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Interactive traffic management for highly automated vehicles

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Abstract

This chapter deals with traffic management in the presence of highly automated vehicles capable of driverless operation in specific Operational Design Domains (ODD). The aim is to present and discuss challenges related to the design and implementation of traffic management measures from multiple perspectives, covering the exchanged messages, the digitization of traffic codes and regulations, the impact on efficiency, and the human factors and reactions to traffic management measures. The potential to increase and optimize the performance of highly automated vehicles by providing external information will also be explored by introducing the concept of Distributed ODD attribute Value Awareness (DOVA).

1 Introduction: Motivation and objectives

An increasing presence of highly automated vehicles or Connected and Automated Vehicles (CAVs) is expected to have a significant impact on traffic management, while stakeholders, such as public agency operators and toll road operators, need to adapt their Traffic Management Center (TMC) policies and procedures. In the meantime, vehicle manufacturers need to adapt their in-vehicle systems to be able to react appropriately to traffic management messages.

The main objective of this chapter is to present and discuss recent developments and future challenges related to the development of traffic management for automated vehicles, looking from a multifaceted perspective. More detailed objectives include the following.

- To provide insights on the needs to develop traffic management of the future, including the roles and responsibilities of the stakeholders.
- To increase understanding of the digital, physical, and operational infrastructure associated with CAVs and traffic management.
- To introduce the concept of Distributed ODD attribute Value Awareness (DOVA).
- To discuss the roles and responsibilities of various stakeholders in translating traffic codes and rules into a machine-readable format, as well as the expected responses of CAVs to these codes and rules.
- To raise awareness on the impacts that operating CAVs in different infrastructure situations may have and the need for traffic management as a means to mitigate negative externalities.

2 Summary of the discussion

2.1 CCAM (meta) taxonomies

Support from the physical and digital road infrastructure can extend the conditions under which connected and automated vehicles can operate safely. Operational Design Domain (ODD) and Infrastructure Support for Automated Driving (ISAD) are key terms in taxonomies related to Connected Cooperative and Automated Mobility (CCAM) but do not yet provide the full picture that has emerged in recent years. It is important to take the full picture into account for collaborating between the actors across sectors (e.g., automotive industry, road infrastructure managers) in order to prepare, pilot, test, and deploy CCAM services in the coming decades, ultimately for the benefit of end users.

CCAM taxonomies comprise the automotive side standardized classifications, i.e., the Levels of Driving Automation (SAE J 3016) and the Cooperation Classes (SAE J 3216). They are complemented by taxonomies on infrastructure suitability such as Infrastructure Support for Automated Driving (ISAD) and Levels of Service for Automated Driving (LOSAD). In addition, they comprise the (automation mode) communication towards users, in order to provide mode-awareness and avoid mode-confusion. Fig. 1 illustrates the CCAM taxonomies. The interplay between the taxonomies is analyzed in more detail in [1].

From an overall perspective, the taxonomies fit well with each other and come to quite consistent results. In a further step, it may be useful to investigate the possibilities of integration into a meta-taxonomy. This advancement should not be an end in itself, but always only a serving tool enabling us to achieve common goals. A recent and even more promising approach, the concept of Distributed ODD attribute Value Awareness (DOVA), is featured in the next subchapter. The cross-sector collaboration is a constitutional feature of it. In other words, what the meta-taxonomy would aim to tie together, is already built into the concept of DOVA.

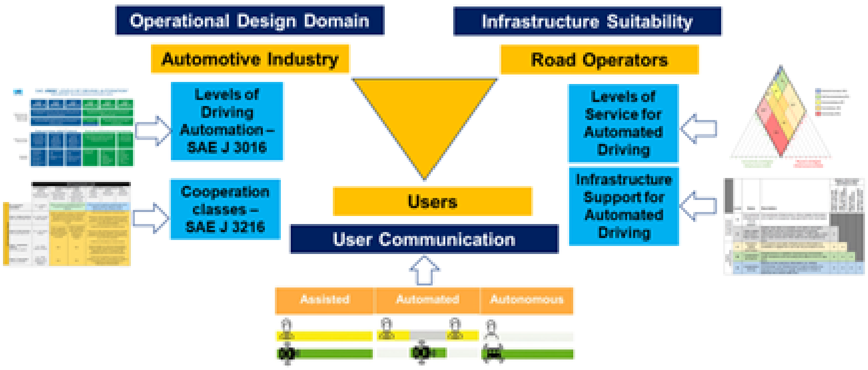

Fig. 1. CCAM Taxonomies by Geissler and Shi [1].

