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Cooperative Automated Driving for managing Transition Areas and the Operational Design Domain (ODD)

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Abstract

When cooperative automated vehicles (CAVs) emerge on urban roads, there will be areas and situations where all levels of automation can be granted, and others where highly automated driving will not be allowed or is not feasible. Complex environments or temporary road configurations are examples of situations leading to takeover requests and are referred to as 'Transition Areas'. Such situations are assumed to cause negative impacts on traffic safety and efficiency, in particular with mixed traffic fleets. The TransAID project is developing a digital infrastructure and dedicated traffic management strategies to assist CAVs at transition areas, and preserve safe and smooth traffic flow. This paper explains the relevance of transition areas and the link to the operational design domain (ODD) of automated vehicles. By combining results from different projects with findings from stakeholder consultation workshops, ODD is discussed in detail and a conceptual structure to guide the discussion is provided.

Keywords: automation, connectivity, infrastructure, transition of control, traffic management, operational design domain, ODD, guideline, roadmap

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1. Introduction

As the introduction of automated vehicles becomes feasible, even in urban areas, it will be necessary to investigate their impacts on traffic safety and efficiency. This is particularly true during the early stages of market introduction, where automated vehicles of various levels of automation, connected vehicles (able to communicate via V2X) and conventional vehicles will share the same roads.

There will be areas and situations on the road where high levels of automation can be granted, and others where it is not allowed or not possible due to, for example, missing sensor inputs, the complexity of the situation, etc. At those locations the so-called Operational Design Domain (ODD) of automated vehicles ends and vehicles may initiate a change of driving mode, thereby handover the control of the vehicle to the driver or perform a minimum risk maneuver (MRM). Hence, such locations are referred to as ‘Transition Areas’ (TAs).

The goal of TransAID is to gain insight into measures that mitigate the (possible) negative impact of unintended Transition of Control (ToC) (i.e. the handover) or MRMs on traffic flow and/or safety. Therefore measures have been developed with one of three goals:

1. **Prevent ToC or MRM**: Apply a solution type to a situation to prevent the ToC or MRM. The vehicle can maintain its automated driving state. As a result, the traffic flow is undisturbed.
2. **Manage or support ToC or MRM**: In some situations, a ToC or MRM might not be preventable and there is no time or space to do it elsewhere. The ToC or MRM can be managed (e.g. indicate a safe spot) and supported (e.g. inform surrounding vehicles to give way).
3. **Distribute (in time and space) ToC or MRM**: In situations where the problem is predictable, but despite the predictability ToC or MRM cannot be prevented, it is best to phase the ToC or MRM. That way, not all vehicles perform a ToC or MRM at the same time at the same place, but sequentially and distributed along the road, thereby minimizing the impact.

The measures are described in more detail in Wijbenga et al. (2018). To design infrastructure-assisted driving at transition areas, situations in which ToCs disturb traffic need to be identified and studied. Especially, why, when, and where exactly ToCs are triggered needs to be better understood. This mostly requires a better understanding of the constructs of the Operational Design Domain of automated vehicles.

The main purpose of this paper is to discuss different perspectives on the ODD of automated vehicles as well as measures – vehicle technology, (digital) infrastructure-related and otherwise – that facilitate automated driving and help preserving and extending the ODD. In addition, this paper summarizes a guideline and roadmap prepared by the TransAID project, which aims to support road authorities and/or service providers dealing with automated driving in the urban environment in general and in transition areas specifically.

2. Cooperative Automated Driving

One common desire across all stakeholders, both public and private, is to exploit the full benefits of connected and automated driving in terms of safety, efficiency and the impact on the environment. The global vision is that automated vehicles, connected vehicles and cooperative intelligent transport system (C-ITS), together, will lead to more sustainable mobility (i.e. zero road fatalities, optimal traffic flow, reduced emissions, reduced congestion and social inclusiveness). There are many views on possible development paths, likely roadmaps and intermediate phases. The European Commission has illustrated the path towards cooperative, connected and automated mobility as shown in the figure below (Barradas, 2018). What is interesting about this figure is the addition of the words ‘negotiate’ and ‘orchestrate’. Similar principles were introduced by the working group Enhanced Traffic Management of the C-ITS Deployment Platform (European Commission, 2017), including terms like:

- *'Cooperative Traffic Management'* - a connected, decentralized, traffic management system in which all stakeholders can act collaboratively, either to provide individually, high quality, profiled services or to preserve the collective's best interest, as for safety, flow efficiency and emission reduction, and
- *'Orchestration of services'* – means to put in place, when appropriate, the traffic management measures by the means of the different stakeholders, public and private, that are required to come together and act accordingly to preestablished agreements.

