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Traffic Management for Connected and Automated Driving

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Abstract

Connected & Automated Driving (CAD) systems can experience a wide variety of situations during their lifetimes. However, the situations experienced could be contextualised to their Operational Design Domain (ODD). Defining the ODD of a CAD system is a key step in ensuring its safety. However, the CAD system also needs to monitor or be aware of its local conditions in real-time and compare them to its designed ODD in order to ensure it is within its safe operating envelope. The ability to measure all attributes that are included in an ODD through onboard sensing remains a challenge for current CAD systems. This paper discusses the concept of Distributed ODD Awareness (DOA) which enables ODD awareness via infrastructure supported sensing or other offboard sensing means. Furthermore, we discuss the role of Traffic Management systems in increasing ODD awareness enabling CAD system deployment.

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Keywords: Automated Driving Systems; Operational Design Domain; Cooperative Automated Driving; Infrastructure support; safety; Traffic Management

1. Introduction

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 (Junietz *et al.*, 2018). Safe deployment not only

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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 (Khastgir *et al.*, 2018), 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) (SAE International, 2021a). 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) ('Operational Design Domain (ODD) taxonomy for an automated driving system (ADS) – Specification', 2020).

Most of the research to date on CAD systems has focused on the vehicle technology, with less attention to the supporting physical and digital road infrastructures. Careful integration of traffic management infrastructure features with the vehicle technology can enable CAD systems to be operated as an intelligent "system of systems", with broader societal benefits. Technological constraints will for the foreseeable future require highly automated driving to be confined to specific Operational Design Domains (ODDs). The ODD constraints are based on the limitations of the sensing, software and control technologies that are used in each CAD system.

The CAD systems on the vehicles must be able to identify whether the local environment in which they are driving satisfies their ODD constraints in order to meet basic functional safety requirements. However, they cannot be expected to know about different situations and conditions that may prevail outside the range or detection capabilities of their sensor systems. This is where intelligent road and traffic management infrastructure can provide important support, informing them about changes in traffic or weather conditions beyond in-vehicle sensor capabilities so that corrective action can be taken by the vehicles or their drivers. This could involve giving drivers ample advance notice about the need to intervene in the driving task, rerouting the vehicle away from a trouble spot, switching the automated driving into a degraded mode of operation, or as a last resort transitioning the vehicle to a minimal risk condition.

Thus, ODD constraints are especially important for higher levels of automation — SAE level 3 and SAE level 4 (SAE International, 2021a). 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 of ODD attribute information can be sensed by the CAD system's on-board sensors, some information can only be supplied by off-board sources such as remote sensors and wireless communication systems. Levels of Infrastructure Support for Automated Driving (ISAD) have been defined as a general way of classifying available roadway infrastructure features that could affect the ODD constraints of CAD systems (Inframix, 2022).

In this paper, we introduce the Traffic Management for Connected and Automated Driving (TM4CAD) project, where we explore the role of infrastructure systems in facilitating safe CAD operations and in creating ODD awareness for CAD systems.

2. Background

As per SAE J3016, 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 (SAE International, 2021a). 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 classified from Level 0 – 5.

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. As per SAE J3216, there are four cooperative automation classes (SAE International, 2021b). These include: Class A – Status-Sharing; Class B – Intent-Sharing; Class C – Agreement-seeking; and Class D – Prescriptive.

2.1. Operational Design Domain and ODD attributes

ODD essentially defines the operating conditions for which a CAD system is designed. It may also be seen from the perspective of the road operators as the operating conditions in which a system should be able to operate safely. It is essential that there be an overlap between the two perspectives on the ODD, CAD manufacturer (or the CAD system designer) and the road operator, for ensuring the safe deployment of CAD systems.

As per SAE J3016, Operational Design Domain (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"* (SAE International, 2021a). ODD definition is key to both the system design and safety assurance process of a CAD system.

The attributes used to define the ODD represent the combination of all the design factors that affect the ability of any CAD system to perform its automated driving functions. Various standards like BSI PAS 1883 ('Operational Design Domain (ODD) taxonomy for an automated driving system (ADS) – Specification', 2020), ISO 34503 (*ISO 34503*, 2022), and SAE J3259, have suggested taxonomies and format for ODD definition. ODD definitions (and attributes) 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.

2.2. Infrastructure Support Levels for Automated Driving (ISAD)

The European Research and Innovation project INFRAMIX (InfraMix, 2022), funded under the Horizon 2020 programme, has developed a scheme for infrastructure support levels for automated driving, in short ISAD levels (Inframix, 2022). 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. National projects such as AUTOMOTO have further elaborated on the attributes for ISAD infrastructure support levels (Finish Transport Infrastructure Agency, 2021).

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. Methodology

As a starting point we identified a wide range of ODD attributes that are relevant to determining the feasibility of CAD operations on highways, the measures of effectiveness for quantifying those attributes, and the ways of providing that attribute information to CAD-equipped vehicles for each highway segment, ultimately to enable CAD systems to be aware of their ODD in real-time.

Moreover, TM4CAD demonstrates the basic mechanisms of ODD management via real-world use cases, which build on the premise of interaction between traffic management systems and CAD vehicles. This will provide National Road Authorities (NRAs) insight into methods to inform CAD systems about the kinds of support they can provide for CAD operations on European roads.

Through a workshop study conducted as part of the TM4CAD project, viewpoints of various NRAs were captured both on the safe deployment of CAD systems as well as the governance structure (section 4.1). To identify NRA requirements on automated vehicle behaviour from a traffic operations perspective, TM4CAD identified for the road authorities a recommended set of issues to discuss with automated driving system developers and automated vehicle fleet operators. In addition, TM4CAD identified priority areas in infrastructure support for automated driving requiring close dialogue and agreement among 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.

