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Assessment of physical road infrastructure to support automated vehicles in an urban environment

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Abstract

When discussing the implementation of automated driving systems, multiple factors need to be considered. Yet, a major factor is technical reliability which strongly depends on the consistent functionality of automated driving systems under varying road infrastructure. Most research (Galileo4Mobility (2018); ADAS&ME (2020); AUTOMATE (2020)) focuses on technical challenges and does not investigate if and to what extent physical road infrastructure (PI) contributes to safe automated driving.
This paper presents the results of the EU project SHOW concerning the PI's role on automated driving in an urban environment. The most relevant PI elements, including lane markings, traffic signs and sight distances are investigated, leading to PI requirements and recommendations for adaptations. A software tool for assessing the automation readiness of a test site with regard to PI is also described.

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Keywords: Automated Driving; Physical Road Infrastructure; Traffic Safety; Urban Automated Mobility;

1. Introduction

As urban automated mobility is expected to be ready for road use in the next decade, further developments are needed to guarantee a fully operational system to provide safe interactions between automated vehicles and the physical road infrastructure. Current research (for instance Galileo4Mobility (2018); ADAS&ME (2020); AUTOMATE (2020)) on automated driving focuses more on the technical challenges of automated driving systems and does not investigate if and how the PI affects automated vehicles and their safe operation.

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This paper presents the methodology and results to address current open questions regarding PI in the context of automated driving to vehicle providers and researchers working on optimizing physical infrastructure for AVs or on the development of HD (High Definition) maps, as part of the H2020 (Horizon 2020) project, SHOW (Shared automation Operating models for Worldwide adoption). SHOW aims to support the deployment of shared, connected and electrified automation in urban transport, to advance sustainable urban mobility (SHOW (2021)).

It is difficult to separate physical and digital infrastructure. While digital infrastructure requires physical infrastructure e.g., to fix sensors on PI assets, many safety challenges associated with physical infrastructure could be overcome with digital infrastructure (e.g., if the sight distance is limited due to PI elements, it can be expanded via V2X (vehicle to x) communication). For the purposes of our work, physical infrastructure elements were defined as follows: road type, road markings, traffic signs, shoulder or kerb, road furniture (Erdelean et al. (2021)).

This paper contains three main sections. The first part synthesizes the findings of an extensive literature review and analysis of stakeholder consultations. The second part presents quality criteria for assessment of physical road infrastructure's role on automated driving, while the third part describes the development of a software segmentation tool to be used by AV test site managers and operators for urban automation mobility site readiness.

2. Literature review and stakeholder consultations results

An extensive desk research was performed across state-of-the-art literature to identify the requirements for physical infrastructure adaptations for automated urban mobility. More than 60 ongoing and completed EU projects, funded under the H2020 funding frame, as well as national initiatives and projects, conference and journal papers were reviewed to investigate the role of PI in automated mobility. Furthermore, a comprehensive literature review was performed to analyse the quality requirements for PI that are necessary for automated driving with regard to safe operation including the visibility and detectability of lane markings, traffic signs and sight distances.

To complement the literature review, an in-depth consultation with urban automation vehicle manufacturers and managers of national and EU projects on automated mobility as well as managers of urban automation pilots was conducted. Questions included, but were not limited to: (i) how was the physical road infrastructure taken into account when preparing pilot tests, (ii) what physical infrastructure elements are considered relevant for the planning of urban automated mobility test sites, (iii) how could infrastructure elements impede the vehicle's operation, (iv) how do the following infrastructure elements influence the vehicle's operation: lane markings, traffic signs, sight distances, slope, road works, road surface etc.

2.1. Lane markings

Lane markings are used to delineate the roads, separate opposite traffic streams and to divide the road area for different road users. They include longitudinal and transverse markings, arrows, text and symbols markings. Lane marking detection (for AV sensors) is influenced by a series of lane marking parameters (Austrian Standards (2018)).

