Traffic Management for Connected and Automated Driving (TM4CAD)

Report on distributed ODD awareness, infrastructure support and governance structure to ensure ODD compatibility of automated driving systems

Deliverable D2.1 Version 1.0

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Consortium partners: MAP traffic management (the Netherlands), Traficon (Finland), Transport & Mobility Leuven (Belgium), WMG, University of Warwick (United Kingdom), Steven Shladover (independent consultant, United States) and Keio University (Japan).

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D2.1 Report on distributed ODD awareness, infrastructure support and governance structure to ensure ODD compatibility of automated driving systems

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Executive summary

The project TM4CAD (Traffic Management for Connected Automated Driving) was selected in CEDR Transnational Road Research Programme Call 2020 for funding with regard to call topic C: Traffic management. The project commenced its activities on 13 September 2021 and is planned to be completed in 18 months after its start.

This deliverable (D2.1) provides a description of work package (WP) 2 of TM4CAD including providing results from an National Road Authority (NRA) stakeholder workshop conducted by the project on the concept of Distributed ODD Awareness (DOA).

TM4CAD project has introduced the DOA 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. This deliverable discusses various ODD attributes and the potential for infrastructure support for real-time information gathering for each of the ODD attributes. Furthermore, change frequency and time criticality of the information availability for each ODD attribute is discussed. Depending on level of infrastructure support and level of CAD on-board sensing, various kinds of information relevant to the ODD can be supplied as part of a DOA framework.

In order to implement the DOA framework, the NRAs and other 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 safety of CAD systems, DOA is also essential for safety of CAD systems, especially for CAD systems with limited on-board sensing capability. This deliverable further discusses how the DOA 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.

Discussions on information quality are not part of this deliverable and will be discussed in D3.1 which is a deliverable of WP3 of the TM4CAD project.

As a result of the NRA stakeholder workshop, this deliverable discusses the roles and responsibilities in the implementation of the DOA framework.

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List of Abbreviations

ADS	Automated Driving System
ADS-DV	Automated Driving System Dedicated Vehicle
BSI	British Standards Institution
CAD	Connected and Automated Driving
CEDR	Conference of European Directors of Roads
CDA	Cooperative Driving Automation
CITS	Cooperative Intelligent Transportation Systems
DDT	Dynamic Driving Task
DOA	Distributed ODD Awareness
DoRN	Descriptions of Research Needs
FRU	Fallback Ready User
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
ISAD	Infrastructure Support for Automated Driving
MRC	Minimal Risk Condition
MRM	Minimal Risk Manoeuvre
NRA	National Road Authority
OD	Operational Domain
ODD	Operational Design Domain
PEB	Programme Executive Board
TMC	Traffic Management Centre
ToC	Transition of Control
UNECE	United Nations Economic Commission for Europe
VRU	Vulnerable Road User

1 Introduction

1.1 TM4CAD

In TM4CAD we explore the role of infrastructure systems across various Infrastructure Support for Automated Driving (ISAD) levels in creating ODD awareness for CAD systems. As a starting point we propose various categories of distributed ODD attribute information and define 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. Moreover, TM4CAD will demonstrate 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 will provide 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 will:

- Identify 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;
- Integrate the different perspectives of the CAD vehicle system developers and the national road authorities and operators to focus on the overlapping areas;
- Introduce the concept of ODD attribute awareness and the role of infrastructure in it;
- Develop 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;
- Provide insights on how to support CAD operation and ODD management, and how ISAD should be refined for traffic management use, and
- Detail how traffic management systems and CAD vehicles can best interact to improve traffic operations.

Figure 1: *Some of the TM4CAD project team members*

The project is carried out by a consortium led by MAP traffic management (MAPtm) from the Netherlands. Other members of the consortium are Traficon (TRA, Finland), Transport & Mobility Leuven (TML, Belgium), WMG, University of Warwick (WMG, United Kingdom), Steven Shladover (independent consultant), and Keio University (Japan).

Team members left to right, top: Sven Maerivoet (TML), Risto Kulmala (TRA), Steven Shladover, Ilkka Kotilainen (TRA); bottom: Jaap Vreeswijk (MAPtm), Siddartha Khastgir (WMG), Anton Wijbenga (MAPtm).

1.2 Deliverable objectives and target audience

The objective of this deliverable is to describe the results of the TM4CAD project's WP2 titled "Concept of ISAD and ODD management" and the Distributed ODD Awareness concept that was introduced in this WP.

The target audience is the CEDR Programme Executive Board (PEB) coordinating the CEDR 2020 research call and the larger body of National Road Authorities (NRAs) that they represent.

1.3 Research Questions and Essential Results

The following Research Questions (RQ), Essential Results (ER) and Operational Results (OR) from the larger list addressed by TM4CAD are tackled by this deliverable (D2.1):

Table 1: *Mapping of Research Questions and Expected Results to Deliverable 2.1*

Research Question / Result	Addressed in paragraph(s)
RQ1: Should NRAs set requirements on the desired behaviour of (partly) automated vehicles on where and how they should drive?	Section 4
RQ3: How does CCAM support the work of traffic management centres and how can traffic management centres support and facilitate the deployment of CCAM?	Section 3.4 – 3.5
RQ4: What kind of information is to be transmitted in the interaction (in both directions) between a traffic management centre and vehicle?	Section 3.2 – 3.3
RQ5: Which information is to be provided by the NRA/roadside and which information can be obtained by the sensors of the moving vehicle itself?	Section 3.2
ER1: Determination of the circumstances (actual traffic conditions, status of the infrastructure, …) under which the traffic control centre would need to lower the ISAD level in order to stop automation taking place and accordingly mitigating measures if applicable	Section 3.4 - 4
ER2: Determination of the circumstances under which the traffic control centre would need to upscale the ISAD level/impose more automated driving	Section 3.4 - 4

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Research Question / Result	Addressed in paragraph(s)
ER5: Definition of the roles and responsibilities in the interaction between OEMs/Service Providers and NRAs on operational level	Section 4
OR1: Description of the possible added value of service providers in the interaction between NRAs and OEMs	Section 3.4 – 3.5
OR2: Description of possible governance mechanisms for ODD management that need to be established	Section 3 - 4

1.4 Preparation of this deliverable

This chapter summarizes results from the TM4CAD and NRA workshop on “ODD-ISAD architecture and NRA governance structure to ensure ODD compatibility” that was held on 14 February 2022.

The workshop had over twenty NRA participants from different European countries. Detailed analysis of the workshop discussions and questions can be found on TM4CAD project website.

Workshop objectives and agenda included the following:

1) Understand basic concepts and define basic terminology associated with ODD definition;
2) Present Distributed ODD Awareness (DOA) concept and relationship to ISAD;
3) Discuss and validate results from the first work-package of the TM4CAD project.

Between each agenda objective, three 30 min interactive parts with moderated discussion were held. Results presented here reflect these discussions and questions raised by the NRAs.

1.4.1 Understandability

In the workshop, the NRAs emphasized the need for understandability of basic concepts and terminology associated with ODD definitions between different ODD functionalities, different levels of automated vehicles (e.g., between level 3 and level 4) and ODD differences among manufacturers and ADS systems (or vehicle type). It was evident from the discussion that a common understanding in-between the NRAs is missing as well as between the NRAs and the CAD system developers. This highlighted the role and the status of standardisation to define common ODD language for better understandability and this was requested by the NRAs.

1.4.2 Feasibility

In the workshop, the NRAs raised a question about feasibility and technical capabilities of the future connected and CAD systems and whether a standardised or dedicated road for Automated Driving Systems (ADS) would be required for safe operation, i.e., required by the CAD system developers, but it was made clear in the response that no CAD developers are demanding or even requesting such special provisions. This highlighted the implications of such measures on the NRAs, both at a financial level in terms of investment in infrastructure but also the need for new skills to enable the NRA workforce to have the required technical capabilities.

1.4.3 Completeness

In the workshop discussion, the NRAs further indicated the need for a road safety discussion on how the ODD relates to regulatory frameworks, and how ODD exceptions are handled and presented for the driver (e.g., defining various Minimal Risk Manoeuvres (MRMs) and Minimal Risk Conditions (MRCs)). They were informed that one of the fundamental technical requirements for all CAD systems will be the ability to recognize when their ODD restrictions are being violated and to ensure that automated operations are ceased prior to departing from the ODD. This simple solution obviates the need for location-specific ODD regulations.

1.5 Relationship with other Work Packages (WPs)

WP 2 sets the framework for the other WPs of TM4CAD. It directly interacts with all other WPs (WP 3, WP 4 and WP 5) (see Figure 2). While introducing the concept of Distributed ODD Awareness, WP2 sets out the ODD attributes whose information could be exchanged between infrastructure and the CAD system. WP3 further defines the quality criteria for such information in order to ensure safe operation of the CAD system. WP4 develops a use case implementation of the DOA concept developed in WP2. Lastly, WP5 lists the requirements (roles and responsibilities) on the NRAs for the DOA concept to be implemented.