These terms underline a more active role for digital and physical infrastructure, including traffic management, to anticipate and facilitate the deployment of automated vehicle systems.

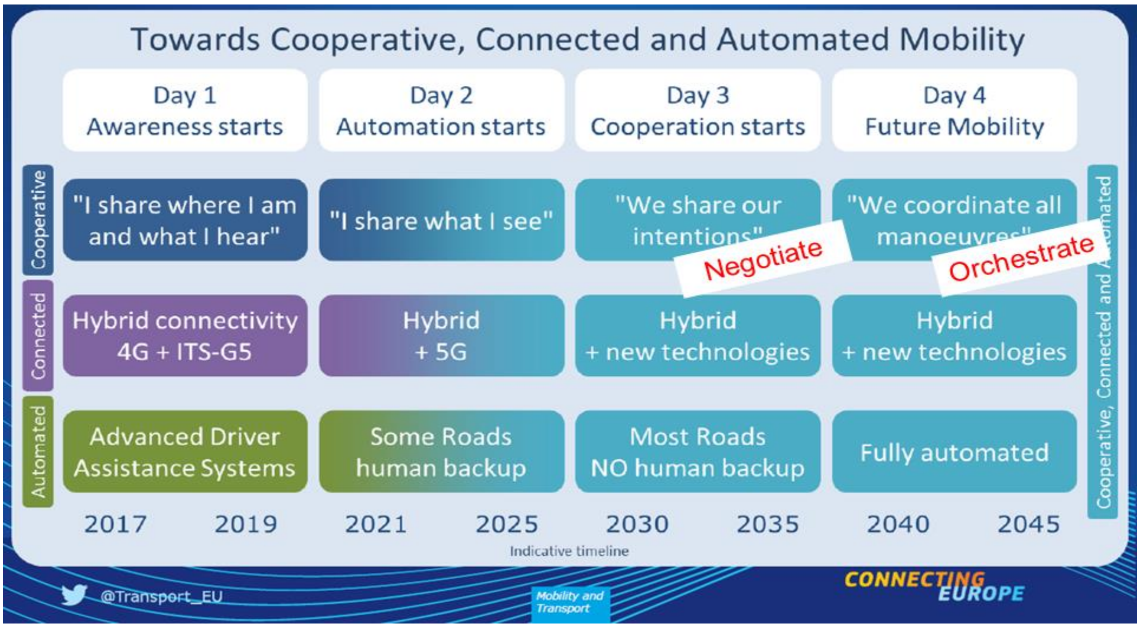

Fig. 1 path towards cooperative, connected and automated mobility

It is important to note that connected driving itself does not necessarily imply cooperative driving. Single traffic participants can theoretically use the additional information for their own individual advantage at the cost of others. Similarly, autonomous driving does not intrinsically cause improved traffic. If everybody decides on his own without a cooperative coordination with other traffic participants, then chaos and traffic collapses may be a consequence. Normally, autonomy is only appropriate in the case of low densities. Automated driving can lead to significant improvements in traffic, because cooperative behavior can be enforced for robots much easier than for human beings. Robots follow their instructions much more precisely than humans, unless these are autonomous robots which decide to do differently (Andata, 2019).

3. Managing the Operational Design Domain

What is relevant about the expected benefits of cooperative, connected and automated driving and when they become available is the operational design domain (ODD) of automated vehicles. ODD is a description of the specific operating conditions in which the automated driving system is designed to properly and safely operate, including but not limited to roadway types, speed range, environmental conditions (including weather, daytime/night time), prevailing traffic law and regulations, and other domain constraints (SAE, 2018). Any automation use case of level 1-4 is usable only in its specific ODD. An ODD can be very limited, for instance a segregated road or a single fixed route on low-speed public streets. A graphical representation of the ODD with a storyline including the Transition of Control (ToC) process is shown in the figure below (STRIA, 2019).

