Road infrastructure support for highly automated driving

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Introduction

Automation is advancing fast in road vehicles and already extending to the higher levels of automation. Currently vehicles with an SAE level 4 (SAE 2021) Automated Driving System (ADS) vehicles are increasing being used in cities in the USA, China and other countries for robot taxi or public transport services. In the near future, Level 4 ADS-equipped vehicles will likely be available in the consumer markets.

A level 4 ADS is capable of operating the vehicle without any human vehicle occupant intervention within its Operational Design Doman (ODD). ODD means the set of conditions in which each driving automation system is capable of performing the dynamic driving task. ODD is defined in SAE (2021) and further explained by BSI (2020). When a level 4 ADS is approaching the end of its ODD, it alerts the vehicle occupant of the exit and requests the occupant to take over the control of the vehicle. If the occupant does not take control of the vehicle, the ADS carried out a Minimal Risk Manoeuvre (MRM). The transition of control can be facilitated if the driver is given a prior alert to pay attention to the driving environment and if sufficient time is available before the intervention is necessary. Naturally the driver can later re-engage any ADS when its ODD conditions are satisfied. Level 4 systems do not require any human intervention but are (by definition) able to perform fallback to achieve a minimal risk condition (stopped and stable) by themselves. (Khastgir et al, 2023)

Several types of ADS exist as listed e.g. by ERTRAC (2024) for different types of road environments including parking facilities and confined areas such as ports and terminals. This article focuses on open roads and streets. It should also be noted that any vehicle can include one or more ADS, and that the ODDs of the two or more ADS in the vehicle might well be quite different from each other.

Why is road infrastructure support needed?

Before 2015, the common belief was that automated driving systems will be able to operate on the same roads where human vehicle drivers can operate their vehicles. The vehicle sensors were capable of outperforming the human senses in some aspects and the AI developments showed much promise. When the level 2 advanced driver support systems were introduced in the market and higher level ADS were being piloted, the ADS community came to the conclusion that ADS would benefit from road infrastructure support. This resulted in attempts to assess the support needs by e.g. Austroads (Germanchev et al., 2019), the INFRAMIX project (Lytrivis et al. 2019), CEDR (Ulrich et al., 2020; DIREC 2023), the Finnish Transport Infrastructure Agency (FTIA 2021), and the European Commission (CCAM WG3 2021). This article sums up the learnings from the work carried out so far.

Firstly, infrastructure support is needed for providing the ODD for the ADS. It is clear that well visible lane markings are a key part of the ODD of a lane keeping system, for instance. Even if such are not available but the ADS is supported by accurate positioning infrastructure, highly accurate digital maps, and necessary landmarks, can provide the necessary ODD for higher automation level lane keeping. The infrastructure support is most important to ensure the continuity of the ODD. Few car buyers are willing to buy a vehicle with an ADS the ODD of which would be very fragmented requiring high number of control transfers between the ADS and the human driver. Thereby the Hi-Drive (2024) project of European vehicle manufacturers has as its main objective the "defragmentation of the ODDs" (Bolovinou et al., 2023).

Second, infrastructure support is needed for providing awareness of the ODD for the ADS. This is especially important when the range of the vehicle sensors does not extend to the vehicle route ahead foreseen for the safe enough length for the transfer of control to the vehicle occupant in case of an ending ODD. 10 seconds could be a safe enough transfer of control period but at a speed of 100 km/h the vehicle will move more than 300 m which extends beyond the range of current vehicle sensors. If the ADS do not know the values of all of its ODD attributes within the critical time period (e.g. the 10 seconds) of the journey, it has to carry out the MRM. If the ODD attribute values of the route ahead can be provided by the road infrastructure and the data is accepted as reliable enough, the ADS can proceed its operation.

Hence, the ODD attribute value awareness support is extremely important on high-speed roads. Thereby it is not surprising that the robot taxis are first major level 4 ADS service covering several low-speed city areas in the USA and China (Bishop 2022).

Thirdly, infrastructure support may be necessary for facilitating automated mobility services. A good example is the provision of safe and secure pick-up and drop-off points for both passengers and goods. These are necessary for robot taxi, public transport and delivery services.

Types of infrastructure support

There are three types of road infrastructure support: digital, physical and operational infrastructure support. Furthermore, communication and positioning infrastructure support are essential to the safe ADS operation.

