Traffic Management for Connected and Automated Driving (TM4CAD)

Pre-Read Material for CEDR TM4CAD 2nd workshop: ODD-ISAD architecture and NRA governance structure to ensure ODD compatibility

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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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1 Operational Design Domain

While improved safety is the biggest motivation for the introduction of Connected and Automated Driving (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*, which prevents their misuse and disuse. Informed Safety means that the “user” is aware of what a 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). The ODD attributes include the characteristics of the physical and digital roadway infrastructure, the availability of external support functions such as GNSS localisation and digital maps (and their accuracy), the weather and lighting conditions, and the traffic conditions (speed, density, and incidents).

As per SAE J3016, an ODD is defined as, *“Operating conditions under which a given driving automation system or feature thereof is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics”.*

Thus, ODD constraints are especially important for higher levels of automation — SAE level 3 and SAE level 4. In order to understand whether its ODD limitations are at risk of being violated so that it needs to cease performing the dynamic driving task, the CAD system needs to be aware of the relevant ODD attributes (e.g., visibility, traffic density, incidents, etc.) in real time to compare it with the design ODD of the system. While some of ODD attribute information can be sensed by the CAD system’s on-board sensors, some information can only be supplied by use of off-board sources such as remote sensors and wireless communication systems.

1.1 ODD Attributes

The ODD attributes represent the combination of all of 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 systems will have the tightest ODD limitations while the most sophisticated systems will have fewer ODD constraints on their ability to drive. 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 will gradually be relaxed and become a less serious constraint on when and where the CAD systems can be used. 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.

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 2.3, we will provide a comprehensive list of the ODD attributes that we have 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):

- 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
    - Special situations (work zones, incident sites, lane or road blockages, emergency vehicles, officers directing traffic, etc.)
- 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
- Ambient environmental conditions (BSI PAS 1883 environmental conditions)
    - Weather (and its 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

1.2 ODD Definition language

In addition to the identifying the ODD attributes there is a need to provide guidance on how to use the attributes to create an ODD description. This requires a structured format or a language concept that enables communication of the relevant ODD characteristics between the roadway infrastructure and CAD-operated vehicles and among their respective stakeholder organisations.

There are multiple international standardisation activities ongoing which are creating a format or a language for ODD definition. These include ISO 34503 and ASAM OpenODD. ISO 34503 defines a format for structure natural language definition of an ODD catering to the needs of NRAs, regulators, and system engineers. On the other hand, 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 specification 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 that the ODD boundary to be binary and provides clear separation The ODD definition language enables users to define such boundary / boundaries and group together a set of ODD attributes with their relations that fall within the operating boundary.

An ODD definition language concept has two parts: the domain model (i.e. the attributes), and the language concepts. ODD attributes may have interdependence and their relationship needs to be defined in a prescribed format. For example, an ODD definition may include that a CAD system can operate on motorways in sunny weather but cannot operate on motorways in rainy weather. Another example may include a CAD system having 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.

1.3 ODD Awareness / Monitoring

While performing the Dynamic Driving Task (DDT), each CAD system needs to be aware of the current values of the ODD attribute values where it is operating, so that it can compare these with its defined ODD boundaries. This is essential for the CAD system to be able to decide whether it is able to continue operating safely. If the current conditions violate its ODD boundaries, it needs to cease operations as safely as it can, either by requesting a human to intervene to resume driving (if it’s a Level 3 system) or by automatically bringing the vehicle to a safe stop (if it’s a Level 4 system), which is referred to as performing a minimal risk manoeuvre (MRM).

Defining an ODD boundary is up to the developer of the CAD system (the vehicle manufacturer or their partner company), who may include sub-attributes or qualifiers, such as temporal elements. For example, an ODD boundary may be defined as up to 2 minutes of reduced visibility by adding a relevant sub-attribute. ODD attributes need to be defined in a way to allow awareness on the part of the CAD system, so that the CAD system remains within the designed and defined ODD limits. In case of an imminent ODD condition violation, the CAD system should be designed to trigger a transition to a Minimal Risk Condition (MRC) or issue a transition demand to the fall-back ready user or change the operating mode to a degraded mode, i.e. lower performance capability mode.

By using certain ODD attributes as part of the ODD definition of the CAD system, there exists an implicit requirement on the CAD system to be able to either measure each of the ODD attributes or seek information from an external (off-board) source about the ODD attribute or infer the information about ODD attributes from other measure parameters.