The attributes of the ODD are directly connected to the way the automated driving system works and the interaction with its environment. An important aspect to realize about the ODD is that there is not one stakeholder who can affect all specific conditions, let alone control them. Therefore, a vehicle manufacturer cannot guarantee that a level 4 vehicle can always drive in L4 mode, but only inside the ODD. And similarly, a road operator would not be able to offer a road on which a L4 vehicle can be guaranteed to drive in L4 mode because factors outside their control (such as adverse weather conditions) may prevent that. However, a mutual goal amongst stakeholders could be to 'manage' the ODD, making it as uninterrupted, stable and predictable as possible, in order to allow as much automated driving as possible thus maximizing the potential benefits that are associated with it. This implies that actions by both vehicle manufacturers and public authorities can help to preserve and extend the ODD of automated vehicle geographically and temporally.

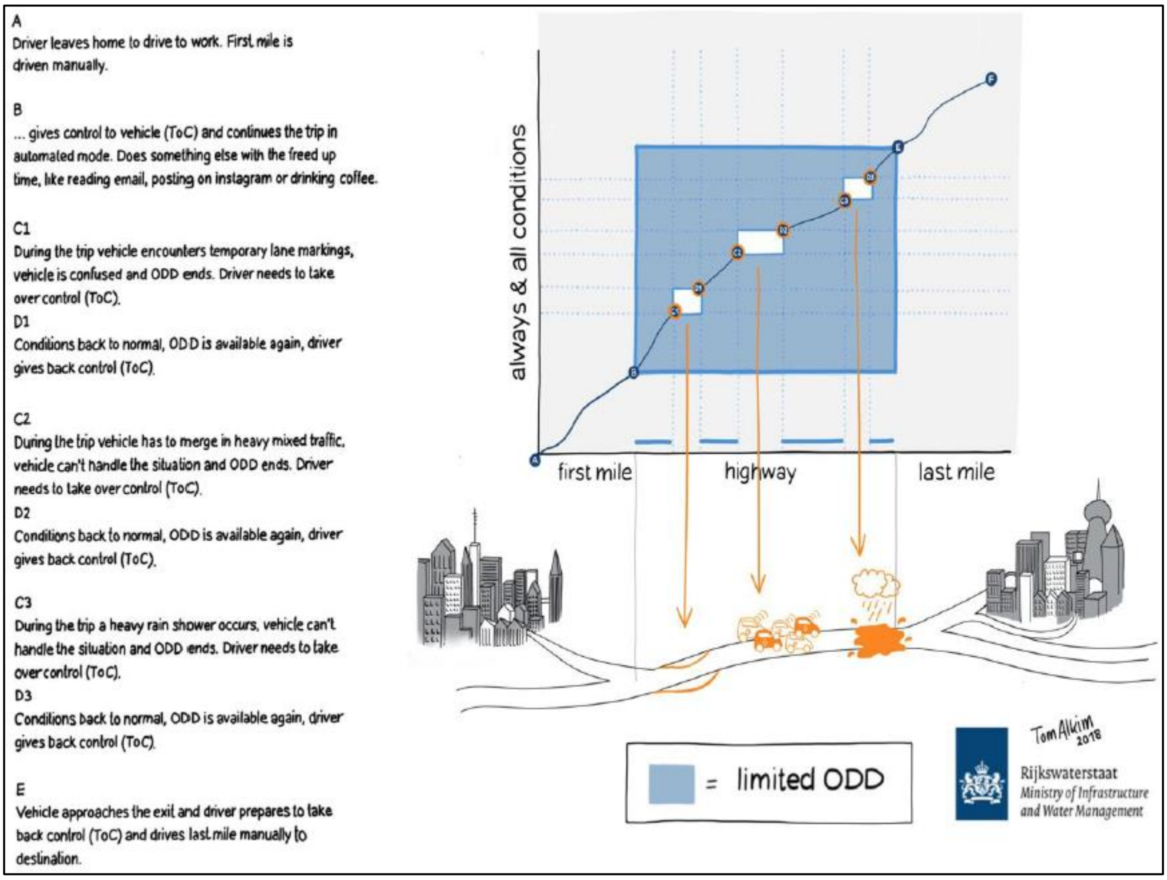

Fig. 2 visual representation of ODD

A different way to look at the path from no automation to full automation is shown in Figure 3. This path essentially has two dimensions: the increase of the automation level and the expansion of the use area. Experiences in recent years have shown that these are hard to achieve simultaneously. One possible alternative is to focus on one of the dimensions at the time, i.e. either increase the level of automation in a given use area, or increase the use area of a given level of automation. Another aspect of the figure is the automation level versus use area combinations that are represented by the 25 cells. Each cell represents a different stage, and a relevant question to derive from this is: what attributes mark the boundaries of these stages, and what is needed to enable a transition to the next level?