2.2 Concept of Distributed ODD attribute Value Awareness

The need to monitor or be aware of each ODD attribute puts an additional overhead on CAVs or Automated Driving Systems (ADS) to be able to measure each ODD attribute. However, measuring each ODD attribute may not be practically feasible from a cost and engineering perspective. However, ODD awareness is key to ensuring the safe operation of the ADS. In order to overcome this challenge, we introduce the concept of Distributed ODD attribute Value Awareness (DOVA) framework building on the DOA framework introduced by Khastgir et al. [2].

The DOVA framework enables the ADS to benefit from off-board sensing infrastructure to become aware of ODD attribute values that may not be able to be measured or sensed by themselves. For example, an ADS may not be able to detect the severity of a visibility impairment from a fog bank that it is approaching. It may be able to receive such information from a roadside weather station that can provide this information through over-the-air communication with the ADS. This enables the ADS to have awareness of this current operating condition and compare it with its designed ODD to establish if the ADS is either inside or outside its ODD.

While the information for some of the ODD attributes could be available via infrastructure, there may potentially be commercial services that can augment ODD information for the ADS.

From a road operator's or traffic manager's perspective, it is important to establish what type of ODD attribute information should be provided via infrastructure and its corresponding quality to enable the safe deployment of ADS. It is also important to consider the needs of road operators and traffic managers to be aware of any ADS approaching the end of their ODD and/or being in a transitional or minimal-risk state.

The operation of the DOVA framework in practice is illustrated in Fig. 2. The ODD attribute information (or from the road operator perspective, local condition attribute information) sharing plays a major role in influencing the driving behavior of a CAV, depending on its technical capabilities and the rules of the road. The traffic management operations affect the rules of the road (i.e., the expected behavior) as well as the status of the ODD / local condition attributes sensed by the vehicle, the road operators' and other stakeholders' monitoring and other data acquisition systems providing the attribute information to the ADS-operated vehicles and other road users.

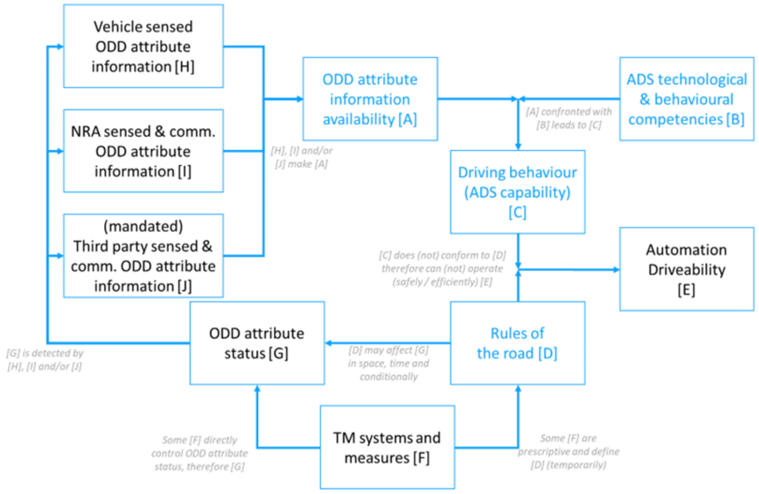

Fig. 2. Distributed ODD Awareness Framework by Khastgir et al. [2].

2.3 Impact of CAVs on traffic flow

Traffic congestion in and around urban areas has a serious detrimental impact on the economic and social life of modern society, as well as on the environment, with negative effects for climate change, which calls for radical solutions [3]. Insofar, typical responses to mitigate traffic congestion externalities have been the expansion of road infrastructure, with huge costs and impact on the environment, and the implementation of traffic management measures, which however may also face various kinds of limitations. The appearance of CAVs has come with the promise to drastically improve safety and mobility, essentially revolutionizing the way how people move around. Whether CAVs have the potential to actually deliver the full range of expected benefits will ultimately depend on three factors: their penetration speed, their effectiveness, and their potential negative impacts. Often, studies tend to be overly optimistic about the future of CAVs by overestimating the first two factors while ignoring the third one. One reason is that vehicles are products manufactured and offered in a market, wherein there is competition for the customers' preferences; thus, it is reasonable to expect that, if no interventions are made, CAVs (are and) will be developed to benefit the individual vehicle and driver, often without a clear view or understanding for the implications, including potential advantages and disadvantages, that they may have for the induced, accordingly modified traffic flow characteristics.