Luminance coefficient (Qd): Daytime dry luminance coefficient is a key factor for lane marking visibility. An object on the road is identified if a sufficient contract exists between the light reaching and reflecting from the object surface and the road surface (Casol et al. (2008)). Austroads (2020) states that the reflection in daylight or under street lighting has limited impact on machine vision performance when other parameters are consistent and at acceptable levels.

Retro-reflectivity (RL) is the capacity of a road marking to reflect light from a vehicle's headlights back to the driving position of a vehicle. RL of pavement markings is also a proxy for night visibility. Pavement markings with a low retro-reflectivity due to ageing, tend also to score low in factors related to daylight visibility (Hadi et al. (2007)).

Lane marking (line) width supports the detection of lane markings on the road surface. Wider lines aid AVs to distinguish between real lane markings and other markings on the road, such as tyre marks or tar seams. A minimum line width of 100 mm is recommended, as are wider line widths (150 mm) to support machine-vision-enabled, lane-guidance functions. When the visibility of pavement markings is good for both RL and Qd, pavement marking line widths, longitudinal lines, whether 100 mm or 150 mm, may be read by machine vision systems with a similar level of success (Austroads (2020)).

Lane colour does not provide relevant information for lane marking detectability. However, even though yellow-coloured lanes are well detected by AVs, the combination of solid white lines and yellow lines can be disruptive for lane keeping functions.

Line spacing, such as dashed lines and exit diverge triangles were identified as having an impact on lane-guiding functions. Automated driving (AD) systems detect solid lines better than dashed lines, although the impact is speed based as well as dependent on the quality of the lane marking.

Lane width influences the detection of lane markings, if the width is less than 3.0 meters, particularly if the narrow lane has no edge lines. Higher lane widths can affect system's detectability, i.e., vehicles can lose lane keeping functions, while narrow lane widths (smaller than 2.5m) can cause system disabling in order to prevent the vehicle bouncing of lane boundaries (Austroads (2020)).

2.2. Traffic signs

Vertical signs are signs situated along the road to inform drivers of road conditions and restrictions along their route. They constitute a source of information and thus, they are designed to stand out of the surroundings. Traffic sign recognition is an important feature for AVs, especially in mixed traffic. In Europe, traffic signs are standardised through the "Vienna Convention on Traffic Signs and Signals", although there is still a significant variation of traffic signs across countries (United Nations Economic Commission for Europe (2008)). Various shapes are used to categorize different categories of signs: circular shapes represent prohibitions, triangular shapes represent warnings and rectangular signs are used for recommendations or information (Møgelmose et al. (2012)).

Several factors characterise and influence the detection of a traffic sign, such as visibility conditions, marking defects and shadows. However, divergent and inconsistent placement of traffic signs can lead to misunderstandings and while human drivers can overcome these discrepancies, traffic sign recognition systems employed by automated vehicles need to learn how to detect and categorize signs under less optimal conditions. Detection methods currently employed include shape-based, colour-based and hybrid methods (Saadna and Behloui (2017); Xu et al. (2019)).

2.3. Sight distances

Sight distances represent the distances where a driver can see another vehicle and respond accordingly. The prescribed sight length for a vehicle stopping should be observed in the directional curve. Intersections should be designed so that for the main road, the driver would have sufficient visibility to stop the vehicle before entering the intersection, while for the side road the driver should have an optimal view to be able to decide whether to cross or connect to the main road without stopping. National guidelines have been defined on the Sight Stopping Distance (SSD) and its requirements, which are dependent on perception-reaction time as well as the design speed (Arndt et al. (2010)).

3. Physical infrastructure requirements for AVs

Based on the analysis of the results of the extensive literature review and the in-depth stakeholder consultations, requirements and suggested adaptations for physical road infrastructure elements for urban automated mobility were defined. This chapter presents detailed requirements for lane markings, traffic signs and sight distances, while also providing recommendations for other physical infrastructure elements.

Lane markings provide input to several automated driving systems related to lane keeping and changing. Table 1 provides a checklist for lane markings for urban automated vehicles.