4. Operating environment

To answer the above question, it is relevant to understand the differences between various operating environments and the how these affect the ability to deploy actual, operational, real world automated vehicle solutions within a reasonable timeframe. To appreciate the difference between controlled, semi-controlled and uncontrolled environments, four key areas need to be considered (Lohmann and Van der Zwaan, 2018):

- Speed: how fast is the vehicle moving and other vehicles in its vicinity? At lower speeds everything is always easier, especially when nearing intersections.
- Intersections: does the vehicle need to deal with cross traffic, other cars or vulnerable road users? Are the intersections on a grade? Is the traffic in them regulated, and if so, how much control is there over the traffic flow?
- Access: is the vehicle segregated in its own separate lane or pathway, or does it need to share the lane with other vehicles? How likely is it that there will be people or vehicles in the lane that are not supposed to be there? What other vehicles does the automated system need to share its lane with? Sharing part of the street infrastructure with a human-driven bus is much easier than with random traffic and pedestrians.
- Behavior: how much control is there over how people use and interact with the system? Human nature dictates that people will always be disobedient and ignore traffic signals. Who are the users?

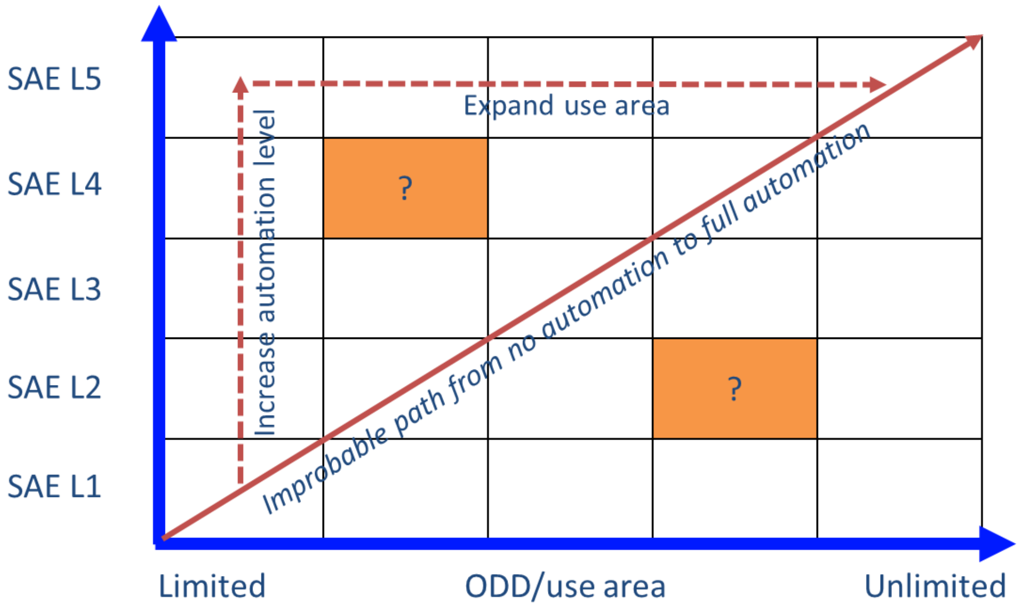

Fig. 3 automated levels versus the ODD use area

Differences in these four areas denote a continuous scale from fully controlled to uncontrolled environments. At one end of the scale is a people mover system operating on private premises along its own track or pathway. At the other, a fully autonomous driverless vehicle navigating busy city streets amongst other traffic. In this sense, car manufacturers and tech-giants talking about automated cars being deployed in the upcoming years (2020 - 2025) are talking about highways. A highway is an environment where all vehicles travel at approximately the same speed, have no at grade intersections, with access restricted to cars and behavior being relatively similar. It is basically a semi-controlled environment and certainly very different from a city center where cars, buses, bikes and pedestrians create an uncontrolled environment, which is much less predictable and more complex.

5. Infrastructure Support Levels for Automated driving (ISAD)

Another way of classification that builds upon the previous sections comes from the H2020 INFRAMIX project (INFRAMIX, 2019), which has developed a scheme similar to the SAE levels for automated vehicle capabilities, only then for digital infrastructure. Involved parties are e.g. different sectors in industry, utilities, infrastructure providers, academia, public authorities.