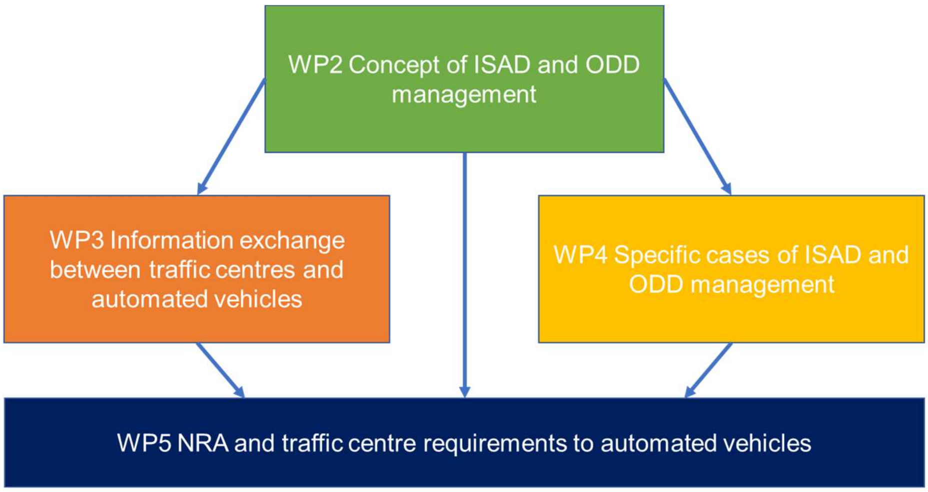


Figure 2: *Relationship of WP2 (and D2.1) with other WPs of TM4CAD project*

1.6 Structure of the document

This document starts with the summary description of the project and this document. It is followed by the objectives of Deliverable 2.1 and its target audience. It then discusses the inputs received from the NRA workshop on the content of this deliverable which have been included in later sections. It then discusses the relationship of the WP2 with other work packages of TM4CAD project.

Next the document introduces the concept of Operational Design Domain (ODD), including ODD attributes, a language for ODD definition and the need for ODD awareness.

Next the concept of Distributed ODD Awareness (DOA) is introduced including a framework for how to implement the same for enabling safe deployment of connected and automated driving (CAD) systems. The document further discusses the role of the DOA framework in the wider CAD safety assurance of CAD and its interplay with ADS technological capabilities, driving behaviour and rules of the road.

The document ends with discussing the roles and responsibilities in the implementation of the DOA framework.

2 Basic Concepts and Terminology

This deliverable starts by introducing some of the basic concepts associated with automation of road transport and defining the key terms that are used to discuss these concepts. This is important to facilitate clear communication about the concepts throughout the rest of this deliverable and the TM4CAD project. The need for the same was also highlighted in the NRA stakeholder workshop (section 1.4). The most important concepts are:

- **Levels of automation:** these describe the distribution of driving roles between humans and the technology installed in the vehicles (defined in SAE J3016 [1] or ISO PAS 22736 (identical contents to SAE J3016 – April 2021 edition);
- **Types of cooperation:** Between vehicles, other road users, and the roadway infrastructure (defined in SAE J3216 [2]);
- **Operational Design Domain (ODD):** The set of conditions in which each driving automation system is capable of performing the dynamic driving task, which is the operational design domain or ODD (defined in SAE J3016 / ISO PAS 22736 and further explained in BSI PAS 1883 (published) [3], ISO 34503 (in development) and SAE J3259 (in development).

One important principle underlying all the technical discussions is that the descriptions of systems for automating road transport are focused on specific driving automation features rather than vehicles, because an individual vehicle may be equipped with multiple automation features that are capable of different kinds of automated operations under different conditions. For example, a passenger vehicle may be equipped with a SAE Level 3 Motorway Chauffer System as well as a SAE Level 4 Automated Valet Parking System. Therefore, a vehicle cannot generally be defined in terms of a unique automation level, cooperation class, or ODD, because its driving automation features could differ from each other in each of these dimensions.

2.1 Levels of driving automation

The levels of driving automation describe the extent of the dynamic driving task (DDT) being performed by the human driver and the extent being performed by the driving automation system. The DDT represents the operational and tactical aspects of driving, but not the strategic tasks such as planning routes or choosing destinations. The DDT tasks include basic steering and speed control plus identifying and tracking hazards in the driving environment, manoeuvring around obstacles and hazards and planning and selecting local paths. The levels of driving automation are:

- **Level 0 – No driving automation:** The human driver performs the complete DDT but may be assisted by collision warning systems or collision mitigation or avoidance systems that act intermittently in response to specific hazard conditions, without changing the driver’s fundamental driving tasks.
- **Level 1 – Driver assistance:** The system performs either lateral (steering) or longitudinal (acceleration and braking) control on a sustained basis, while the human driver performs all other dynamic driving tasks and therefore remains fully engaged in driving.
- **Level 2 – Partial driving automation:** The system simultaneously performs lateral and longitudinal control on a sustained basis, while the human driver continues to perform object and event detection, recognition and response tasks. Therefore, although the driver’s hands and feet may be off the steering wheel and pedals, he

or she still needs to remain fully engaged in the driving task and needs to continuously monitor the performance of the system to be prepared to intervene when necessary. Level 1 and 2 systems are considered driving assistance or driver support systems because the human driver is still in charge and needs to make all safety-critical decisions. The higher-level automation systems are considered Automated Driving Systems (ADS) because they are capable of operating without continuous human supervision under at least some conditions.

- **Level 3 – Conditional Driving Automation:** The system is capable of performing the complete DDT under certain limited conditions (within its ODD), but it depends on a human "fallback-ready user" (FRU) in the driver's seat to intervene when it requests help to contend with situations that it cannot handle by itself. The human FRU can shift attention to other activities while the Level 3 ADS is performing the DDT but needs to be alert enough to respond promptly to any requests to intervene. So, he or she could be conducting work or leisure activities online but could not go to sleep while the system is driving.
- **Level 4 – High Driving Automation** – The system is capable of performing the complete DDT under certain limited conditions (within its ODD), and it does not need an attentive driver or FRU to ensure safety. It must be capable of bringing the vehicle to a stable, stopped condition (a "minimal risk condition" or MRC) as necessary to respond to internal failures or external hazards in the driving environment. Level 4 automation may be applied on ADS-dedicated vehicles (ADS-DV) that are only intended to be driven by the ADS and therefore do not need conventional human driver control interfaces (steering wheel and pedals) or it may be applied on vehicles that are also intended to be driven by human drivers and therefore have conventional driver control interfaces.
- **Level 5 – Full Driving Automation** – The system is capable of performing the complete DDT under all conditions in which humans are capable of driving, so it has no ODD constraints. Similar to Level 4 automation, it must be capable of bringing the vehicle to an MRC as necessary to ensure safety, and it may be applied on ADS-DVs or on vehicles that can also be driven by human drivers using conventional control interfaces. Because of the technical challenges, this is unlikely to become reality until many decades in the future, so it is only a long-term dream rather than reality.

2.2 Classes of cooperative automation

Cooperative Automated Driving (CAD) systems combine driving automation with the use of wireless communications to enable various kinds of cooperative driving behaviours. The cooperation may be vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), infrastructure-to-vehicle (I2V), vehicle-to-pedestrian (V2P), or vehicle-to-anything (V2X), the most general category. These forms of cooperation may enable a quantitative enhancement to the functionality of a driving automation system or a qualitative extension to new functionality.

The cooperative automation behaviours have been classified into four classes, with alphabetical classifications so that they can be easily combined with the numerical levels of automation. These classes are defined at a generic level so that the cooperating entities on both the sending and receiving ends of the wireless communication link could be vehicles, local infrastructure devices, cloud-based infrastructure, or vulnerable road users. The cooperative automation classes are the following:

- **Class A – Status-Sharing (“Here I am and here is what I see”):** Class A systems exchange information about their current conditions and about the current status of their environment as detected by their own sensors. This could be a vehicle reporting on its current location and velocity and the external objects that its sensors see, an infrastructure sensor reporting on the locations and velocities of all moving objects within its field of view, or a traffic signal controller reporting on its current signal phase.
- **Class B – Intent-Sharing (“This is what I plan to do”):** Class B systems add to status sharing information by also sharing information about their intended future actions, to help nearby entities to anticipate their behaviours. This could include vehicles reporting on their acceleration and braking commands or desires to change lanes or traffic signal controllers reporting on the time remaining until their next phase change.
- **Class C – Agreement-seeking (“Let’s do this together”):** Class C systems actively negotiate future actions to improve traffic flow and safety. This could involve vehicles and their local infrastructure devices collaborating to facilitate smooth lane changing and merging manoeuvres by jointly deciding who goes ahead of whom.
- **Class D – Prescriptive (“Do this” and “I will do as directed”):** Class D systems command other entities to take specific actions to improve overall traffic flow or safety. This could be variable speed limit signs commanding changes in the allowable maximum speed or emergency vehicles commanding other vehicles to get out of their way.

2.3 Operational Design Domain

While improved safety is the biggest motivation for the introduction of CAD systems, ensuring their safe introduction is also the biggest challenge. Safe deployment not only needs safe technology, but also safe use of the technology. Due to the infinite variety of situations a CAD system will encounter in its lifetime, it would be unreasonable to claim absolute safety of CAD systems, suggesting absolute safety is a myth.

However, we can still safely introduce CAD system by imparting *Informed Safety* [4], which has the potential to prevent their misuse and disuse. Informed Safety means that the “user” (i.e., driver or operator) is aware of what the system can and cannot do. An aspect of Informed Safety involves understanding the “conditions” in which the CAD system is capable of operating safely. The CAD industry calls these conditions the Operational Design Domain (ODD) [1]. The ODD is the complete combination of conditions in which a driving automation system is capable of operating. Although people often find it convenient to think of this in purely location-based terms, it includes much more than just the geographic location. The ODD attributes include the characteristics of the physical and digital roadway infrastructure, the availability of external support functions such as GNSS localization and digital maps (and their accuracy), the weather and lighting conditions, and the traffic conditions (speed, density and incidents) [3].

Thus, ODD constraints are especially important for higher levels of automation — SAE level 3 and SAE level 4 [1]. If the ODD conditions are not satisfied, these systems cannot be guaranteed to be capable of operating safely. In order to understand whether its ODD limitations are at risk of being violated, the CAD system needs to be aware of the relevant ODD attributes (e.g., visibility, traffic density, incidents, etc.) in real time to compare them with the design ODD of the system. While some ODD attribute information can be sensed by the CAD system’s on-board sensors, some information may only be supplied by off-board sources such as remote sensors and wireless communication systems.