The digital infrastructure contains primarily the digital representation of the road infrastructure and its users i.e. traffic. The physical infrastructure includes the road and its devices as well as the physical environment of the road. The operational infrastructure contains the systems, tools and facilities for operating the maintenance and management of traffic, incidents, road works etc.

The European Commission (EC 2021) and CEDR (Kulmala et al. 2020) concluded that due to the large costs and long life-cycle of physical infrastructure changes as well as the major benefits of the so-called "no regret" actions on digital infrastructure, the emphasis of road infrastructure support investments by road operators should focus on digital infrastructure.

Digital, communication and positioning infrastructure

The different attributes of digital, communication and positioning infrastructure are addressed below.

HD maps

The digital map providers are providing the HD maps also for the use by ADS, but the major issue has been the updating of the content as the road and its environment are changing continuously. The European Commission's regulation on the provision of EU-wide real-time traffic information services regulation declares that "accessibility and regular update of data by road authorities and road operators are essential for enabling the production of up-to-date and accurate digital maps that are a key asset for reliable ITS applications." It also encourages digital map providers to timely integrate relevant data updates into their existing map and map update services. Furthermore, it is stressed that digital map providers and service providers should collaborate with public authorities to correct inaccurate data in order to comply with public policies on road safety. (EC 2022)

The updating of the HD maps requires close cooperation with the operators of ADS-equipped fleets.

Digital models, shadows and twins

The road operators are currently developing different digital representations of their infrastructure to serve their own processes while these will certainly be useful for supporting ADS either via their fleet operators or via HD map content. According to the state of the art of these digital representations (Soni et al. 2024) in 2030, digital shadows of the road infrastructure as well as traffic status will be available in many European countries.

Today, many road operators and traffic managers are providing real-time information on incidents, roadworks, events, traffic volumes, speeds and travel times on parts of their road network as open data focusing on the parts with most transport problems. The basic issue with the use of such data is that the ADS developers do not trust the data from road operators and traffic managers sufficiently enough to utilise it in their decision making (Kulmala et al. 2023).

Digital/electronic rules and regulations

The general rules of the road and specific traffic management related regulations such as traffic sign information including dynamic speed limits, temporary weight and dimension restrictions, and urban vehicle access regulations as well as traffic circulation and management plans are to be provided by EU member states according to the Commission delegated regulation on real-time traffic information (EC 2022). This will definitely support the ADS if regarded as reliable enough by the vehicle and ADS industry.

Communication infrastructure

The basic assumption of the automated driving community is that safety-critical information to the level 4 vehicles will be provided as C-ITS (Cooperative ITS) messages. This means that C-ITS services and infrastructure must be in place. With regard to infrastructure, the national coverage by cellular networks can be complemented by hotspot coverage of short-range communications (ETSI ITS-G5 or C-V2X). The recent study by Kilpiö et al. (2024) shows that the existing 4G networks already provide the required C-ITS communication infrastructure in almost all situations in Finland with regard to service availability, reliability and integrity.

Positioning infrastructure

The basic solution for positioning is satellite positioning with four global satellite systems in place. GPS positioning has long been used supported by a few land-based support systems. The cm level accuracy can be reached even in northern Finland via investment in land stations. However, the GALILEO HAS (High Accuracy Service) is expected to provide the necessary positioning accuracy with the basic service already providing <20 cm accuracy (EUSPA 2024).

Physical

The different attributes of physical infrastructure support are discussed below.

Dedicated lanes or roads

The allocations of specific lanes or roads for highly automated vehicles has been proposed to fully utilise the safety and efficiency benefits of automated driving. It is likely socio-economically feasible only when the majority of the vehicles on the road have Level 4 ADS.

Lanes

The basic demand is that the bearing capacity of the lanes needs to be sufficient for truck platooning, for instance allowing platoons of three trucks moving with headway of 15 m.

The lanes could be made narrower than today when all or most vehicles are highly automated, but this could cause increased rut formation that needs perhaps to be addressed via "artificial tyre wander" where vehicles adapt their lateral position in order not to drive along the same trajectories.

Machine readable road markings and signs

Lane marking retro-reflectivity is recommended to be at least 100 mcd/lx/m2 on a dry road and the luminance contrast ratio larger than 2:1 for SAE level 2 lane keeping systems. It is also important that there are no contradictory markings. Thereby after road works e.g. repaving, new markings should be done without delay and temporary markings totally deleted. The importance of road markings will likely decrease when most vehicles have Level 4 ADS.