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

Fig. 4 Infrastructure Support Levels for Automated driving (ISAD)

The so-called Infrastructure Support Levels for Automated driving (ISAD) aims to classify and harmonize the capabilities of a road infrastructure to support and guide automated vehicles . What is particularly interesting is the interplay between the ODD, the SAE automation levels, the ISAD. Clearly they are related, but not interchangeable nor perfectly compatible. Again, for an holistic approach the involvement, collaboration and cooperation between relevant (inter)national parties involved in automated driving is required.

6. Automation readiness

So how can public authorities prepare for automated driving? What can they do to facilitate, anticipate and/or regulate automated driving? Various initiatives have been trying to identify and structure possible actions that cities can take to progressively introduce automated driving. One of them is the H2020 CoEXist project (CoEXist, 2019), which has developed a CAV-ready framework for cities which proposes actions that cities can take to progressively introduce CAVs into their policy and planning processes . Three phases have been identified: (1) becoming CAV aware; (2) planning for automation (including defining measures), and (3) implementation of measures. A range of actions are proposed according to the three phases and considering different mobility aspects: policy, planning, infrastructure, capacity building and traffic management.

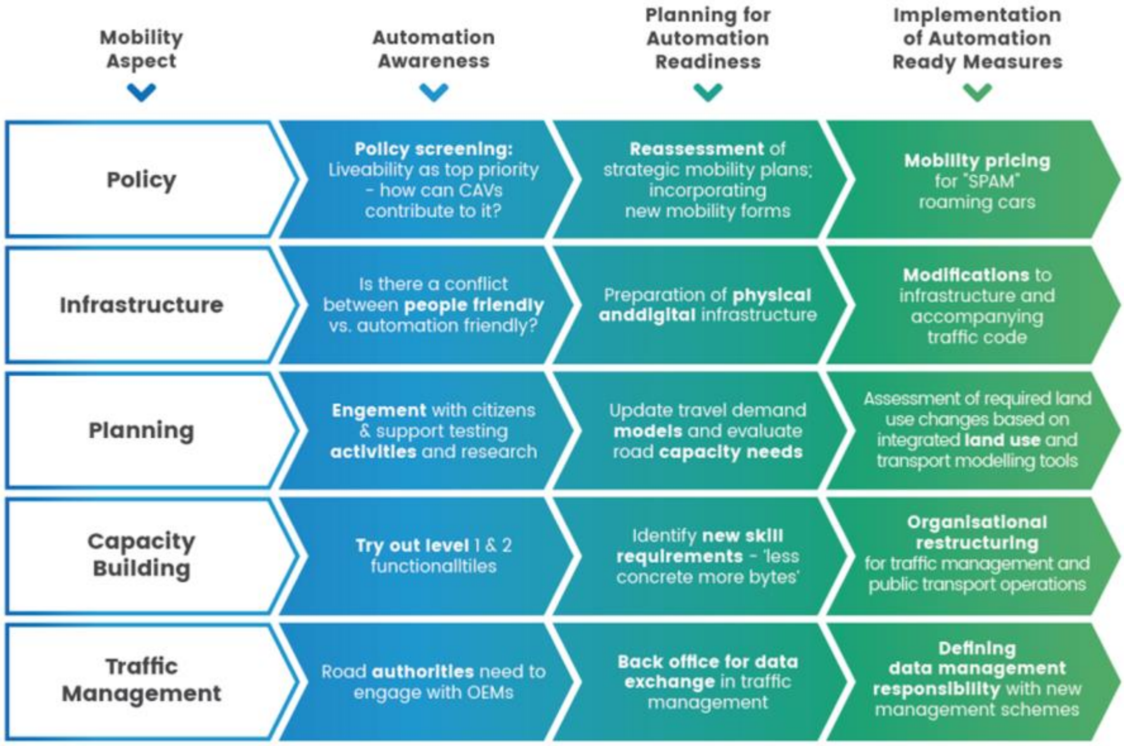

Fig. 5 Overview of three phases towards automation-readiness with examples of measures

7. Findings from stakeholder consultation workshop

The TransAID project has organized multiple stakeholder consultation workshops to advance on the topics presented above. The workshops aimed to gather feedback on the project results, as well as to hear the stakeholders' view on the impact of prospective automated vehicles introduction. Most importantly, the stakeholders were asked about their ambitions and interests related to role and responsibilities in future scenarios of automated vehicle presence. The most relevant stakeholders are authorities and policy makers, road operators, vehicle manufacturers and suppliers, road infrastructure and traffic service providers, test and certification institutes, academia and knowledge institutes, future product owners and standardization bodies. A selection of findings from these workshop is given below.