2.4 ODD attributes

The ODD attributes represent the combination of all the design factors that affect the ability of any CAD system to perform its automated driving functions. They are likely to vary among different CAD systems, especially among systems that are intended to perform different transportation functions, delivering different transportation services. The ODD attributes are also important discriminators among different CAD systems, since the most primitive or limited capability systems will have the tightest ODD limitations while the most sophisticated and higher capability systems will have fewer ODD constraints on their ability to drive in an automated manner. At the earliest stage of introduction of CAD systems to public service, the ODD restrictions will be most significant, but as the technology advances the ODD restrictions may gradually be relaxed and become a less serious constraint on when and where the CAD systems can be used. However, it is important to highlight that all CAD systems will at all times have some level of restrictions as per their ODD definition.

Another way of viewing this is to consider that the strongest infrastructure support for automated driving will be needed at the time of market introduction, but the need for that support will gradually diminish over time.

In order to ensure various NRAs and the CAD system developers have a common understanding of an ODD and its attributes, it is important to establish a standardised set of ODD attributes. Standardisation activities have been undertaken both nationally and internationally in this regard. The British Standards Institution (BSI) published the BSI PAS 1883 which provides a taxonomy of ODD attributes. SAE have initiated an activity SAE J3259 which is dealing with a similar scope. ISO are working on ISO 34503 which is focussing on a ODD attribute taxonomy as well as a high level ODD definition format.

From the roadway infrastructure side, it's important to consider the full range of ODD attributes that could be relevant to any CAD system that may use each segment of roadway. In Section 3.2, we provide a comprehensive list of the ODD attributes that have been identified for consideration within the TM4CAD project, but at this introductory stage we just indicate the general categories of ODD attributes that need to be considered for supporting CAD deployment and for reporting readiness to any approaching CAD-equipped vehicle (as per BSI PAS 1883 [3]):

- Physical roadway infrastructure (BSI PAS 1883 Scenery element) attributes:
    - Geographic location (boundaries for legal or technically feasible automated driving, special zones, etc.)
    - Class of roadway and any relevant physical characteristics of the roadway (pavement surface and marking conditions, grade, curvature, shoulders, lane widths, etc.)
    - Traffic control devices (signage, signals, tolling, access controls, etc.)
    - Active lane reference indicators
    - Barriers or fences to protect against intrusion by animals or unauthorised road users
    - Road surface conditions (roughness, state of repair, friction, snow, or ice accumulations, etc.)
    - Road shoulder conditions – availability as emergency refuge
- Roadway operational attributes (BSI PAS 1883 dynamic element):
    - Traffic conditions (local traffic speed and density, density of various categories of

VRUs and animals)
    - Traffic management strategies and devices
    - Traffic incident conditions
    - Special situations (work zones, incident sites, lane or road blockages, emergency vehicles, officers directing traffic, etc.)
- Ambient environmental conditions (BSI PAS 1883 environmental conditions):
    - Weather (and influence on road surface conditions)
    - Visibility (lighting, obscurants)
    - Electromagnetic interference
- Digital information to support CAD operations:
    - Digital map availability and level of detail
    - GNSS and wireless communication availability and performance
    - Traffic management information communicated to CAD vehicles

2.5 ODD definition language

In addition to identifying the ODD attributes there is a need to provide guidance on how to use the attributes to create an ODD specification or definition. This requires a structured format or a language concept that enables clarity in communication between CAD system developers and NRAs and other road network operators regarding the ODD attributes.

There are multiple international standardisation activities ongoing which are creating a format / language for ODD definition. These include ISO 34503 [5] and ASAM OpenODD [6]. ISO 34503 defines a format and a structured natural language definition of an ODD catering to the needs of NRAs, regulators and system engineers, while ASAM OpenODD provides a machine executable format for using ODD definition as part of virtual testing process.

One of the main use cases of an ODD description is to check that, during testing and deployment phases, any situations can be mapped to the ODD boundary and determined whether they are inside or outside the ODD. This requires the ODD boundary to be binary and provides clear separation The ODD definition language enables users to not only define the ODD but also to objectively define the ODD boundaries and group together a set of ODD attributes with their relations that fall within the operating boundary. For example, a CAD system may be able to handle motorways on sunny days but not during rainfall.

An ODD definition language concept has two parts: the domain model (i.e., the attributes), and the language concepts. The domain model includes the set of ODD attributes and their relationships, and the language concept includes the syntax and semantics of the format.

2.6 ODD awareness / monitoring

While performing the dynamic driving task (DDT), an ADS needs to be aware of the near real-time ODD attributes' values, so that the ADS can compare the current external conditions with the defined ODD. This is essential for the ADS to be able to decide on triggering of the minimal risk manoeuvre (MRM) or issuing a request for human intervention to take over the DDT. During trials, the monitoring of the ODD attributes may be performed by the in-vehicle safety operator or by fleet operators.

ODD attributes may have interdependence and their relationship may be defined in a prescribed format. For example, an ADS may have a maximum allowable speed of 70 km/h in the absence of rainfall, and a reduced maximum allowable speed of 40 km/h in the presence of rainfall. The fleet operators or the ADS itself may decide, for example, to reduce the maximum allowable speed when it is raining as compared to sunny conditions in order to ensure safe operation within ODD boundaries.

Defining an ODD boundary is up to the manufacturers' discretion and may involve sub-attributes or qualifiers, such as temporal elements. For example, an ODD boundary may be defined as up to 2 minutes of heavy rainfall by adding a relevant sub-attribute. ODD attributes need to be defined in such a way to allow awareness on the part of the ADS, so that the ADS operations remain within the designed and defined ODD limits. In case of an imminent ODD exit, the ADS should be designed to trigger a transition to a Minimal Risk Condition (MRC) or issue a request to intervene to the fall-back ready user or change the operating mode to a degraded mode, i.e., lower performance capability mode.

While the role of the human user (driver, fallback-ready user or fleet operator) is not part of the ODD definition, the ODD needs to be defined in a way that it is understandable to the human user to enabling them to take into account the ODD limits for the safe use of the ADS feature. Furthermore, understandability of the ODD definition and the awareness mechanisms is also key for the NRAs in order to understand which CAD systems will be capable of operating on which parts of their network.

2.7 ODD definition and local condition description

The advantage of a structured format for defining the ODD of ADS is that all manufacturers define the ODD of their systems in the same way, using the same recognizable set of attributes and attribute values, i.e., the ODD definition language. The usefulness of such a common definition language extends beyond the definition of the ODD of ADS; it can also be used to describe real-life location conditions, i.e., the operating domain of the ADS.

This dual use of a single set of attributes means that in one case attribute values are used to describe the competency of an ADS, whereas in the other case attribute values are used to describe a local condition. Both these use cases are pertinent from an NRA's perspective. The uniformity of this procedure allows relatively easy comparison of the defined ODD of the ADS with the real-life local conditions, as shown in the figure below (Figure 3).

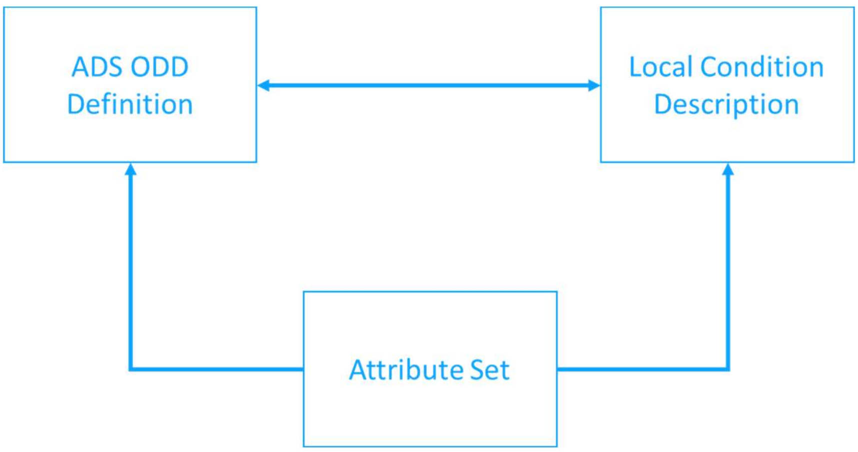


Figure 3: *Dual use of the ODD attribute set*

2.8 Infrastructure Support Levels for Automated Driving (ISAD)

The European Research and Innovation project INFRAMIX [7], funded under the Horizon 2020 programme, has developed a scheme for infrastructure support levels for automated driving, in short ISAD levels [8]. The aim of these levels is to classify and harmonise capabilities of a road infrastructure to support automated vehicles. The rationale for proposing this classification scheme is to find a mechanism to augment the limitations of environment perception of automated vehicle on-board sensors with the numerous traffic and environmental sensors already present at the road infrastructure. In anticipation to this, information shortage at the vehicle side can be compensated by information provided by the road infrastructure. Moreover, as these levels can be assigned to parts of the road network, they can give automated vehicles and their operators guidance on what the INFRAMIX project calls 'readiness' of the road network for CAD system deployment.

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

Figure 4: *Infrastructure Support Levels for Automated Driving (ISAD). Source: INFRAMIX*

There are five ISAD levels (A to E), which suggest a potential relationship with the SAE levels of driving automation. The previous sections indicate there is a complex interplay between the automation level of an ADS, its class of cooperation, its ODD definition, real-life local conditions, and attribute information availability. It is clear that ISAD levels are related to this but are at the same time by no means interchangeable with SAE levels of driving automation. The following chapters will discuss this in more detail.

3 Distributed ODD Awareness (DOA) framework

3.1 Introduction

The need to monitor or be aware of each ODD attribute puts an additional responsibility on the CAD system to monitor each ODD attribute. However, directly measuring each ODD attribute may not be practically feasible from a cost and engineering perspective. However, ODD awareness is key to ensuring safe operation of the CAD system. In order to overcome this challenge, we introduce the concept of Distributed ODD Awareness (DOA).