Table 1. Infrastructure requirements for lane markings for AVs in an urban environment (Erdelean et al, (2021))

Parameter	Road condition	Road elements	Threshold
Road design	All road conditions	All road elements	Clear continuous lines on both sides of the lane with no extended gaps and a consistent lane width
Work zones	All road conditions	All road elements	Halt the practice of mixing yellow and white pavement markings on construction sites
Road maintenance	All road conditions	All road elements	Remove redundant markings and phantom markings to minimize any adverse effects on lane detection Apply minimum (road markings) standards at road segments with low-quality road markings
Retro reflectivity	Dry	• Tunnels (length ± 100m) • Unsignalized intersections (intersection centre ± 50m) • Level crossing (± 50m) • Pedestrian crossing (± 25m) • Bus bay (± 25m) • Cyclist crossing (± 25m)	150 mcd/lx/m^2 (millicandelas per lux per square meter)
		• All other road elements	100 mcd/lx/m^2
Luminance coefficient (daytime)	Dry	• Tunnels (length ± 100m) • Unsignalized intersections (intersection centre ± 50m) • Level crossing (± 50m) • Pedestrian crossing (± 25m) • Bus bay (± 25m) • Cyclist crossing (± 25m)	130 mcd/lx/m^2
		• All other road elements	100 mcd/lx/m^2
Contrast ratio (daytime)	All road conditions	All road elements	Minimum 3:1 contrast ratio between longitudinal pavement markings and the surrounding substrate

While automated vehicles may receive sign information via digital infrastructure or an integrated HD map, traffic signs may still function as a landmark, aiding AVs in their localization. Table 2 provides a checklist for traffic signs for AVs in an urban environment.

Table 2, Infrastructure requirements for traffic signs for urban automated mobility (Erdelean et al, (2021))

Parameter	Road condition	Road elements	Threshold
Sign condition	All road conditions	All road elements	Traffic signs are in a good condition without any wear, that means all symbols are depicted without any damage, and there is no distortion to the physical parts of the sign
Sign position	All road conditions	All road elements	Traffic signs are placed in proper condition, without any tilting
Sign visibility	All road conditions	All road elements	Traffic sings are easily visible from the road without any obstruction (trees or other foliage or infrastructure)
Digital signs	All road conditions	All road elements	If there are digital traffic signs, they need to be readable by AV's sensors or wirelessly inform the vehicle via telematic means
Comprehensibility of signs	All road conditions	All road elements	Traffic signs are placed in logical sequences and manner without contradicting each other

Sight distances are highly relevant for human drivers to ensure road safety; therefore, roads are usually designed according to current standards for SSDs. While the reaction time of AVs may be faster than of human drivers, sight distance is a road infrastructure characteristic that should be evaluated when implementing urban automated mobility. Table 3 provides a checklist for sight distances for AVs in an urban environment

Table 3. Infrastructure requirements for sight distances for urban automated mobility (Erdelean et al, (2021))

Parameter	Arc conditions	Crossroads	Threshold
Road design	All arc conditions	All crossroads	Roads are designed according to standards and there are no abnormal design solutions that could interfere with visibility along the route
Obstructions	All arc conditions	All crossroads	If there is any obstruction along the route (tree, parked cars etc.), it needs to be checked whether it influences the visibility negatively
Reflective surfaces	All arc conditions	All crossroads	Make sure there are as little high contrast and shiny areas along the route as possible in order to prevent phantom detections by certain sensors
Intersection design	All arc conditions	All crossroads	The intersection design allows for a safe entering and/or crossing the road with enough visibility to allow the AV to detect other traffic and act upon it

Table 4 presents requirements and suggested adaptations for a wider set of infrastructure elements that can influence and affect the operation of automated vehicles in an urban environment.