7.1 Road authority perspective

Infrastructure support and traffic management for vehicle automation generally is positively received by road authorities. However, they point out that there is a need of increasing infrastructure capabilities (sensing, computing and communications) to take the most advantage measures in a dynamic way. All stakeholders fully agree that connectivity is needed for higher levels of automation. In addition, it would require big efforts to digitalize road infra and dynamic (traffic management) schemes. Due to the effort required, the services might not be feasible in the short term in urban scenarios. Therefore, it makes sense to start on motorways and then consider applicability to urban roads.

The role, tasks and responsibilities of different stakeholders, both public and private, was highlighted as an important topic. Most of these which exist today are likely to exist in the future, therefore need to be considered in the ODD space appropriately. On the one hand this implies that automated vehicle systems might be enabled by road authority and infrastructure actions, while on the other hand it must remain feasible to inform and regulate (automated) vehicle systems. Moreover, when factors and systems external to the vehicle, like digital and physical infrastructure, would become an integrated and trusted part of the ODD, this will pose new reliability and liability issues that need to be understood.

In the future, dedicated lanes for automated vehicles could be considered as an incentive for automated driving to reach long term goals of safety/efficiency. However, due to possible reduced capacity (blocking a lane for remaining traffic), it is best to use dynamic assignment which takes into consideration the traffic composition. However, at the beginning and end of dedicated lanes there is a likelihood for a transition area which could need an additional form of support measures.

Finally, the topic of liability and regulation was raised frequently. It was acknowledged that there is the need to adapt traffic rules for automation, for example, to differentiate speed/relevance areas for different categories of vehicles. In addition, infrastructure must be authorized by road authorities to provide advice (that possibly break traffic rules) in a fast dynamic way or be mandated for recurrent situations.

7.2 Operational Design Domain

One cannot expect that automated vehicles will solve all possible situations in the future via algorithms and/or machine learning. The ODD will always have limitations for the foreseeable future. Defining this ODD is very complex, has a lot of parameters and it is necessary to create a common understanding of the concept. Cities expressed high interest in getting insights into the ODD restrictions of the OEMs and to define criteria for ODDs. Some form of ODD should be shared between road authorities and OEMs. Moreover, the definition of the ODD should be a joint effort. A frequent topic of discussion was the variables and their units and scales that could enable describing the ODD systematically. This would enable stakeholders to interpret the ODD in the same way and to plan actions that could contribute to a more continuous ODD.

There is much interest to understand the attributes of the ODD. In other words, the factors that make or break the vehicle’s ODD. Examples of ODD attributes are: road, speed range, shoulder or curb, road markings, traffic signs, road furniture, traffic, weather conditions, digital map, positioning, connectivity, information systems, etc. Discussions on this topic revealed that there are many differing perspectives to most ODD attributes and that each contains many sub-attributes. Interestingly, for various attributes the discussion could go into two directions. One being the assumption that ODD attributes are requirements from vehicle automation systems to their environment to enable automation. The other being the assumption that vehicle automation systems should be capable to handle most ODD attributes, hence the attributes are a requirement to the vehicle automation system. For example, high quality road markings could be seen as an enabler of automation, but reversely vehicle automation systems must also be able to cope with poor road markings.

Also the interdependency of ODD-attributes was discussed and there was generally consensus that few attributes are fully independent, which implies that some elements of operations is enabled by multiple attributes and that some attributes are interchangeable. Considering the interchangeability of attributes, or in other words the complementarity of attributes, it was suggested that it is needed to look more closely at driving tasks of the vehicle automation system as opposed to use cases. For example longitudinal and lateral driving tasks. This allows to better isolate the required capabilities of the automation system and to identify the functions of this system and their needs in order to execute the driving task. Such an approach may prevent that the importance of ODD attributes is overestimated or underestimated, which is something that easily occurred while discussing them and a single attribute was put in the spotlight.