The DOA 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 (continue driving, switch to an alternate route, reduce speed of the ADS compatible with the reduced visibility, or pull over to the shoulder to stop until the visibility conditions are safe enough to proceed).

While information for many of the ODD attributes could be made available via public infrastructure, there may also be commercial services that can provide ODD awareness information for CAD systems. Continuing with the foggy condition example, a commercial service could potentially collect visibility data from suitably equipped vehicles travelling on the highway network and integrate it into a real-time visibility map of the area which they can provide over cellular data networks. Alternatively, another commercial service could obtain similar information from high-resolution weather satellite data and store it on the cloud for long-range wireless access by CAD systems that are subscribed to their service.

From an NRA perspective, it is important to carefully evaluate what type of ODD attribute information should be provided via NRA infrastructure, and the requirements on its corresponding quality (accuracy, timeliness, availability) to enable safe deployment of ADS. There will be trade-offs involved in determining the priorities for NRA investments in installing and operating infrastructure devices versus contracting with private providers or leaving this entirely to the private market between providers and users. Different decisions are likely for different NRAs, depending on their specific local circumstances (technical, financial and operational).

TM4CAD provides the road authorities a recommended set of questions to discuss with CAD system developers and automated vehicle fleet operators. We highlight the priority areas for the NRA from the perspective of providing infrastructure support for automated driving using the DOA framework. We believe this requires close dialogue and agreement between road authorities, traffic managers, CAD system developers and automated vehicle fleet managements to arrive at solutions that are acceptable regarding the safe, efficient, and sustainable road network operation.

The information exchange for ODD awareness needs to be two-way. An ODD exit can apply to many ADSs and the number of vehicles leading to a large number of minimum risk manoeuvres. Thereby, the ADSs must supply information on ODD exit risks and of any MRMs carried out with sufficient detail and location accuracy. This is essential for the safe and efficient traffic management of the road network.

3.2 ODD attribute information source

The general categories of ODD attributes were introduced in Section 2.1, but here we discuss more specific details about enumerating the ODD attributes that will determine whether any specific CAD system will be able to operate a vehicle on a specific section of roadway. These are subdivided into broad categories and the potential sources of information about these attributes are identified in the following tables. Some of these attributes are expected to be detectable by the CAD systems on the vehicles, using their onboard sensors, but for others the CAD systems will need to depend on infrastructure-based sensors and I2V communication to inform them about these attributes on the road segments they are entering.

We should also expect that the CAD systems will vary widely in sophistication and capabilities, so the vehicle category is subdivided into low-end and high-end systems to recognise that some of the attributes will only be detectable by the most advanced CAD systems. We distinguish between capabilities of a low-end CAD systems and a high-end CAD system as these will potentially possess varying levels of sensing capabilities and thus, have a varying capability of ODD awareness based on on-board sensing only.

While BSI PAS 1883 defines ODD from a perspective of properties of each of the attributes, Table 4.2.1 classifies various ODD attributes from their relevance and implication to NRAs and begins with some of scenery element attributes (quasi-static physical attributes of the roadway and its environment). These are attributes that change only rarely or over extended period of time, so they are well suited to incorporation into map databases. Those maps could be installed onboard the vehicles or in “the cloud” or at a traffic management centre. All of this information should be known on the infrastructure side, but the vehicles’ CAD systems will have limited capabilities to acquire this information unless they are supplied with detailed map databases (which could be a discriminator between the low-end and high-end vehicle systems in addition to their sensing capabilities).

The more advanced CAD systems would be able to sense many of these attributes within a limited range ahead of their current locations (a few hundred meters at most) but would not be able to sense it for an entire roadway segment before entering that segment. If many vehicles are equipped with advanced sensing and V2X communication capabilities, their CAD systems could potentially share the information with each other without needing to depend on the infrastructure, but that is a long-term rather than near-term prospect.

Table 2: *Quasi static physical attributes of the roadway and its environment (part of BSI PAS 1883 scenery attributes)*

ODD Attribute Type	**Vehicle Sensed (Limited range)**		**Infrastructure Sensed or Communicated**
	Low-End	**High-End**	
Locations of road boundaries, intersections, entrance and exit ramps (basic road features)	Y	Y	Y
Zone boundaries (school zones, traffic management zones, special infrastructure support zones)		?	Y
Roadside landmarks to support localisation referencing		Y	Y
Special-purpose localisation references (buried cables, magnets, etc.)		Y	Y
Quality of pavement marking visibility (3 or 4 quality classes)	Y	Y	Y
Load-bearing capacity of roadway or bridge structures			Y
Road surface damage (potholes, large cracks, ruts)			Y
Game fence locations and condition			Y
Vegetation obscuring sight angles or visibility of signs or other traffic control devices, at specific locations		Y	Y
Road geometry constraints such as horizontal and vertical curvatures, grades, lane widths, number of lanes, lane use restrictions…		Y	Y
Road shoulder conditions on both sides (widths, load-bearing capacity,…)			Y
Notifications of locations with occluded visibility (blind intersections or driveways)			Y

Table 3: *Dynamically changing road surface conditions (part of BSI PAS 1883 scenery attributes)*

ODD Attribute Type	**Vehicle Sensed (limited range)**		**Infrastructure Sensed or Communicated**
	Low-End	**High-End**	
Wet pavement surface		Y	Y
Ice on pavement surface		Y	Y
Cold pavement surface (potential for ice if wet)			Y
Road surface friction		Y	Y
Light to moderate snow/slush accumulation on surface			Y
Heavy snow/slush accumulation on surface			Y
Light to moderate flooding (puddles) on surface			Y
Heavy flooding – potentially impassable to low-profile vehicles			Y

Table 3 identifies the operational attributes of the roadway that determine how the CAD systems can perform the dynamic driving task. These include the objects and events that occur on the road surface that the CAD system needs to understand in order to safely perform the DDT. Although the infrastructure can provide this information throughout the road network (provided that it is suitably equipped), even the most advanced vehicles can only provide this information within the detection and identification range of their sensor systems (no more than a couple of hundred meters), which provides only very limited time for their CAD systems to make decisions and take corrective action.

Table 4: *Operational attributes of the roadway (part of BSI PAS 1883 scenery attributes)*

ODD Attribute Type	**Vehicle Sensed (Limited range)**		**Infrastructure Sensed or Communicated**
	Low-End	**High-End**	
Temporary static signs (road works, special events, detours)	Y	Y	Y
Maintenance vehicles using portions of roadway right of way i.e. carriageway (trimming foliage, ploughing snow, clearing debris,…)		Y	Y
Work zones (road works – construction and rehabilitation)		Y	Y
Incident recovery events (crash scenes, crime scenes, dropped loads, landslides, avalanches…)		Y	Y

ODD Attribute Type	Vehicle Sensed (Limited range)		Infrastructure Sensed or Communicated
	Low-End	High-End	
Availability of specific C-ITS information services			Y
Availability of real-time merging guidance or assistance at motorway interchanges or entrance ramps			Y
Real-time lane-specific speed limit information availability at specific locations.			Y
Obstacles or debris on road surface (categories such as large discrete objects, distributed smaller objects, continuum of debris such as mud slide or accumulation of sand)		Y	Y
Roadside objects that change their locations over time, such as parked vehicles or trash cans (and could potentially confuse map matching)			Y
Routing advisory information (travel times via different routes)			Y
Traffic rules and regulations in digital form, updated in real time			Y

Table 4 identifies the diverse kinds of digital information that could be provided from the infrastructure to the CAD systems, primarily associated with dynamically varying conditions that are not well suited for incorporation into a map database. This category assumes the use of wireless communication to transmit the information from the infrastructure to the CAD systems in the vehicles. The infrastructure sources could be local traffic control devices such as traffic signal controllers, the local traffic management centre, a regional or national traffic management centre, or something broader than that (such as GNSS systems or international weather satellites). The more advanced CAD systems would be able to sense some of the same information within the immediate vicinity of their host vehicle (within a few hundred meters at most) but could not detect it for entire road segments before entering those segments, which is why the infrastructure support becomes extremely important.

Table 5: *Digital information support for CAD operations (part of BSI PAS 1883 environmental conditions attributes)*

ODD Attribute	**Vehicle Sensed (Limited range)**		**Infrastructure Sensed or Communicated**
	Low-End	**High-End**	
Variable message sign contents (could be visible and communicated by wireless means)	Y	Y	Y
Locations where V2I/I2V communications are available now, by specific technology (ITS G5, LTE-V2X, WiFi, 4G or 5G cellular) and uplink and downlink capacities			Y
Locations where GNSS differential correction signals are available now, by GNSS service (GPS, Galileo, GLONASS)			Y
Locations where GNSS coverage is NOT available now, by GNSS service			Y
Electronic toll collection systems and their associated pricing, especially when these are dynamic based on traffic conditions or time of day	Y	Y	Y
Locations of incidents that represent traffic impediments or safety hazards (crashes, stopped traffic, objects blocking part of the road) – by lane and milepost or lat /long coordinates			Y
Emergency vehicle locations and direction/speed of travel of each one			Y
Temporarily blocked or closed road locations			Y
Highway shoulder locations occupied by vehicles or debris		Y	Y
Remote human support (remote assistance or remote driving) via wireless communications to aid the CAD system to cope with situations it does not fully understand			Y

Table 5 covers information about the ambient environment surroundings of the roadway section where the CAD system is driving that affects the ability of the CAD system to drive safely. These are largely associated with impairments to the ability of the onboard sensors to detect the driving environment features and to avoid crashes with others.