4. ODD awareness and Distributed ODD Awareness

One of the implicit requirements of defining an ODD is the need to monitor/measure or be aware of each of the attributes used in the ODD definition, in real-time. This is essential to establish if the CAD system is inside or outside is defined ODD boundary. As mentioned earlier, the early deployments of CAD system will have constrained ODD definitions which in turn would require the CAD system to implement a mechanism to be aware of its current local conditions and compare the same with its defined ODD.

While it may be possible to have onboard sensing for some of the attributes (e.g., road layout via HD maps etc.), for certain attributes (e.g., visibility range) the CAD system may not be able to measure via onboard sensing systems. In such cases, it will need to depend on off-board sensing mechanisms (e.g., a weather station or traffic management centre) to provide real-time information about ODD attributes' values. We call such an architecture a Distributed ODD awareness (DOA) architecture which will be essential for safe and early deployment of CAD systems.

As the CAD system will depend on off-board sensing systems, there will be an implicit requirement on the connectivity attribute of the ODD. For example, due to the safety critical nature of the information about certain attributes, the CAD system may require a given latency and signal strength specifications for it to ensure safe operation. Enabling such an infrastructure to provide these services would require the NRAs to invest in the infrastructure and also require an agreement between the NRAs and the CAD system developers. There will be a need to create a governance structure for both decision making process on which ODD attribute information can be provided via infrastructure as well as the quality of the information.

4.1. Governance structure

Table 1 illustrates the possible roles and responsibilities among various stakeholders and 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.

Table 1. Roles of stakeholders and their responsibilities in the various phases of DOA 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
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

Figure 1 shows the logical flow and causal relationships among several elements involved in the implementation of the DOA Framework and the role of Traffic Management in it. 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. Finally, to build upon the idea of automated driveability / suitability maps, the DOA framework presented in this paper 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.

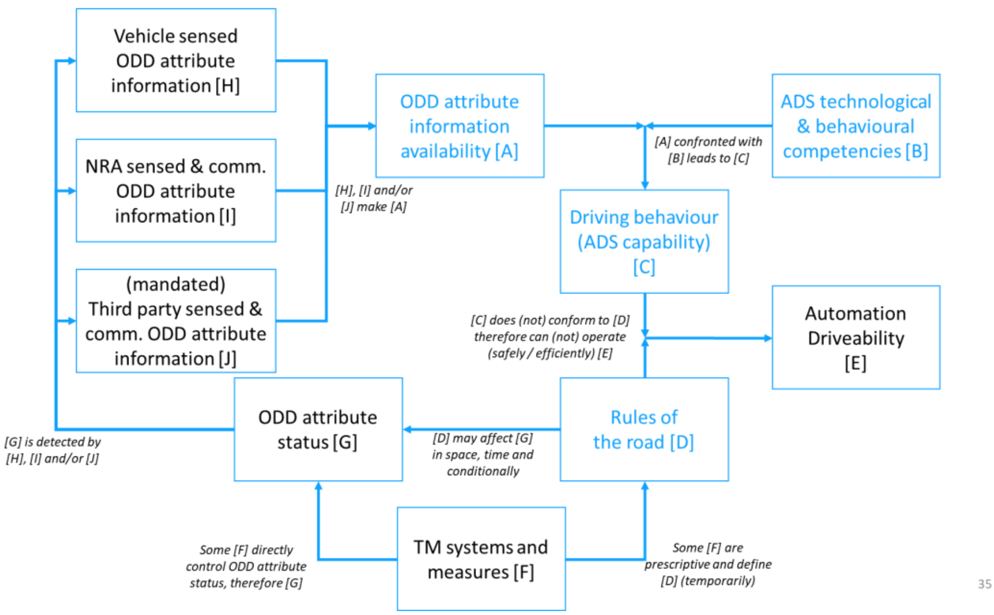

Fig. 1. Illustration of various possibilities for ODD attribute information source and their links with wider CAD system safety assurance

5. Discussion

As national road authorities and infrastructure providers are a key stakeholder in the implementation of the DOA framework, we held a workshop *"ODD-ISAD architecture and NRA governance structure to ensure ODD compatibility"*. The workshop had over twenty NRA participants from different European countries. The key findings from the workshop on the needs from the NRAs are as follows:

5.1. 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.

5.2. 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.

5.3. 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 constraint violations 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 safety regulations. Nevertheless, the NRAs expressed a wish that CAD systems will inform road operators and especially traffic managers about any MRMs that they carry out on the road network.

6. Conclusion and future works

TM4CAD aims to increase understanding of the issues associated with providing real-time information about ODD-relevant conditions and the role of the national road authorities and operators, including specifically traffic management centres in providing these solutions.

One of the main contributions of TM4CAD is the introduction of the concept of "Distributed ODD Awareness". The distributed ODD awareness concept focusses on the aspect that the vehicle equipped with the Automated Driving System (ADS) can acquire real-time information about the ODD attributes by both on-board (on vehicle) sensing and off-board sensing mechanisms (e.g., via infrastructure). The concept of distributed ODD awareness is especially relevant to the near-term deployment of CAD systems to ensure their safe operation by providing infrastructure support, which may reduce the need for some expensive high-fidelity on-board sensors.

The implementation of the DOA framework will highlight any needs to improve information flows and quality and develop traffic management processes and tasks while revealing existing gaps of knowledge in the domain. Future work will include operationalising the Distributed ODD Awareness concept on real-world use cases to establish the feasibility of the concept and identifying how road authorities can best prepare their infrastructure (both physical and digital) for use by CAD-equipped vehicles. One of the most important conclusions of this paper is that no infrastructure classification (scheme) by itself can provide a guarantee of automation drivability.

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