Table 4. PI requirements and adaptations for AD (Erdelean et al, (2021))

PI element	Requirements and suggested adaptations
Traffic lights	Should be detected and recognised by the AVs. V2X systems should be implemented to allow communication between the vehicles and the traffic lights, for challenging traffic situations, such as roadworks.
Slope	Slopes higher than 8% would impede an AV's operation (e.g., overheating leading to vehicle stop for a cool down period, potential mechanical issues in winter conditions due to the power distribution between the wheels). Shuttles are able to drive on slopes up to 8% permanently.
Parking	Can be an obstruction to traffic signs and road markings. Moreover, parked vehicles on narrow two-way roads can stop the vehicle. Parking along the route of an AV should be prohibited or located off the actual driveway.
Roadside vegetation	Should be trimmed through maintenance or be situated completely outside the AVs sensor area, as it poses an issue for the sensors and GPS signal strength, causing unnecessary braking and stopping of the vehicle.
Roadworks	They severely impact the AV's ability to navigate autonomously, as the vehicle must deviate from the programmed path, needing manual intervention (ODD (Operational Design Domain) breakdown). If the roadwork is controlled with traffic lights, V2X communication would be necessary to ensure automated and scheduled passing. An additional issue is the dust/particles caused by the roadworks that could degrade the vehicle's sensors.
Terminals/stations	PT hubs and stations should be safely reached by the AV and are included in the vehicle's predefined path. Access for wheelchairs for public transportation is necessary.
Separation of lanes	The general recommendation is to have separate driving lanes for AVs. However, in practice, separate lanes are not a perquisite for deploying shuttle buses, as long as other requirements are fulfilled.
PI for localization purposes	PI structures can improve LIDAR (Light Detection and Ranging) localization for optimum operation, as fixed elements can also serve as reference points for vehicle localization.
Road condition	Poor road conditions influence the visibility of features such as road gradient, curvature, lane width, condition of road markings and traffic signs. Transparent, wet (mirror like surface), monotonous and light absorbent material surfaces should be avoided, as it can impede LIDAR localization. Sandy roads should also be avoided, as they can raise dust from the ground, which can be detected as an obstacle by the AVs.
Bicycle lanes	Separation of bicycle lanes from the road used by the AVs is highly relevant, either through lane markings or clearly defined on a HD map used by the vehicle.
Pedestrian crossings/facilities	Pedestrian crossings are usually included in the predefined path of the vehicle. Pedestrian paths and facilities should be separated as much as possible from the paths used by the AVs.
Tram lines/crossings	Operating AVs on streets with tram lines is possible, however crossing tram lines and railway crossing is challenging (e.g., field of vision, detection of oncoming trams/trains). Visible traffic signs, markings and clear line of sight should be ensured. V2X communication and inclusion of this infrastructure element in a HD map is also recommended.
Pavement types	Asphalt is the preferred road surface for AVs, as driving on brick or granite pavement leads to strong vibrations that can cause hardware issues to vehicles (e.g., cables can be disconnected).
Road geometry	Should be detected and recognised by the AVs themselves; in practice, the road geometry is programmed in the predefined path of the vehicle.

4. Segmentation tool

Collecting data on the current physical road infrastructure is highly relevant for the preparation of urban automated mobility deployment. To this end, a software tool was developed to provide test site operators and managers with a methodology for a quick scan road safety assessment concerning lane markings, traffic signs and sight distances. The SHOW segmentation tool is able to classify different road elements and provide test site representatives with a clear picture on the readiness of physical infrastructure for urban automation deployment (Erdelean et al. (2021)). The concept revolves around analysing individual road segments – where a road segment is defined as a length of roadway between two points with the same traffic volume and physical characteristics over the length of the segment (TRB (2010)) – and is based on guidelines defining road safety inspection (RSI) and road safety auditing (RSA) (FSV (2012a); FSV (2012b)).