Table 6: *Ambient environment attributes (weather, visibility, and electromagnetic environment) (part of BSI PAS 1883 environmental conditions attributes)*

ODD Attribute	Vehicle Sensed (Limited range)		Infrastructure Sensed or Communicated
	Low-End	High-End	
Wind speed range and direction			Y
Visibility range with rain/snow/sleet/hail in visible light spectrum	Y	Y	Y
Visibility range with rain/snow/sleet/hail in lidar infrared spectrum		Y	Y
Rainfall rate in mm/hr (likely much less useful than visibility range)			Y
Snowfall rate in qualitative ranges (flurries, light, medium, heavy, blizzard and white-out)			Y
Visibility range with other particulate obscurants (smoke, fog, dust, sand, volcanic ash) in visible light spectrum	Y	Y	Y
Visibility range with other particulate obscurants (smoke, fog, dust, sand, volcanic ash) in lidar infrared spectrum		Y	Y
Predicted significant changes in key weather attributes, including direction and size of change and estimated future time of the change			Y
Qualitative ambient lighting conditions (night/no illumination, night with illumination, dawn/dusk, day/sunny, day/cloudy, day/partly cloudy)	Y	Y	Y
Quantitative ambient lighting conditions (illuminance order of magnitude in lux)		Y	Y
Special challenging lighting conditions (sharp shadows on road, bright sun at low angle)		Y	Y
Electromagnetic interference (where in E-M spectrum, continuous vs. intermittent and level of strength/severity)			Y

Table 7: *Roadway operational attributes (traffic conditions) (part of BSI PAS 1883 dynamic element attributes)*

ODD Attribute	Vehicle Sensed (Limited range)		Infrastructure Sensed or Communicated
	Low-End	High-End	
Current average traffic speed and density by lane and road section			Y
Current percentage of heavy vehicles in traffic stream, by lane and road section			Y
Special events creating abnormal traffic conditions and their locations (sporting events, concerts, festivals, etc.)			Y
Locations with high density of pedestrians			Y
Locations with high density of cyclists or users of micro-mobility devices			Y
Locations with dynamic traffic access changes – time of day or traffic condition dependent access to specific lanes or zones			Y

These tables have listed the types of information that are relevant to defining the ODD for a CAD system, but the binary indicators (Yes or No) on each row of each table do not provide a complete representation of the ODD. Additional dimensions representing the magnitudes of the values attached to each attribute (such as curve radius or speed limit) and the quality of the information (such as accuracy and availability) will also be important in providing a complete description of the ODD. The ODD attribute information quality will be discussed further in Work Package 3 (D3.1).

3.3 Understanding change frequency of ODD attribute Information

From an NRA perspective, in addition to the possibility of providing ODD attribute information via infrastructure, an important consideration is the **time criticality of the information change and refresh rate** when it is provided via infrastructure. The criticality of the change and refresh rate will influence the level of investment required in the infrastructure (measurement equipment and connectivity setup) to deliver the requirements for achieving ODD awareness. Other important considerations that will also influence the level of investment will be the required spatial resolution (how close together do consecutive measurement sites need to be?), and the required measurement accuracy and availability (what are the consequences of data being unavailable?).

We propose that the frequency of changes in ODD attribute information be classified broadly into the following categories:

- Category 1: Changes very seldom
- Category 2: Changes every (few) days
- Category 3: Changes every (few) hours
- Category 4: Changes every (few) minutes
- Category 5: Changes every (few) seconds

We foresee that the majority of ODD attributes that may benefit from Infrastructure supported sensing would be part of Categories 2-4, while keeping in mind the feasibility of measuring and making the information available to CAD systems. Tables 8-12 provide categorisation of the ODD attribute information as per their time criticality.

Table 8: *Information change frequency of Quasi static physical attributes of the roadway and its environments (Scenery element attributes as per BSI PAS 1883)*

ODD Attribute type	Information Change Frequency Category				
	Cat 1	**Cat 2**	**Cat 3**	**Cat 4**	**Cat 5**
Locations of road boundaries, intersections, entrance and exit ramps (basic road features)	x				
Zone boundaries (school zones, traffic management zones, special infrastructure support zones)		x			
Roadside landmarks to support localization referencing	x				
Special-purpose localization references (buried cables, magnets, etc.)	x				
Quality of pavement marking visibility (3 or 4 quality classes)		x			
Load-bearing capacity of roadway or bridge structures	x				
Road surface damage (potholes, large cracks, ruts)		x			
Game fence locations and condition	x				

ODD Attribute type	Information Change Frequency Category				
	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5
Vegetation obscuring sight angles or visibility of signs or other traffic control devices, with specific locations		x			
Road geometry constraints such as horizontal and vertical curvatures, grades, lane widths, number of lanes, lane use restrictions…	x				
Road shoulder conditions on both sides (widths, load-bearing capacity,…)	x				
Notifications of locations with occluded visibility (blind intersections or driveways)	x				

Table 9: *Information change frequency of dynamically changing road surface condition (Scenery element attributes as per BSI PAS 1883)*

ODD Attribute type	Information Change Frequency Category				
	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5
Wet pavement surface			x		
Ice on pavement surface			x		
Cold pavement surface (potential for ice if wet)			x		
Light to moderate snow/slush accumulation on surface			x		
Heavy snow/slush accumulation on surface			x		
Light to moderate flooding (puddles) on surface			x		
Heavy flooding – potentially impassible to low-profile vehicles			x		
Locations with dynamic traffic access changes – time of day or traffic condition dependent access to specific lanes or zones				x	

Table 10: *Information change frequency of Operational attributes of the roadway (Scenery element attributes as per BSI PAS 1883)*

ODD Attribute type	**Information Change Frequency Category**				
	Cat 1	**Cat 2**	**Cat 3**	**Cat 4**	**Cat 5**
Temporary static signs (road works, special events, detours)			x		
Maintenance vehicles using portions of roadway right of way, i.e., carriageway (trimming foliage, plowing snow, clearing debris,…)			x		
Work zones (road works – construction and rehabilitation)			x		
Incident recovery events (crash scenes, crime scenes, dropped loads, landslides, avalanches…)			x		
Availability of specific C-ITS information services	x				
Availability of real-time merging guidance or assistance at motorway interchanges or entrance ramps				x	
Real-time lane-specific speed limit information availability at specific locations.				x	
Obstacles or debris on road surface (categories such as large discrete objects, distributed smaller objects, continuum of debris such as mud slide or accumulation of sand)				x	
Roadside objects that change their locations over time, such as parked vehicles or trash cans (and could potentially confuse map matching)				x	
Routing advisory information (travel times via different routes)			x		
Traffic rules and regulations in digital form, updated in real time		x			

Table 11: *Information change frequency of connectivity attributes*

ODD Attribute type	Information Change Frequency Category				
	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5
Variable message sign contents (could be visible and communicated by wireless means)				x	
Locations where V2I/I2V communications are available now, by specific technology (ITS G5, LTE-V2X, WiFi, 4G or 5G cellular) and uplink and downlink capacities		x			
Locations where GNSS differential correction signals are available now, by GNSS service (GPS, Galileo, GLONASS)	x				
Locations where GNSS coverage is NOT available now, by GNSS service	x				
Electronic toll collection systems and their associated pricing, especially when these are dynamic based on traffic conditions or time of day	x				
Locations of incidents that represent traffic impediments or safety hazards (crashes, stopped traffic, objects blocking part of the road) – by lane and milepost or lat/long coordinates				x	
Emergency vehicle locations and direction/speed of travel of each one				x	
Temporarily blocked or closed road locations				x	
Highway shoulder locations occupied by vehicles or debris				x	
Remote human support (remote assistance or remote driving) via wireless communications to aid the CAD system to cope with situations it does not fully understand				x	

Table 12: *Information change frequency of ambient environment attributes (weather, visibility and electromagnetic environment)*

ODD Attribute	Information Change Frequency Category				
	Cat 1	**Cat 2**	**Cat 3**	**Cat 4**	**Cat 5**
Wind speed range and direction				x	
Visibility range with rain/snow/sleet/hail in visible light spectrum				x	
Visibility range with rain/snow/sleet/hail in lidar infrared spectrum				x	
Rainfall rate in mm/hr (likely much less useful than visibility range)				x	
Snowfall rate in qualitative ranges (flurries, light, medium, heavy, blizzard and white-out)				x	
Visibility range with other particulate obscurants (smoke, fog, dust, sand, volcanic ash) in visible light spectrum				x	
Visibility range with other particulate obscurants (smoke, fog, dust, sand, volcanic ash) in lidar infrared spectrum				x	
Predicted significant changes in key weather attributes, including direction and size of change and estimated future time of that change			x		
Qualitative ambient lighting conditions (night/no illumination, night with illumination, dawn/dusk, day/sunny, day/cloudy, day/partly cloudy)			x		
Quantitative ambient lighting conditions (illuminance order of magnitude in lux)			x		
Special challenging lighting conditions (sharp shadows on road, bright sun at low angle)			x		
Electromagnetic interference (where in E-M spectrum, continuous vs. intermittent and level of strength/severity)					x

Table 13: *Information change frequency of dynamic elements (as per BSI PAS 1883)*

ODD Attribute	Information Change Frequency Category				
	Cat 1	**Cat 2**	**Cat 3**	**Cat 4**	**Cat 5**
Current average traffic speed and density by lane and road section				x	
Current percentage of heavy vehicles in traffic stream, by lane and road section				x	
Special events creating abnormal traffic conditions and their locations (sporting events, concerts, festivals, etc.)				x	
Locations with high density of pedestrians				x	
Locations with high density of cyclists or users of micro-mobility devices				x	
Locations with dynamic traffic access changes – time of day or traffic condition dependent access to specific lanes or zones			x		

3.4 DOA framework implications

A Distributed ODD Awareness (DOA) framework can potentially be implemented or enabled in various forms by the NRAs. This means that the choice of making ODD attribute information available to the CAD systems lies with the NRAs. For example, one particular NRA might choose to provide weather related ODD attribute information while another might choose not to provide any such information.