2 Distributed ODD Awareness (DOA) framework

2.1 Introduction

The need to monitor or be aware of each ODD attribute puts an additional overhead on the CAD system to be able 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) framework.

The DOA framework enables the ADS to benefit from off-board sensing infrastructure to become aware of ODD attribute values which it may not be able to measure or sense directly. 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 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 to be 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 available via 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 real-time visibility map updates that 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 think carefully about what type of ODD attribute information should be provided via 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 to be best for different NRAs, depending on their specific local circumstances.

TM4CAD provides the road authorities a recommended set of questions to discuss with CAD system developers and automated vehicle fleet operators. In this workshop and subsequent deliverable 2.1, we highlight the priority areas for the NRA from the perspective of providing infrastructure support for automated driving. 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.

2.2 ODD Attribute information source

The general categories of ODD attributes were introduced in Section 1.1, but here we get more specific 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 of 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.

While BSI PAS 1883 defines ODD from a perspective of properties of each of the attributes, Table 2.2.1 classifies various ODD attributes from their relevance and implication to a 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.

Furthermore, 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. Thus, having a varying capability of ODD awareness based on on-board sensing only. Table 2.2.2 identifies dynamically changing road surface conditions (part of BSI PAS 1883 scenery attributes).

Table 2.2.1 – Quasi static physical attributes of the roadway and its environs (part of BSI PAS 1883 scenery attributes)

ODD Attribute	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 2.2.2: Dynamically changing road surface conditions (part of BSI PAS 1883 scenery attributes)

ODD Attribute	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
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 2.2.3 identifies the operational attributes of the roadway that determine how well 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 2.2.3: Operational attributes of the roadway (part of BSI PAS 1883 scenery attributes)

ODD Attribute	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 (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

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
Ice on pavement surface		Y	Y
Cold pavement surface (potential for ice if wet)			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 2.2.4 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 so important.

Table 2.2.4: 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 2.2.5 covers information about the ambient environment surrounding 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 2.2.5: 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 that 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 2.2.6: 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.

2.3 Understanding Time Criticality 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 refresh rate** when it is provided via infrastructure. The criticality of the 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 time criticality of 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.

Table 2.3.1: Time criticality of physical attributes of the roadway

ODD Attribute	Time Criticality 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 localisation referencing	x				
Special-purpose localisation 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				

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 2.3.2: Time criticality of road surface condition attributes

ODD Attribute	Time Criticality 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 impassable to low-profile vehicles			x		

Table 2.3.3: Time criticality of Operational attributes of the roadway

ODD Attribute	Time Criticality 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 (trimming foliage, ploughing snow, clearing debris,…)				x	
Work zones (road works – construction and rehabilitation)				x	
Incident recovery events (crash scenes, crime scenes, dropped loads, landslides,				x	

avalanches…)					
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 2.3.4: Time criticality of digital information support for CAD operations

ODD Attribute	Time Criticality 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 2.3.5: Time criticality of ambient environment attributes (weather, visibility, electromagnetic environment)

ODD Attribute	Time Criticality 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			x		

(night/no illumination, night with illumination, dawn/dusk, day/sunny, day/cloudy, day/partly cloudy)					
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 2.3.6: Time criticality of roadway operational attributes (traffic conditions)

ODD Attribute	Time Criticality 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	

2.4 DOA framework implications

A Distributed ODD Awareness (DOA) framework can potentially be implemented 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.

