5 Summary

The aim of the CEDR Transnational Road Research Call 2020 “Impact of CAD on Safe Smart Roads”, was to prepare the national road authorities on future challenges of connectivity, digitalization and automation to get to an autonomously well-managed traffic flow. In order to do so, two projects were funded, respectively DiREC and TM4CAD.

Both projects started in September 2021 but finished a half year apart from each other, TM4CAD in March 2023 and DiREC in August 2023. A final conference was organized on 20-21 November 2023. This conference allowed the project consortia to present their results to the Programme Executive Board as well as to each other and some invited stakeholders and provided an opportunity to further discuss the results and their implications for NRAs. The project’s results, open questions and next steps for implementation are summarized in this report.

Both projects have delivered a framework for NRAs to address future challenges of connected and automated mobility. The CAV-Readiness Framework (CRF) by DiREC and the Distributed ODD attribute Value Awareness (DOVA) framework by TM4CAD. A logical next step would be to apply them in practice, preferably in close liaison and cooperation with the European automated vehicle industry stakeholders. This is also how most of the open questions should be addressed in further research, projects and collaborations.

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Appendices

Appendix 1 – Final conference programme

CEDR Impact of CAD on Safe Smart Roads
Final Conference

Date: 20-21 November 2023

Location: Flemish Agency for Roads and Traffic, Koning Albert-II-laan 20, Brussels
5th floor – meeting room 5P25

Programme day 1 (20 November)

(in-person and virtual session)

13.00 – 14.00	Registration and business lunch
14.00 – 14.15	welcome and introduction (Kristof Rombouts)
14.15 – 15.30	DiREC results (Ianto Guy)
15.30 – 15.45	break
15.45 – 17.00	TM4CAD results (Risto Kulmala, Sven Maerivoet, Hironao Kawashima, Tom Alkim)
17.00 – 17.20	plenary discussion and questions
17.20 – 17.30	summary and closing remarks

19.00 Dinner TBD

Programme day 2 (21 November)

(in-person only)

09.00 – 09.10	welcome + setting the scene (Kristof Rombouts)
09.10 – 10.00	DiREC results (Ianto Guy)
10.00 – 10.15	break
10.15 – 11.05	TM4CAD results (Risto Kulmala, Sven Maerivoet, Hironao Kawashima, Tom Alkim)
11.05 – 11.30	AV experiences in SF implications for NRAs (Kristof Rombouts, Tom Alkim)
11.30 – 12.30	plenary discussion based on statements moderated by Tom Alkim
12.30 – 12.45	identify next steps
12.45 – 13.00	summary and closing remarks
13.00 – 14.00	End of conference and lunch

Appendix 2 – Codified Rules of the Road

In TM4CAD Deliverable 5.1 "Recommendations for the dialogue between NRAs and automated vehicles developers", one of the identified requirements for digital infrastructure, relevant for road operators in light of desired competencies and behaviour of automated vehicles, is that rules of the road must be defined in "machine readable" form for use by CAD developers and operators. In the annex of the deliverable an example was given based on UK Highway Code Rule 195 related to an urban scenario (giving way to pedestrians on a zebra crossing). After reviewing the document, the PEB requested another example related to a highway scenario. Therefore, in this appendix rule 162 (overtaking on the highway) of the UK Highway Code is given.

To enable the road operators to define *good behaviour* for CAD systems, the next step is the introduction of a novel codified rules of the road concept [1]. This is required along with a common set of ODD attributes, in similar spirit as to how a *regular* rules of the road[2] defines the expected behaviour from human drivers. This will enable manufacturers and road operators to communicate in a common, predefined language, and allow for changes in CAD traffic throughput due to ODD and infrastructure support changes. This good/expected behaviour of CAD systems will form part of a behaviour library, while operating conditions will be part of (instantiations of) the ODD. The benefit of this is that any CAD system, as well as road operators, can adopt and follow these codified 'rules of the road', with the goal of them being unambiguous, verifiable and explainable.

This method is already being discussed in the UK, based on road authorities' and manufacturers' needs and interests. Simultaneously, this approach will encompass expected behaviour in certain operating environments, therefore providing a close link with the ODDs. In the following, we give some insights into the process of turning the highway code into a more deterministic/mathematical format (Douglas, 2022).