As ODD attribute information is essential for the safe deployment of the CAD systems, it is essential that the NRAs publish details of what type of ODD attribute information (if any) is being provided for CAD systems on the road in a particular area or region.

The choice of ODD attribute information to be provided by NRA will not only depend on their ability to measure and make the ODD attribute information available, but also on the quality of the information that is required for safe operation of the CAD systems, and which are highest in priority for that NRA. This choice will have cost implications, as higher quality data would warrant higher investment in infrastructure.

3.5 CAD safety assurance

ODD attribute awareness via the DOA framework is one factor influencing the safe operation of the CAD systems. The other factors influencing CAD safety assurance and automation driveability include:

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

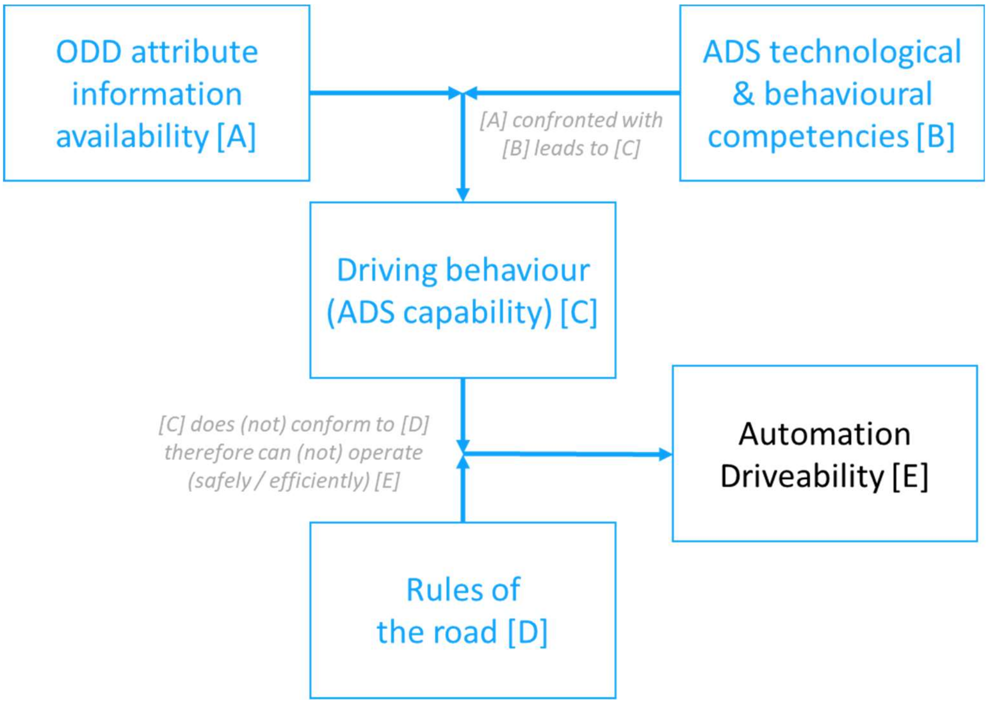


Figure 5: *Relationships among ODD awareness, ADS capabilities, rules of road and safety assurance.*

It is important to note that while the DOA framework enables provision of ODD attribute information, it doesn't guarantee safe operation of CAD systems. This is enabled through a handshake mechanism between various factors listed earlier. ODD attribute information via the DOA 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 capable to decide driving behaviour that can be considered safe and efficient, therefore can operate in the particular local condition. Others, like Rijkswaterstaat in an assessment of their road network [9] and the AVENUE21 project [10] referred to this condition as 'automated driveability', i.e. the suitability of road sections for operation of ADS based on characteristics of these road sections. In this deliverable a more nuanced perspective is provided as the suitability is subject to many specifics, related to ADS' ODD definition and the actual real-life local conditions, which means that automation driveability cannot be guaranteed on a spatial dimension alone.

3.5.1 ADS technological and behavioural competencies

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.

Each ADS developer will decide the right level of technological sophistication to apply to the ADS on each of its vehicles, based on its market segment and intended use cases. Cost considerations will be an important constraint since the vehicle must be affordable to the target customers (e.g., individuals, fleet operators etc.). These will limit the number and variety of sensors that can be used, as well as the capabilities of the communication systems and computing platforms. Infrastructure support can augment the capabilities of the technologies installed in the vehicles, so that less expensive vehicles can reach performance that would only be achievable by the most expensive vehicles on roadways that provide no infrastructure support. This means that locations that provide more extensive infrastructure support will be able to gain the transportation system benefits of automated driving on a larger fraction of the vehicle fleet.

Some 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).

3.5.2 Rules of the road

Rules of the road govern safe behaviour of traffic participants, which include human driven vehicles as well as CAD systems. A concept that is in development currently and in discussion at the UNECE forums (UNECE FRAV) involves creation of a codified version of the rules of the road for CAD systems. The concept describes the rules of the road in terms of ODD attributes and behaviour competencies.

If one compares the scope of ODD attributes and the content of current "rules of the road for human drivers" (e.g., UK's Highway Code [11]), a large overlap of scenery aspects and environmental condition aspects can be observed. It is therefore plausible to follow an ODD attribute-based approach and an ODD taxonomy, to model the environmental and scenery aspects of the "rules of the road". In addition, what is not part of the ODD but is also important for the safety assurance of CAD systems is the behaviour aspect. Behaviour can be further divided into ego (vehicle under test) behaviours and other road users' behaviours.

Any rule of the road can be classified into two categories:

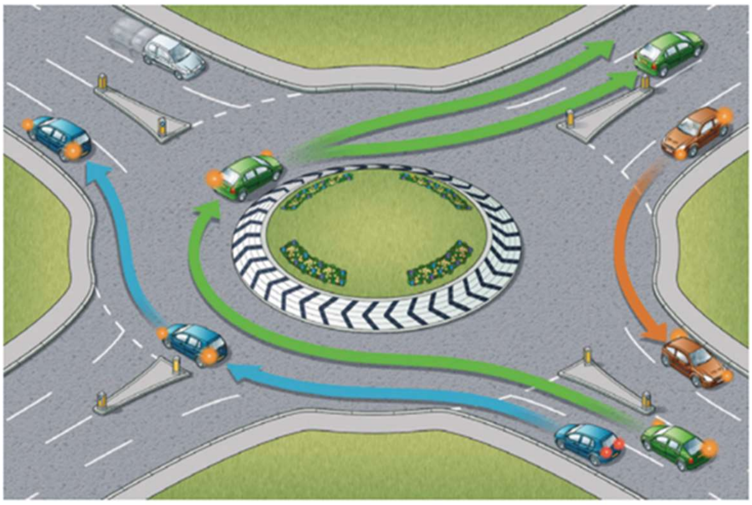
- Doing some "behaviour" "somewhere"
- NOT doing some "behaviour" "somewhere"

While doing or not doing some behaviour can be defined as part of an ADS's behavioural competencies, "somewhere" could be considered as "operating condition" or part of the ODD definition. Therefore, each rule of road will have an ODD attribute factor and a behavioural competency factor.

Taking an example from the UK's Highway Code which governs the behaviour of the traffic participants, Rule 185 (also see Figure 6), which states:

"When reaching the roundabout you should:

- *give priority to traffic approaching from your right, unless directed otherwise by signs, road markings or traffic lights;*
- *check whether road markings allow you to enter the roundabout without giving way;*
- *If so, proceed, but still look to the right before joining;*
- *watch out for all other road users already on the roundabout; be aware they may not be signalling correctly or at all;*
- *look forward before moving off to make sure traffic in front has moved off."*



Rule 185: Follow the correct procedure at roundabouts

Figure 6: *Rule of Road (source UK Highway Code)*

One could identify ODD attribute elements (in blue) and behaviour competency elements (in yellow). However, the rule doesn't make any mention of the weather conditions. For human drivers, it is expected that the human drivers will be able to judge the weather conditions and make a judgement on driving conditions. However, for CAD systems, this assumption is not valid and the responsibility of monitoring weather attributes and subsequent response (behaviour display) will lie with the CAD system. As discussed earlier, we don't expect all vehicles to have the capability to be able to measure weather attributes, so infrastructure support is likely to be needed in order for CAD systems to have ODD awareness.

Another example is the Highway Code Rule 227, which states *"Wet weather. In wet weather, stopping distances will be at least double those required for stopping on dry roads"*. This rule provides a direct relationship between an ODD attribute (wet weather) and the behaviour of the vehicle (at least double-stopping distance). In order for the CAD system to adhere to this rule, it is essential for the CAD system to be aware that the current operating condition is *"wet weather" (*more detailed information attribute information may be needed), i.e. its ODD awareness.

3.5.3 Driving behaviour

The driving behaviour of the CAD system should be determined by the combination of the applicable local driving regulations ("rules of the road") and the technical capabilities of the CAD system. Together these set boundaries on aspects of driving behaviour such as speed, the gaps chosen for vehicle following and lane changing, and the deference accorded to other road users at potential conflict points. The rules of the road generally define the outer limits of driving behaviour that should be allowed, such as speed limits, but it's also important to recognise that in some special situations it may be preferable to accommodate limited deviations from the normal rules of the road. For example, if a lane is partially blocked by a stalled or improperly parked vehicle, it may be necessary for a CAD-driven vehicle approaching the blockage to cross the roadway centreline and intrude into an opposite-direction lane in order to pass the blockage. Human remote support to authorise this deviation could be provided by the vehicle fleet operator. Such deviations should be explicitly listed as part of the "rules of road" and subsequently will no longer remain deviations from the expected behaviour.