Shoulders

Shoulders are important for minimal risk manoeuvres, which means they should be wide enough to provide a safe place to park the vehicle safety. On motorway carriageways, an outer shoulder at least 2 m wide and an inner shoulder at least 1,25 m wide could be sufficient.

Lay-bys and rest areas

Such areas may be useful for truck platoon formation as well as minimal risk manoeuvres.

Road surface condition

The requirements on major highways do not differ from the current ones including no potholes nor major damages, and at most 20 mm rut depth. The quality of maintenance operations may need to be enhanced.

Road infrastructure elements to support positioning including landmarks

It is likely that on roads in monotonous surroundings and in street canyons affecting satellite positioning landmarks will likely be required to provide additional positioning accuracy to satellite positioning. The details of the landmarks will need to be investigated further.

Pick-up/drop off facilities

Specific passenger or goods pick-up and drop-off facilities are needed for various automated mobility services. These facilities need likely to involve spaces for passengers waiting for their rides and to have shelters against the elements such as rain and snow. The facilities likely require transforming some streetside parking spaces into such facilities. In central business areas of cities such should exist in each block.

Parking facilities

While it is still too early to know how personal mobility will change due to self-driving or driverless vehicles, changes in parking facilities can be expected. In any case, the on-demand public transport vehicles and robot taxis need parking facilities while waiting for their next ride. The facilities itself need to be planned to accommodate fully automated parking as well as the battery charging of vehicles – the basic assumption is that the Level 4 vehicles will be electric.

Passive infrastructure for communication and positioning infrastructure

It is likely that some supporting infrastructure for communications and positioning are needed in specific locations such as tunnels.

Operational

The operational infrastructure includes the tools, systems and services to operate and maintain the road transport infrastructure and transport system.

Monitoring of traffic conditions

The continuous monitoring of road, traffic, and environmental conditions is essential for maintaining the digital shadow of the road transport system. The current monitoring systems do not usually meet the quality requirements of highly automated driving especially with regard to road network coverage as the fixed monitoring stations are located typically kilometres apart. The improvement of the monitoring systems by vehicle sensor data along the whole network is the logical solution, which can be implemented due to fleets of ADS-equipped vehicles themselves.

Maintenance of road infrastructures

All types of road infrastructure need to be maintained to keep up their ability to facilitate transport services including automated mobility. Winter maintenance facilitates automated mobility by removing ice and snow from the roads and by preserving sufficient road surface friction, while the other road maintenance repairs damages and wear from road surface and structures as well as removes vegetation obstructing vision and visibility of road sings. Also, the digital and operational infrastructure systems and devices need to be maintained.

Traffic management

The safe operation of the ADS requires firm knowledge of the "rules of the road" concerning the road section used. Traffic management centres have a dominant role in setting and managing such rules via their road, junction, bridge and tunnel traffic management systems. In the future, the traffic management centres need real-time information from ADS fleet operators about any MRMs occurring on their network as well as the ODD attributes behind the loss of the ADS' ODD in order to be able to a) react to the possible safety risks caused by the MRMs and b) to commence any actions to remedy the relevant ODD attribute situation.

Access control and geofencing

The ADS fleet operators and managers use geofencing or other related tools to ensure that their ADSs are operated on only such roads and areas for which they are designed. Naturally, the road and street authorities can also utilise access control tools to distinguish parts of the road transport system, where level 4 ADS of specific types can or cannot be used. The access control can also be quite dynamic to take into account the occurrence of incidents, events and other situations disturbing the operation of the road transport system and the use of ADS.

Local traffic management

Roadworks, incidents and events may well lead to situations, where parts or all of the road carriageway are temporarily blocked from normal use. It is important that the local traffic management measures for guiding the vehicles safely past the road sections having such situations are carried out in a manner interpreted correctly also by the ADS via the vehicle sensor data input. This calls for full compliance to the local traffic management, signing and road marking standards.