One important aspect to consider is that CAVs are going to be *safe by design*, meaning that it is expected that no vehicle released on a large scale in the market is going to be taking any risk while driving, for either the occupants or other users surrounding the vehicle. However, this is not what typically happens with a vehicle driven by humans, who, actually, and in particular while traffic flow is perceived high, typically take risks, such as performing cut-in maneuvers or driving with (too) low headway distances from the preceding vehicle. Most often these risks do not lead to serious consequences, and the reason is that human drivers have developed a good perception and capability of anticipating the behavior of other drivers and what could be their reactions caused by such risky maneuvers. Also, other external factors, together with formal and informal communication that takes place between drivers, play a role in this context (e.g., eye contact between drivers, and the use of devices such as indicator lights and horns). However, all these aspects are extremely difficult to be coded and included in the design of automated vehicle operation.

The effects of the above-mentioned combined factors may thus lead to a deterioration of traffic characteristics, such as road capacity. This implies that an infrastructure designed to accommodate a certain capacity may not be able to sustain the same number of vehicles, which, in turn, would deteriorate the efficiency of the current transportation system. Various research has tried to quantify such reduction, resulting in numerical differences but similar trends ([3], [4], [5]). The most promising solution to such an issue involves moving forward with the design and deployment of cooperative connected and automated systems, where automated vehicles should not behave as selfish entities, but they should act in a coordinated manner, either through centralized or decentralized management policies to achieve a benefit for the overall traffic system. Several management strategies have been proposed to improve the efficiency of systems with connected and automated vehicles, also in the presence of mixed traffic (see, e.g., [6], [7], [8]), which have the potential to mitigate the externalities potentially caused by automated vehicles on traffic characteristics, bringing unprecedented benefits for the overall traffic system performance. In fact, connected and automated vehicle systems provide increased opportunities for more efficient implementation of management strategies, where CAVs may actuate more precise commands ordered by, e.g., infrastructure-based intelligence. Furthermore, the granularity of traffic management measures, which currently depends on the installation and operation of dedicated infrastructure, could be arbitrarily defined once it is enabled by automated vehicles, and there could be different measures implemented, e.g., by lane, by destination, or by other criteria for vehicle selection.

2.4 Codifying traffic rules for CAVs

While driving, human drivers are expected to adhere to road traffic rules to ensure a smooth and safe flow of traffic on roads. Similarly, CAVs will also be expected to follow traffic rules to ensure a smooth flow in heterogenous traffic as well as ensure predictability of their behavior. Thus, as part of the assurance process for CAVs, they will need to be tested against the road rules. At the same time, an NRA would like to ensure that CAVs driven on their road networks also adhere to road traffic rules.

Rules of the road for human-driven vehicles require a certain level of interpretation on the part of the human drivers where they make an intuitive driving decision (e.g., understanding when is there a "suitable gap" to overtake a vehicle on the road). Such judgment will need to be made and hardcoded into the intelligence systems of the CAVs. In order to verify their behavior's compliance with the rules of the road, there is a need to codify the rules of the road to enable objective assessment.

To this end, an ODD-based codification process for the rules of the road has been proposed by the United Nations Economic Commission for Europe (UNECE) Functional Requirements for Automated Vehicles (FRAV) informal working group [9]. The approach is also relevant for NRAs to understand the relevance of specific traffic rules and the CAVs' driving decisions when deployed in a specific ODD.

The operational design domain (ODD) refers to the operating environment in which vehicles can operate safely. As defined in the BSI PAS 1883 ODD taxonomy [10], it covers environmental conditions such as rainfall, scenery elements such as drivable areas, and dynamic elements such as macroscopic traffic behavior and designated speed of the subject vehicle.

If one compares the scope of ODD and the content of current "rules of the road for human drivers" (e.g., the UK's Highway Code or the Vienna Convention's Rules of the Road), a large overlap of scenery aspects and environmental conditions aspects can be observed.

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

- *Doing* some "behavior" "somewhere"
- *Not doing* some "behavior" "somewhere"

While doing or not doing some behavior can be defined as part of CAVs' behavior capabilities, "somewhere" could be considered as an "operating condition" or part of the ODD definition. Thus, each rule of the road is a combination of aspects of ODD and behavior capabilities.

From an NRA perspective, understanding the ODD definition, i.e., the various ODD attribute values and their relationship with real-world routes will provide guidance on the applicable rules of the road for the CAVs. This can enable traffic flow planning and monitoring in a heterogenous traffic flow.

2.5 Remote monitoring and support for CAVs

For most of the current deployments of CAVs around the world, remote monitoring and/or support is being used and it is regarded as a necessity. Perhaps over time, when CAV's capabilities increase, such support may be minimized or even become obsolete, but for the foreseeable future it is certainly indispensable.