The driving behaviour of the CAD system is primarily governed by its technological capabilities.

These capabilities are limited by its ODD constraints, generally associated with the ability of the CAD system sensors to detect, recognise, and understand all the hazards in the driving environment. Road geometry (horizontal and vertical curvatures) will limit the line of sight of vehicle sensors, and ambient weather conditions and obscurants will limit the range of optical sensors. These sensor limitations will in turn bound the maximum speed at which the CAD system can ensure driving safety, which may be less than the legally permitted maximum. Other ODD constraints will also limit the speed of automated driving and other aspects of the CAD behaviour, including limitations on which behavioural competencies the CAD system may be able to perform.

Infrastructure support can enable a wide range of enhancements to the driving behaviour of CAD vehicles, improving traffic safety and efficiency. Some representative examples include:

- Real-time traffic signal phase and timing information enables the vehicles to adjust their speed profiles approaching signalised intersections to avoid unnecessary stops and dilemma zone uncertainties, and to save energy and emissions by smoother driving;
- Real-time advance information about traffic jams and incidents can enable re-routing to avoid the problem locations or more gradual (and therefore safer and more efficient) speed reductions approaching those locations (as well as earlier alerts to fallback-ready users of Level 3 automation systems to give them ample time to more safely resume the dynamic driving task);
- Advance information about adverse pavement friction enables the vehicles to reduce speed upstream of the slippery site to reduce the risk of loss of vehicle control;
- Variable speed limits and advisories can harmonise traffic flow upstream of bottleneck locations, enabling higher traffic throughput at the bottleneck and reduced delays;
- Higher-fidelity digital maps can improve the vehicles' ability to track the lanes in locations with challenging geometry and lines of sight and to recognise and avoid hazards in those locations;
- Higher-contrast pavement markings and higher-visibility signs will enable CAD-driven vehicles to maintain the posted speeds, consistent with human drivers, under a wider range of adverse visibility conditions;
- Infrastructure-based sensor systems, combined with V2X communication about the objects that those sensors detect and track, could provide CAD systems with enhanced knowledge about approaching hazards (other vehicles or VRUs), enabling them to perform unprotected left turns at intersections where they would otherwise lack sufficient visibility to do so safely

3.5.4 Societal introduction

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 [4]. One of the key aspects of building trust in technologies is to ensure that society has a strong and robust framework to ensure safe introduction of the CAD technologies. This is especially important as it is hard to build trust once it has been negatively impacted due to any crashes or mishaps.

NRAs and governments have a duty of care to implement safeguards for this by creating a robust approval mechanism for CAD systems. At the same time, by providing infrastructure support and the implementation of the distributed ODD awareness concepts, NRAs have a potential to not only enhance safety of CAD system but also lead to their earlier deployment leading to early realisation of the societal benefits from these technologies.

As CAD systems will be used for a wide range of users, it is important that the design of such systems take into consideration the impact of human factor elements and prevent any bias or discrimination against any specific segments of the society into the development process of the CAD systems. NRAs will need to work with relevant approval bodies in individual countries to ensure that the deployment of CAD systems and the subsequent realisation of their benefits is accessible and equitable for the wider society.

4 Distributed ODD Awareness: governance structure

The roles and their responsibilities in the various phases of the DOA implementation are described in Table 14.

Table 14: *Roles of stakeholders and their responsibilities in the various phases of Distributed ODD Awareness framework implementation*

	Responsibility in DOA framework implementation			
Role	**Development**	**Deployment**	**Operation**	**Maintenance**
ADS provider	Development of the framework concept	Provision as part of ADS	Use of DOA in automated driving	Fix any problems
Vehicle manufacturer	Input to development	Deployment in vehicles	Monitor the use of DOA in vehicles	Fix any problems
Vehicle fleet operator	-	Adaptation of processes	Supervise the use of DOA in vehicles	Report problems in use
Vehicle owner/ driver/ occupant	-	Agreement on take-up	Use of ADS, resume control of vehicle when exiting ODD or leaving MRC	Report problems in use
Road authority/ operator	Input to development	Deployment in road infrastructure and related contracts with various service contractors	Monitor the use of DOA at the infrastructure side	Report problems in use; fix problems related to own infrastructure
Traffic manager	Input to development	Deployment at TMC and roadside systems and related contracts with various service contractors	Use of DOA in traffic management	Report problems in use; fix problems related to own services, systems, and infrastructure
Traffic information service provider	Input to development	Deployment in service portfolio and service adaptation	Provision of services facilitating DOA	Report problems in use; fix problems related to own services
Digital map provider	Input to development	Deployment in digital maps	Provision of services facilitating DOA	Report problems in use; fix problems related to own services
Meteorological service provider	-	Adaptations in service	Provision of real-time data related to DOA	Report problems in use; fix problems related to own services
Road works or maintenance operator	-	Adaptation of processes	Provision of real-time data related to DOA	Report problems in use; fix problems related to own operations
Rescue service provider	-	Adaptation of processes	Provision of real-time data related to DOA	Report problems in use; fix problems related to own operations

	Responsibility in DOA framework implementation			
Role	**Development**	**Deployment**	**Operation**	**Maintenance**
Law enforcement	Input to development	Adaptation of processes	Provision of real-time data related to DOA, enforce legal aspects of DOA use	Report problems in use; fix problems related to own operations
Communication infrastructure provider	Input to development	Adaptation of communication network capacity if and where needed	Operate the communications networks	Fix problems in own services and infrastructure
Transport authority	Input to development	Regulate the deployment if necessary	Monitor the status of DOA operation	Monitor the status of DOA maintenance
Communication authority	Input to development	Regulate the deployment if necessary	Monitor the status of DOA operation	Monitor the status of DOA maintenance

The table does not specify the stakeholder that assumes the roles presented in it. The stakeholder roles may well differ between countries. In addition, they might well vary within a country. For instance, the road operator role on highways may be assumed by the NRA while on rural roads this may be done by the region and on city streets by the municipality in question.

The roles may also be specific to some locations only – the NRA or city may assume the role of a communication infrastructure provider when providing roadside C-ITS stations at selected hotpots, while the mobile phone network operators assume the communication infrastructure provider role for cellular networks over the whole road and street network.

The NRAs will naturally assume the role of the road authority or operator. In addition, in many countries they may also have the role of the traffic manager and information service provider. In some countries, they can also have some duties of a transport authority, road works or maintenance operator, and communication infrastructure provider. Some of these roles are specified in national laws while some roles can be adopted by the NRA voluntarily.

The NRAs will thereby typically carry the responsibility for the physical, digital, and operational road infrastructure support for the DOA. This means providing the relevant ODD attribute information for the ADS or ensuring via contracts that the contractors working for them will provide that information.

5 Conclusions

This deliverable D2.1 has been written from an NRA's perspective to highlight the factors involved in the decision-making process for infrastructure investment to enable the Distributed ODD Awareness (DOA) framework for early deployment of CAD systems. The feedback received during an engaging and fruitful NRA stakeholder workshop highlighted the need for a common language and understanding of various ODD concepts and the distributed ODD Awareness concept among various stakeholders. Chapters 2 and 3 aim to meet this request.

In order to implement the DOA framework, NRAs' roles and responsibilities have been identified in chapter 4. 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. TM4CAD's next workshop will be held with CAD system developers and vehicle manufacturers.

5.1 Relationship between DOA framework and ISAD

This deliverable discussed basic concepts and terminology associated with defining the Operational Design Domain (ODD) of Automated Driving Systems (ADS). It referred to several standards and frameworks commonly used for classification of ADS and road infrastructure capability. Figure 7 illustrates the linkages between these frameworks.

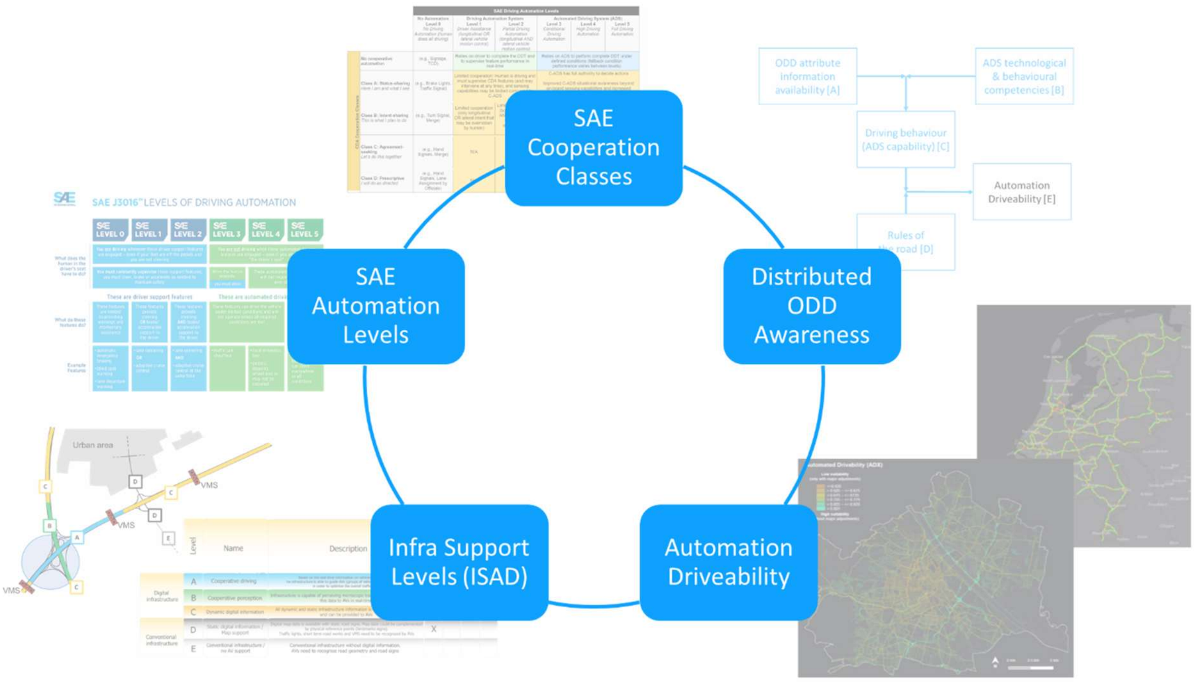


Figure 7: *Relationship between ODD, ISAD and Automation level frameworks*

One of the most important conclusions from this deliverable is that NO infrastructure classification (scheme) by itself can provide a guarantee for (SAE level) automation drivability. This can be further explained by giving a brief recap of the main principles presented in this document:

- An ADS when active continuously monitors the condition/status of ODD attributes (see section 2.6);
- Distributed ODD awareness implies different sources have information about ODD attribute(s) condition/status (see section 3.1);
- Some ODD attributes and ODD attribute information are (exclusively) within the sphere of influence of NRAs (see section 3.2);
- Absence of (quality) ODD attribute information can be critical to an ADS, potentially causing an unexpected ODD exit, leading to a request for human intervention or an MRM (see section 2.4);
- ODD attribute awareness does not by itself lead to automation drivability, but satisfying the complete set of ODD conditions does, and
- Based on ODD attributes' condition/status an ADS determines if it is within its ODD and if it can/cannot operate (see section 3.5).