Finally, it was signaled that some kind of trade-off exists between the complexity of the vehicle environment, the vehicle ODD and the vehicle's driving performance, like the driving velocity. Instead of assuming that an automated vehicle system is in or out its ODD, as a binary variable, the driving performance of the vehicle might be adapted in such a way (e.g. reduce velocity) that the automation system can cope with the situation at hand, therefore remains in its ODD. This means that the precise situational and environmental conditions of the automated vehicle are decisive when describing the ODD of use cases. Which in turn reveals the sheer contrast between a desire to address specific conditions (e.g. causes for disengagement and takeover requests) on the one hand, and on the other hand the inability to be exhaustive in terms of situational, environmental and other ODD characteristics (i.e. an infinite number of conditions). Clearly, a different perspective or more abstract compromise is needed.

7.3 Conceptual structure for ODD

Based on the stakeholder consultation workshops, a summary of the dimensions to the operational design domain of automated vehicles was made and is shown in Figure 6. This figure is a first attempt to take a broader perspective and to acknowledge the interrelation of the seven dimensions that are shown. Each is discussed briefly below.

- **Vehicle automation capabilities**: these are typically the well-known automation levels defined by SAE in J3016. On a more detailed level these capabilities resemble the driving tasks (e.g. longitudinal and lateral control) and related functions (e.g. perception, planning and execution) that will or will not be performed by the vehicle automation system, depending on the automation level.
- **Scene**: a description of the driving environment and the extent this environment is controlled, semi-controlled or uncontrolled. Access (restricted, shared, open), intersections (cross traffic yes or no) and behavior (homogeneous or heterogenous behavior of other road users) are the three key areas to be considered, which are further described in section 4 of this paper.
- **Physical infrastructure measures**: these are typically road-related attributes such as road surface, road markings, traffic signs and signage, physical separators, road furniture, etc. The insert in Figure 6 shows an example of level crossing barriers, which creates a different scene for the automated vehicles on this particular track.
- **Digital infrastructure measures**: these are typically associated with infrastructure-to-vehicle communication services that can provide information, warnings and regulations to vehicles on the road. It also includes roadside sensing, cooperative perception, digital maps and dynamic digital information. Much of these are covered by the ISAD levels, which are described in section 5 of this paper.
- **Situational / environmental conditions**: traffic situations or scenarios that vehicles may encounter can be categorized in planned (or recurring) versus unplanned (or non-recurring) cases that occur at fixed locations versus any location. They might be caused by factors like traffic, incidents and weather conditions, but also road layout (e.g. gradient and curvature), obstructions blocking vision, light, etc.
- **Geofenced areas / roads**: ideally the operational design domain of vehicles can be specified using geofences, road type or similar. Through elimination of aspects, some manufacturers and developers (like Ford and Lyft, see inserts) have limited road networks to automation eligible routes. The main challenge is that unforeseen scene, situational and environmental factors can never be ruled out completely, therefore it is difficult to constrain the vehicle automation capabilities to a geographical area, unless the vehicle manufacturer can safely deal with any scenario within that area.
- **Vehicle / system operational performance**: vehicle automation capabilities are often evaluated against safety criteria only. However, operational performance expressed by travelling comfort, the driving speed (and thereby the travel time), number of stops, number of handovers of control, number of minimum risk maneuvers, etc. deserves attention too. On the one hand they can be observed when the state-of-the-art is deployed in real-world situations, while on the other hand a good understanding of the expectations (or minimum requirements) of the vehicle or service performance is a necessity.

The assumed interrelation of these dimensions is such that if a vehicle automation system fulfills certain driving tasks in a given scene and under particular situational and environmental conditions, this results in some operational performance. As the driving conditions change, the vehicle automation capabilities may be supplemented by physical and/or digital infrastructure measures in order to maintain the same level of operational performance. Alternatively, the vehicle operational performance may be degraded, for example by reducing the driving velocity, to allow the vehicle automation system to safely deal with a traffic situation without initiating a takeover request. However, not every road or situation is suitable for degrading the vehicle operational performance, therefore the operational performance may become an explicit requirements to the automation capabilities. It are these dynamics of these seven dimensions that needs to better understood and commonly agreed.