Remote monitoring and support involves a human operator providing instructions, permissions, or waypoints to the vehicle, or remotely driving it when the vehicle cannot execute one or more of its driving tasks [11]. It is considered most useful when the vehicle encounters unknown situations or when illegal actions are required. Remote support has many benefits, such as enabling operations, ensuring safety, and increasing public acceptance. The purpose and tasks of the operator can be very diverse for different modes and environments, ranging from confined areas for cargo movements to passenger vehicles on public roads. There are four levels of remote support: no assist, remote assist, remote control, and shared control [11]. Remote control is temporary full operational control typically used to resolve a situation, while shared control involves remote human driving with the vehicle controlling the on-board crash avoidance systems or remote assessment of a situation and providing concrete operational guidance recommendations.

The key elements of remote support for CAVs are a stepwise approach to building experience and trust with such operations, addressing human factors in remote operation, and defining the role of the human operator. There is still a need for further research on higher operational speeds and resulting increased safety risks, investigating edge cases, and looking at the ODD from a system-to-system perspective beyond the scope of only the vehicle.

Overall, remote support is expected to play a crucial role in achieving safe and comfortable highly automated transport services in mixed traffic. The implementation of remote support requires addressing various technical and operational challenges, and further research is needed to ensure its effective deployment

2.6 From automating vehicles to automating traffic

Up until now, the design of AVs and CAVs by manufacturers has considered essentially a static road network, where infrastructure characteristics and regulations are embedded in the vehicle system and do not respond to dynamic external inputs [12], [13]. The dynamic components have been limited to interactions with other vehicles or obstacles, essentially only for safety purposes, while decisions are taken advantaging the individual vehicle only. Limited work has been done on standardizing messages for Advanced Traveler Information System [14], whereas there is no standardization on the response that vehicles may implement once such messages are received. On the other hand, a large body of research (see, e.g., [6]) has suggested various ways of implementing active traffic management strategies that interact directly with CAVs via messages exchanged among vehicles or with the infrastructure; however, due to the limitations above, such strategies have not been implemented. Efforts in this area should give the possibility to the main stakeholders involved in traffic management, namely, public agency operators and (toll) road operators, to exchange active traffic management-related messages with CAVs. Vehicle manufacturers and OEMs should consider such features in the design of future CAV systems aiming at a harmonized integration of CAVs within the transport system, also considering design principles that are not selfish but would lead to collective systemic benefits.

In the meantime, traffic management stakeholders, such as public agency operators and (toll) road operators, need to adapt their Traffic Management Center (TMC) policies and procedures to account for the increasing presence of CAVs so that both existing and novel traffic management measures, involving, for example, flow metering, variable speed limits, lane use management (including hard shoulder running), dynamic rerouting, and, in general, real-time messaging, are able to seamlessly interact with the operation of CAVs through the use of connected vehicle-to-infrastructure (V2I) communications. This will require an upgrade of the (mostly digital) infrastructure, to account for the improved sensing and actuating capabilities that will be moved from the infrastructure to the CAVs, as well as the development of data fusion engines, which would be capable of processing various types of traffic and vehicle data, resulting in efficient monitoring of the operational traffic situation.

Research efforts should support such developments and actively enable such transitions focusing, among other aspects, on the dynamic responses needed to be designed into the CAV, the standardization of these messages, responses to that messaging, as well as integration with the upgraded digital infrastructure and its novel decision support system widely employing innovative data fusion engines.

3 Conclusions and future needs

This chapter reflects and builds on some of the discussions that took place during the session on “Interactive traffic management for highly automated vehicles” at the Automated Road Transportation Symposium – ARTS 22.

It is becoming obvious that traffic management is an essential enabler for highly automated vehicles to be part of a safe and efficient traffic system, where a certain level of support from and interaction with the infrastructure are necessary requirements for future traffic systems with automated vehicles (e.g., for improving the ODD or implementing traffic rules). In addition, traffic management should serve to address unanticipated negative effects of automated vehicles (e.g., impacts on traffic efficiency), which are otherwise expected to decrease the current road and network capacities, with potentially negative economic externalities.

Finally, understanding and incorporating human factors in automated vehicles and traffic management design, regarding both strategies and responses, is essential in order to raise acceptability, ensure wider adoption of vehicle automation, and generate positive effects for society as a whole.

To achieve all of the above, there is a need to seek more collaboration among stakeholders, e.g., involving vehicle manufacturers, road authorities, and researchers to better frame the problems and achieve better, more sustainable, solutions by multidisciplinary approaches.

In particular, further research is needed on human factors, involving both the automated vehicle occupants and the interactions with other entities (e.g., interactions with human-driven vehicles in mixed traffic conditions, with pedestrians and other active modes, and multimodal traffic in general). Finally, the acceptability of traffic management measures, when not coded as rules, should be better investigated.

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