Going further and addressing the perspective of the National Road Authorities more specifically, the flow diagram shown in section 3.5 can be expanded based on the following:

- Some TM measures affect ODD attributes and have regulatory implications on driving rules (e.g. prescriptive measures like the regulatory speed limit or lane closure);
- Infrastructure support levels for automated driving (ISAD) levels resemble the availability of (information provision of) different clusters of ODD attributes;
- Most ODD attribute information is of Cooperative Driving Automation (CDA) Cooperation Class A: Status-sharing (of real-time local conditions);
- Some TM measures have planned short-term effects and/or deliver advisory non-binding information intended to suggest actions to road users, therefore are of CDA Cooperation Class B: Intent-sharing, and
- Some TM measures with regulatory implications are of CDA Cooperation Class D: Prescriptive.

Figure 8 shows the logical flow and causal relationships among several elements. It shows that ODD attributes have a state in a real-time condition, which must be sensed in some way before attribute information can be made available. The next TM4CAD deliverable (D3.1) will discuss in further detail the information exchange between traffic management and automated vehicles, in particular information needs, quality and governance.

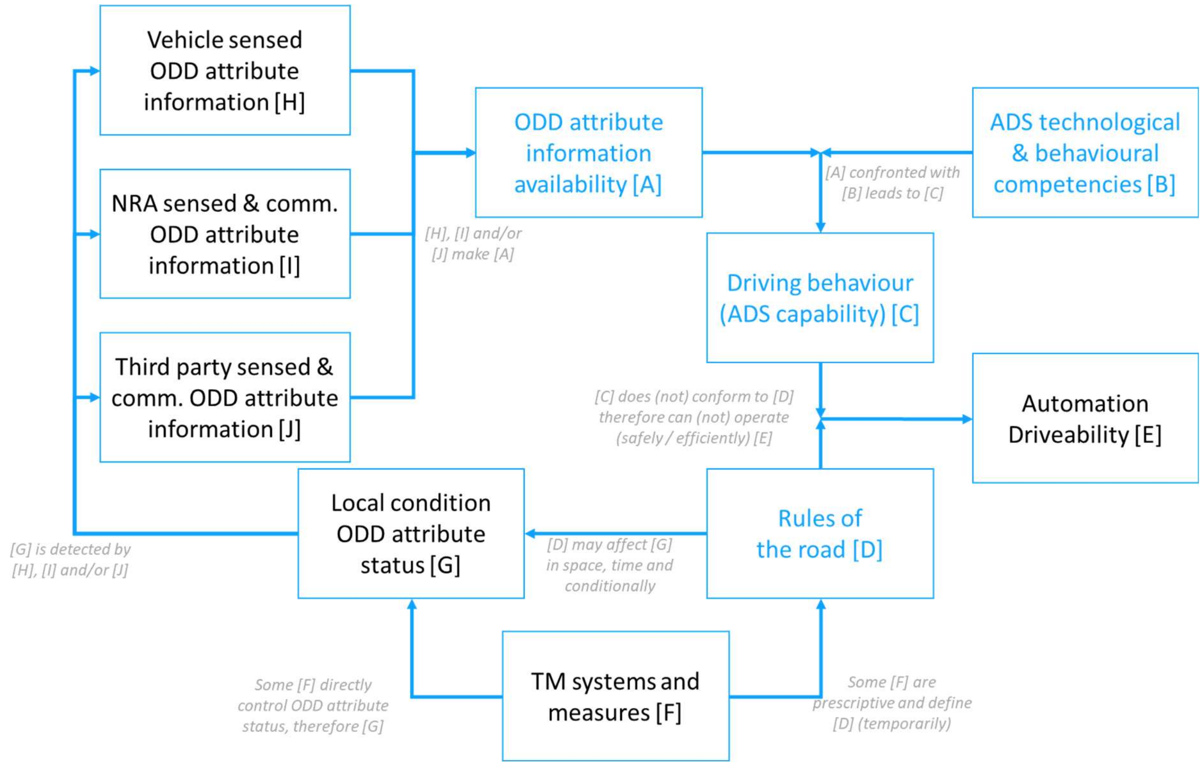


Figure 8: *Illustration of various possibilities for ODD attribute information source and their links with wider CAD system safety assurance*

Finally, to build upon the idea of automated driveability / suitability maps, the DOA framework presented in this deliverable implies that: ODD attribute information availability when projected on a road network can support a geographical road classification system which is based on ODD attributes present and their information quality. However, it is important to highlight that information availability is only one out of various factors related to safe operation of CAD systems.

5.2 Progress to the Research Questions and Expected Results

The following table summarises achievements, knowledge gaps and future research activities related to the Research Questions (RQ), Essential Results (ER) and Operational Results (OR) that are addressed by the TM4CAD project in this deliverable.

Table 15: *Answers to various research questions and essential results addressed by D2.1*

Research Question / Essential Result	Achievements, gaps and outlook
RQ1: Should NRAs set requirements on the desired behaviour of (partly) automated vehicles on where and how they should drive?	**Section 3** and **section 4** provide an overview of the activities involved in setting the requirements and the decision-making process for ODD attribute information availability via infrastructure. We introduce the concept of distributed ODD awareness which NRA could enable. Decisions on infrastructure investment should be made by NRAs in consultation with various stakeholders including CAD system developers and vehicle fleet operators, vehicle manufacturers, local authorities etc.
RQ3: How does CCAM support the work of traffic management centres and how can traffic management centres support and facilitate the deployment of CCAM?	**Section 3.5** illustrates the link between CCAM enabled distributed ODD awareness concept and CAD safety assurance. CCAM support can enable ODD awareness. An example of CAD systems supporting traffic management centres is when CAD systems notify traffic management about ToCs and especially MRMs including accurate location and reason for MRM in a manner to be detailed in WP3. This deliverable doesn't cover details on the information quality for ODD awareness. This will be further discussed in deliverable 3.1 of TM4CAD project.
RQ4: What kind of information is to be transmitted in the interaction (in both directions) between a traffic management centre and vehicle?	**Section 3.2** and **section 3.3** highlight the basis for the decision-making process for selecting information to be transmitted between infrastructure and vehicle.
RQ5: Which information is to be provided by the NRA/roadside and which information can be obtained by the sensors of the moving vehicle itself?	**Section 3.2** and **section 3.3** highlight the basis for the decision-making process for selecting information to be transmitted between infrastructure and vehicle.

Research Question / Essential Result	Achievements, gaps and outlook
ER1: Determination of the circumstances (actual traffic conditions, status of the infrastructure, …) under which the traffic control centre would need to lower the ISAD level in order to stop automation taking place and accordingly mitigating measures if applicable	Suggested use case focus: local conditions that occur regularly, with ODD attribute status that is infrastructure-sensed and changes frequently. **Section 3.2** lists the specific ODD attributes that each CAD system can use to determine whether it is capable of safe operations on the road segment in question. Moreover, **Section 2** and **Section 3** explained basic concepts and terminology, which are summarised in **Section 5.1**. These show that the presumption of a traffic control centre starting and stopping automated driving systems is not realistic, therefore the essential result should be rephrased carefully in consultation with NRAs.
ER2: Determination of the circumstances under which the traffic control centre would need to upscale the ISAD level/impose more automated driving	**Section 3.5** and **section 4** highlight the decision-making process. It is important to mention the ISAD levels will need to be complemented by ODD attribute information availability in order to move between ISAD levels. Additionally, this will also depend on the individual CAD system's capability and architecture (low-end or high-end vehicle). The traffic control centre cannot and must not attempt to require more automated driving than each CAD system is capable of performing under the prevailing ODD attribute conditions. Moreover, as explained in this deliverable and summarised in **Section 5.1**, it is not the traffic control centre but the CAD system that decides whether it can operator or not, given the information it has about the local condition.
ER5: Definition of the roles and responsibilities in the interaction between OEMs/Service Providers and NRAs on operational level	**Section 4** illustrates the various roles and governance structure needed to implement the distributed ODD awareness concept.
OR1: Description of the possible added value of service providers in the interaction between NRAs and OEMs	**Section 1.4** highlights the results of the NRA stakeholder workshop which discussed the need for a common understanding and language between NRAs and OEMs on ODD and the distributed ODD awareness concept.
OR2: Description of possible governance mechanisms for ODD management that need to be established	**Section 4** illustrates the various roles and governance structure needed to implement the distributed ODD awareness concept.

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