ODD attribute value awareness provision

According to the results of CEDR's TMCAD project (Khatsgir et al. 2022), the DOVA (Distributed ODD attribute Value Awareness) concept should be implemented for safe operation of highly automated driving. The DOVA 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 by itself. 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 information for some of the ODD attributes could be available via infrastructure, there may potentially be commercial services which can augment ODD information for the ADS. (Khastgir et al. 2022)

Fleet management including remote management

For a number of automated mobility services, fleet management and operation is an integral part of the service as the service is best operated with a fleet of ADS-operated vehicles rather than a single vehicle. The fleet manager is responsible for the correct and safe operation of the ADSs of its fleet and can respond to requests for assistance from the passengers or the ADS. The assistance will likely be provided remotely by giving instructions on what to do and how to proceed. The fleet managers will also provide their ADSs updates of the HD map information, rules of the road, real-time digital shadow of the road transport status, etc.

C-ITS service provision

In order to receive safety-relevant warnings, collective perception and other C-ITS messages, a stakeholder must exist to send such messages to the ADS. Such service providers exist only in a few countries today.

Governance of infrastructure support

The infrastructure support will typically be governed by the stakeholder owning and managing the infrastructure in question. Table 1 provides a possible governance of the infrastructure support earlier described.

The governance of some new operational infrastructure elements such as distributed ODD attribute value awareness provision and C-ITS service provision is still quite open as many alternatives exist and no commonly agreed European governance models exists so far.

Table 1 Tentative governance of the infrastructure support elements

Road infrastructure support element	Governor of the element
Digital infrastructure	
HD maps	Digital map providers, vehicle manufacturers
Digital models, shadows and twins	Depends on use case
Digital/electronic rules and regulations	National road transport regulatory agencies
Communication infrastructure	Communication network operators
Positioning infrastructure	National positioning agencies
Physical infrastructure	
Dedicated lanes or roads	Road operators
Lanes	Road operators
Machine readable road markings and signs	Road operators
Shoulders	Road operators
Lay-bys and rest areas	Road operators, rest area service providers
Road surface condition	Road operators
Positioning support including landmarks	Road operators, national positioning agencies
Pick-up/drop off facilities	Road operators, cities
Parking facilities	Road operators, cities, mobility service providers
Passive infrastructure for comms and GNSS	Road operators, Cities
Operational infrastructure	
Monitoring of traffic conditions	Road operators, traffic managers
Maintenance of road infrastructures	Road operators, traffic managers
Traffic management	Road operators, traffic managers
Access control and geofencing	Road operators, traffic managers, fleet operators
Local traffic management	Road operators, traffic managers, police, rescue
ODD attribute value awareness provision	Fleet operators, traffic managers, service providers
Fleet management incl. remote management	Fleet operators
C-ITS service provision	Service providers, PPP

Costs of infrastructure support

AS stated earlier, the level 4 ADS can not likely operate on the existing road networks without a need to transfer vehicle control back to the human vehicle occupant quite frequently. To make the continuous ADS operation possible i.e. to provide a continuous ODD for the ADS requires support from the infrastructure. There is a cost issue involved here: the existing road infrastructures do not provide the required structure without enhancements., which in turn cost money and other resources.

The Finnish study (Finnish Transport Infrastructure Agency 2021) proved that on a modern motorway the physical infrastructure does not require any specific investments additional to what needs to be done in any case to maintain the infrastructure.

The key cost additions will likely result from investments in digital infrastructure. HD maps and digital shadows require considerable investments to develop and especially to maintain them updated in real time. The 5G/6G communications and Galileo HAS infrastructure will likely be deployed and maintained driven by other domains than transport, although specific short-range communications and positioning support infrastructure may need to be deployed at key hot spots of the road and street networks.

For many aspects of the operational infrastructure, the provision of infrastructure support to level 4 ADS likely means strict compliance to standards and higher quality level of operations compared to the situation today, which will increase costs. It is clear, however, that also the ADS fleet operators carry a part of these costs by providing vehicle sensor based data to improve the situational picture facilitating the operation infrastructure functions and by complying to the guidance from the operational infrastructures.

The magnitudes and stakeholder allocations of the costs for ODD attribute awareness provision, fleet and remote operation centres, and C-ITS service provision are still unclear due to lack of longtime service provision.

Conclusions

During the last decade we have moved from the general agreement that driverless or self-driving vehicles can operate wherever human-operated vehicles can to the agreement that such automated vehicles need considerable infrastructure support, especially on high-speed roads. Vehicle sensors and software including AI are developing fairly quickly, however. This might mean that after the next 10 years, the self-driving vehicles need much less support than now foreseen. Thereby it is wise to make “no regret” investments that in addition to providing infrastructure support to self-driving vehicles will also benefit all other road users as well.

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