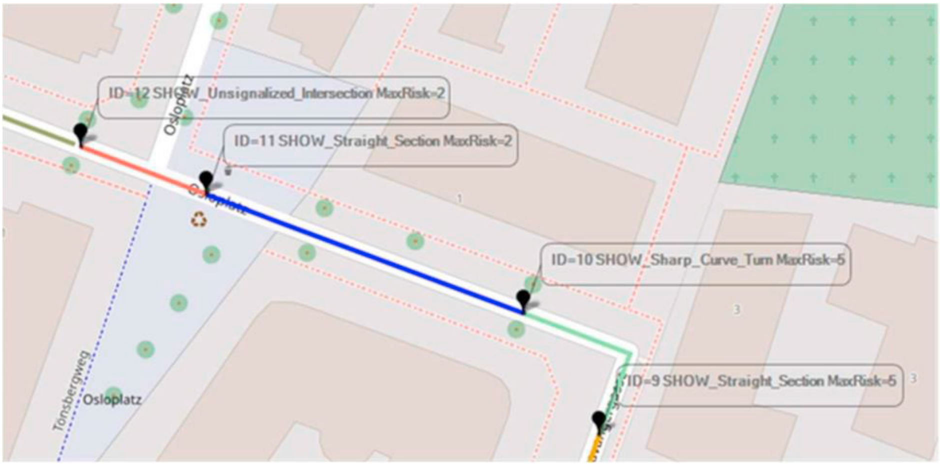

Fig. 1. Graphical representation of investigated road segments.

Figure 1 presents the outcome of the tool, which is a graphical representation of all road segments evaluated plus a hazard/risk level for each. The checklists developed for the evaluation of lane markings, traffic signs and sight distances were integrated in the software tool and used by the test site managers during the inspections of the automated test sites to allocate a risk/hazard level. The checklists allocate individual grades from 1 to 5 according to the personal assessment of the site manager. For example, if multiple phantom markings were identified on a road segment, hazard level 5 (i.e., numerous phantom markings present) was attributed to that part of the site.

The finished software tool functions similarly to routing mapping systems, i.e., the user can look through a digital map and move the display window to a specific area of interest. After filling the checklists for a specific road segment, a summary of the allocated risk levels is provided. The output displays both the individual risk per category (roadside equipment, traffic information and rules etc.) as well as the highest risk value in general. The outcome of the evaluation process is a graphical representation of all road segments investigated including the road element annotation plus the respective hazard/risk level.

5. Summary and outlook

The deployment of automated mobility will bring new opportunities to improve the safety, efficiency and mobility of the transportation systems. Vehicle manufacturers and researchers are developing and deploying automated systems that can function on today's road transport system, despite the current infrastructure. Improving and adapting the physical road infrastructure to automated vehicles could however speed up deployment, avoid costlier technology needed to overcome infrastructure challenges and increase the reliability of AVs.

This paper provides a detailed description and analysis of physical road infrastructure requirements and adaptations relevant for urban automated mobility, based on several rounds of literature reviews, stakeholder surveys and consultations. Furthermore, a software tool for the classification and assessment of road infrastructure elements for

AD to be used by urban automation site managers is presented. The analysis reveals that physical road infrastructure currently plays only a minor role in the deployment of urban automated mobility and is not considered a priority for testing automated vehicles in an urban environment. Automated shuttle solutions are aimed to be deployable anywhere without major investments from the city authorities or critical infrastructural adaptations. However, at the moment the infrastructure of most cities does not necessarily support a wide deployment of automated vehicles, beyond carefully pre-selected routes.

Nevertheless, infrastructure measures and adaptation are necessary to ensure seamless AV operation at current urban pilot sites. This includes the optimization of the road condition, improving the quality of lane markings, regular maintenance of roadside vegetation, ensuring safe access to PT (Public Transport) stations, installation of additional landmarks for the optimization of a vehicle's navigation and road and traffic sign maintenance. Furthermore, as automation will continue to be deployed at a wider scale, AVs will have to overcome several challenges related to the overall road environment:

- Occurrence of road damages, requiring road monitoring and damage maintenance, which will demand investments from infrastructure operators
- Higher speeds, which will bring new challenges in terms of localization, detection and safety
- Interaction with vulnerable road users
- Traffic events such as illegal parking, temporary roadworks and other spontaneous and unpredictable events.

While it is clear that physical road infrastructure needs to be adapted to support the wide deployment of urban automated mobility, the degree of adaptation has to be further investigated in large-scale demonstration for automated driving in the coming years.

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