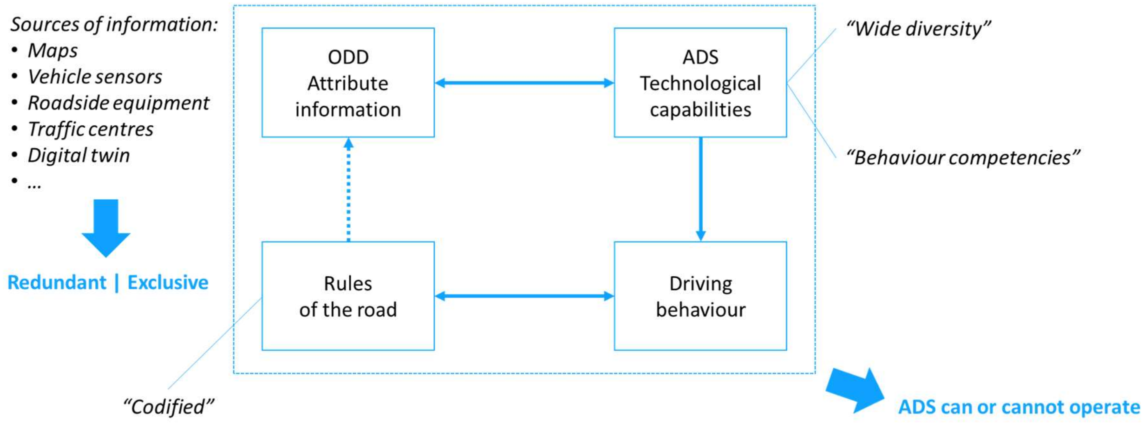
As ODD attribute information is essential for the safe deployment of the CAD systems, it is essential that the NRAs publish details of what type of ODD attribute information (if any) is being provided for CAD systems on the road in a particular area/region.

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 priority level of the information as required for safe operation of the CAD systems that are highest in priority for that NRA. This choice will have cost implications, as higher quality data would warrant higher investment in infrastructure.

2.5 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 include:

1) Technological capabilities of the CAD system
2) Driving behaviour of the CAD system
3) Rules of the Road



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 behaviour while complying with the rules of the road.

2.5.1 ADS Technological capabilities

The technological sophistication of each CAD system will determine its ODD limitations and the behavioural competencies if 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 are safe 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 uses. Cost considerations will be an important constraint since the vehicle must be affordable to the target customers. 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 vehicle 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 (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);

2.5.2 Rules of the Road

These 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 involves creation of a codified version of the rules of the road for CAD systems. The concept considers the rules of the road as a function of ODD and behavioural competencies.

If one compares the scope of ODD and the content of current "rules of the road for human drivers" (e.g., UK's Highway Code), a large overlap of scenery aspects and environmental condition aspects can be observed. It is therefore plausible to follow an ODD 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 ADS's behavioural competencies, "somewhere" could be considered as "operating condition" or part of the ODD definition.

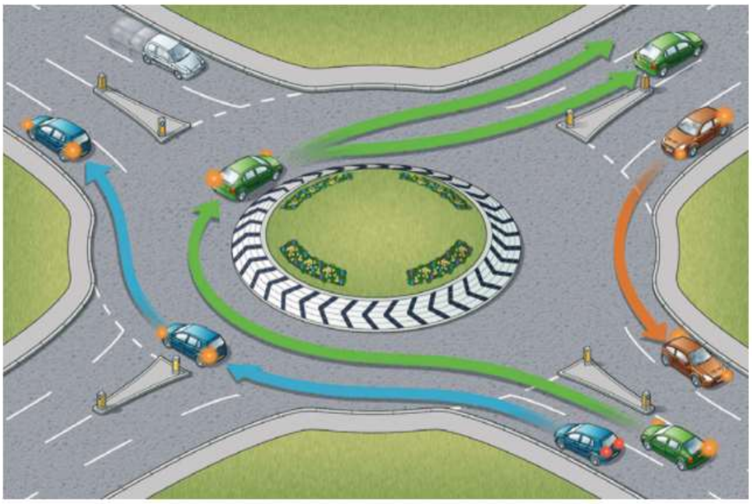
Therefore, each rule of road will have an ODD factor and a behavioural competency factor.

Taking an example from the UK's Highway Code which governs the behaviour of the traffic participants, Rule 185, 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."*

CEDR
Conférence Européenne des Directeurs des Routes
Conference of European Directors of Roads



Rule 185: Follow the correct procedure at roundabouts

Source: UK Highway Code Rule 185

One could identify ODD 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 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.

2.5.3 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. These each 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 or it could be made available by the road operator as part of its digital infrastructure support.

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 Implementing Distributed ODD Awareness framework

3.1 Roles and responsibilities

The roles and their responsibilities in the various phases of the DOA implementation are described in Table 3.1.1

Table 3.1.1: Roles of stakeholders and their responsibilities in the various phases of Distributes 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	-	Adaptation of	Provision of real-time data related to	Report problems in use; fix problems

provider		processes	DOA	related to own operations
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 NRAs naturally assume the role of the road authority or operator. In addition, in many countries they 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 and road works of maintenance operator.

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