Two of the relevant topics for CAD system driving safely are:

- The CAD system should comply with traffic rules.
- The CAD system should interact safely with other road users.

In addition, the CAD system should respond in line with traffic laws to markings and signals.

To this end, it becomes paramount to create verifiable requirements that can be used to create relevant scenarios. As an example, consider UK Highway Code Rule #162:

Rule 162 of the Highway Code is stated below.

Rule Text
Before overtaking you should make sure *- the road is sufficiently clear ahead* *- road users are not beginning to overtake you* *- there is a suitable gap in front of the road user you plan to overtake.*

[1] UNECE FRAV 33rd Meeting: FRAV-33-39: (UK) An Approach to Defining Codified Rules of the Road
[2] A highway code is a set of information, advice, guides, and mandatory rules for road users in a specific country. Its objective is to promote road safety, and it applies to all road users including pedestrians, horse riders, and cyclists, as well as motorcyclists and drivers. It gives information on road signs, road markings, vehicle markings, and road safety. It can also give extended information on vehicle maintenance, licence requirements, documentation, penalties, and vehicle security. In an international context, a highway code may be following the treaty set out by the Vienna Convention on Road Traffic.

Rule 162 delineates the prerequisites that should be met before initiating an overtaking manoeuvre, encompassing considerations such as the road's visibility, ongoing overtaking actions by other road users, and the presence of an appropriate gap ahead of the vehicle to be overtaken.

Rule 162 (ODD & Behaviour Terms)
The rule is re-stated below highlighting important terms.

Before overtaking you should **make sure**
- the **road** is sufficiently **clear ahead**
- **road users** are **not beginning** to **overtake you**
- there is a **suitable gap in front of the road user you plan to overtake**.

Note that the statements are all a combination of ODD and behaviour. Terms that are ODD and behaviour related are respectively highlighted in yellow and green.

Rule 162 (Predicates and Functions)
For Rule 162, we construct the following predicates:

Predicate	Description
isEgo(x)	x is the Ego
isAhead(x,y)	x is ahead of y
isOtherRoadUser(x)	x is a non-Ego object
isClearAhead(x)	x is clear ahead
isOvertaking(x,y)	x is overtaking y
hasSuitableGapAhead(x)	There is a suitable gap ahead of x
canOvertake(x,y)	x can overtake y
isOnRoadLane(x,y)	x is on road-lane y

In First-Order Logic
Rule 162 is a rule that identifies whether an overtake manoeuvre can be performed. If the conditions of the rule are true, then an overtake manoeuvre can be acted upon, otherwise it must be abandoned. Further, this rule implicitly also identifies which actor the ego can overtake.
For ease of understanding, the rule may be broken down into four logical statements, that are logically related, with the relationship being stated as the last rule. Predicates are used to construct the logic specification for the rule.

The parameters for the rules: the ego vehicle (x), the lane (y), other actor (w), and actor being overtaken (z).

The rules are as follows:

*Rule (**a**):*	**isEgo**(*x*)	x is the ego
*Rule (**b**):*	**isOnRoadLane**(*x*,*y*) ∧ **isClearAhead**(y)	x is on road-lane y and y is clear ahead
*Rule (**c**):*	**isOtherRoadUser**(*w*) ∧ **isOvertaking**(*w*,*x*)	w is overtaking x

*Rule (**d**):*	**isAhead**(z,*x*) ∧ **hasSuitableGapAhead**(*z*)	suitable gap in front of the road user you plan to overtake.
The Rule	(**a**) ∧ (**b**) ∧ (¬**c**) ∧ (**d**) → **canOvertake**(*x*,*z*)	

Overall, the previous serves to show that it is useful to use ODD-based rules of the road to attain a wider safety assurance. Hence:

- Each rule of the road (anywhere) will always be a function of ODD and behaviour competencies.
- Each scenario (irrespective of the system under test), will always have ODD attribute information and behaviour information.

All this information can be mapped using labels/tags.

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Final Programme Report from CEDR Research Programme Call 2020 Impact of CAD on Safe Smart Roads

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Conference of European Directors of Roads

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