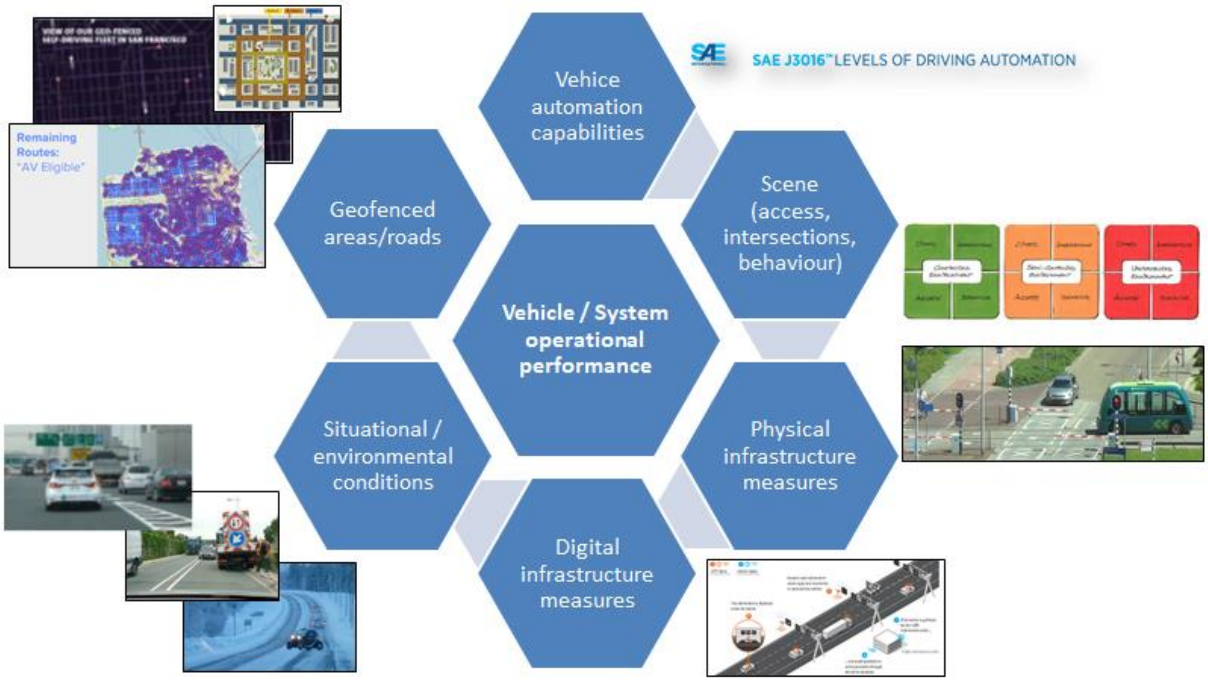

Fig. 6 Conceptual structure for operational design domain based on 7 dimensions

8. Guideline for managing Transition Areas (and ODD)

The TransAID project is developing digital infrastructure and dedicated traffic management strategies to assist connected automated vehicles in better anticipating the end of their operational design domain, i.e. to transition areas ahead, and preserve a safe and smooth traffic flow. In the summer of 2020, the TransAID project will publish a 'how-to' guideline and roadmap for road authorities and/or service providers for dealing with automated driving in the urban environment in general and in Transition Areas specifically. It will contain concrete required activities and possible road infrastructure modifications that local authorities can undertake, to anticipate or facilitate the introduction of automated driving. TransAID strives to describe how an intelligent and digital infrastructure can accommodate the introduction of automated driving, also when the entire spectrum from vulnerable road users to conventional vehicle to highly automated vehicles co-exist. The roadmap will include recommendations for steps to be taken by policy-makers, OEM's, infrastructure systems providers, standards-development organizations among others.

The preparation of the guideline and roadmap will be preceded by a meta-analysis of simulation and field study results, as well as stakeholder consultation workshops of which first findings were described in this paper. More workshops will take place in the coming year. This activity is performed in close cooperation with other H2020-projects working on the topic of digital and physical infrastructure: ARCADE, INFRAMIX, CoExist and EU European ITS Platform (EIP).

As a summary and preliminary outlook, the guideline and roadmap of the TransAID project will include recommendations in the following areas:

- **Information services** for automated vehicles.
- **Traffic control measures** for automated driving.
- **Traffic regulations** for automated driving.
- **Spatial planning** for automated driving, MRM-havens specifically.

- Application of **V2X message sets** and proposed extensions.
- Requirements for **roadside equipment and signaling**, for all vehicle modes.
- **Urgency** of interventions based on market penetration (mixed traffic) forecasts.
- **Priority** of interventions based on situational characteristics.
- Actor **roles and interaction models** for automated driving and traffic management.

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