Transportation Research Part E 169 (2023) 102989

Contents lists available at ScienceDirect

Transportation Research Part E

journal homepage: www.elsevier.com/locate/tre

Implications of automated vehicles for physical road environment: A comprehensive review

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ARTICLE INFO

Keywords:
Autonomous vehicles
Automated driving
Road infrastructure
Physical infrastructure
Challenges

ABSTRACT

Automated vehicles (AVs) have received intense attention in academia and industry around the world in recent years, but the imminent introduction of AVs brings new challenges and opportunities for transportation networks and built environments. It is important to understand the potential infrastructure-related requirements of AVs and their impact on road infrastructure in order to assess the readiness of the existing road network and prepare plans for future roads. This paper seeks to address what the implications of automated vehicles will likely be for the road infrastructure based on a comprehensive literature review. To investigate this issue, two broad questions were framed: What are the potential effects of AVs on physical road infrastructure; and What do AVs require from road infrastructure for safe driving. A total of thirteen key topics around infrastructure have been identified from the existing literature regarding vehicle automation that needs to be considered during either the initial phase of deployment or transition to full automation. In the light of the identified topics, the paper presents potential changes and challenges, making recommendations for future research directions to ensure a safe and efficient operation.

1. Introduction

In recent years, research and developments in automated driving technologies (e.g., sensing and artificial intelligence), as well as regulatory reforms around the world, have enabled rapid progress in the development of automated vehicles (AVs) (Bagloee et al., 2016; Campbell et al., 2010; Eskandarian et al., 2021). Simply defined, automated driving technologies allow for the transfer of some or all driving responsibilities from a human driver to a computer-based system (SAE International, 2021). Automated driving, together with electrification and shared mobility, is currently recognised as one of the three ongoing revolutions in road transportation (Huggins et al., 2017; Jaller et al., 2020), although there is some controversy. AVs have the potential to enhance people's lives in a variety of ways, including increasing accessibility of people with limited ability of transportation provisional, reducing parking demand, reducing travel time and transportation costs, and reducing fuel and emissions consumption (Bagloee et al., 2016; Eskandarian et al., 2021; Fagnant and Kockelman, 2015; Gavanas, 2019; KPMG, 2012; Shladover and Bishop, 2015). More importantly, AVs have

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https://doi.org/10.1016/j.tre.2022.102989
Received 8 March 2022; Received in revised form 31 October 2022; Accepted 5 December 2022

the potential to improve road safety by eliminating some accidents caused by human error such as driving too fast, driver distraction and fatigue, although their expected benefits are essentially untested (Ye et al., 2021) and are largely speculative as new types of accidents may emerge from this huge paradigm shift (Robinson et al., 2017). On the other hand, the literature points out some of the potential negative impacts of AVs, such as security and privacy concerns due to the risk of cyberattacks, or congestion due to the increased vehicle miles travelled caused by the attractiveness of vehicle use and empty trips (Bagloee et al., 2016; Currie, 2018; Litman, 2020; Soteropoulos et al., 2019; Tengilimoglu and Wadud, 2022; Makridis et al., 2018).

In short, advances in vehicle and information technology has increased research into impacts of AVs on many aspects: e.g. travel behaviour (Ashkrof et al., 2019; Gruel and Stanford, 2016; Harb et al., 2021; Wadud, 2017; Wadud and Huda, 2019; Zmud and Sener, 2017), traffic flow and operation (Mahmassani, 2016; Mesionis et al., 2020; Do et al., 2019), urban form and land use (Chapin et al., 2016; Gavanas, 2019; Malysheva, 2020; Stead and Vaddadi, 2019), emission and energy use (Kopelias et al., 2020; Wadud et al., 2016), policy and legislation (Fagnant and Kockelman, 2015; Litman, 2020; Milakis et al., 2017), safety (Robinson et al., 2017; Peiris et al., 2020) etc. However, the implications of AVs for road infrastructure have not yet been studied adequately and rigorously (Rashidi et al., 2020; Engholm et al., 2018; Cavoli et al., 2017). In particular, scientific study into the impacts of vehicle automation on physical infrastructure (Farah et al., 2018) and road design concepts is still in its infancy (Washburn and Washburn, 2018; Saeed, 2019; Intini et al., 2019; Khoury et al., 2019; Rana and Hossain, 2021). Most of the research on AVs to date has concentrated on vehicle technology itself or digital infrastructure (Farah, 2016), and the issues related to safety and reliability are mainly seen from a vehicle standpoint (Carreras et al., 2018; Ehrlich et al., 2016). This vehicle-centric vision also poses difficulties for vehicle and information technology industries and infrastructure owner-operators (IOOs)[1] in communicating with each other and sharing expectations (Carreras et al., 2018). Thus, the infrastructure requirements to facilitate AVs have not been clearly defined so far (Nitsche et al., 2014; Lu et al., 2019; Transport Systems Catapult, 2017; Lawson, 2018).

However, current road infrastructure is designed for human drivers and may not be able to integrate vehicles with high levels of automation (Lengyel et al., 2020; Liu et al., 2019). In other words, it is not known whether existing road infrastructure and the surrounding environment are ready for the safe and efficient operation of AVs during the nascent stages of implementation (Johnson, 2017). Human drivers have a good ability to adapt in situations where road markings and traffic signs are absent, and they can make complex inferences in real-time and exhibit acceptable behaviour even when they cannot consistently see the road scene, for example when they are blocked by a large truck (Farah, 2016). On the other hand, current sensor technologies and software adopted in AVs rely heavily on the presence of specific road environments and infrastructure (Soteropoulos et al., 2020; Van Brummelen et al., 2018). On-road testing points to worrying evidence that existing urban and particularly rural roads may struggle to support automated driving (Peiris et al., 2020).

Contrary to limited interest in the past decade, there has been growing attention to the physical road environment and its influence on the safe operation of AVs (SMMT, 2019; KPMG International, 2020). A number of recent research projects and action plans on road infrastructure for automated vehicles have acknowledged the need for comprehensive infrastructure planning for AVs (Gill et al., 2015; Gyergyay et al., 2019; Huggins et al., 2017; Johnson, 2017; Ehrlich et al., 2016; Erhart et al., 2020; Amelink et al., 2020). A recent report for the European Parliament, for example, points out that the quality of road infrastructure is vital for the effective adoption of artificial intelligence applications for transport and infrastructure must meet much higher quality standards, especially as the level of vehicle automation rises (Evas and Heflich, 2021). Also, many efforts have been made in recent years to develop new risk assessment and safety verification methods for automated driving systems as their launch to market without proof of safety would be unacceptable neither to society nor to legislators. Among these efforts, scenario-based approaches, in which individual traffic situations are tested through virtual simulation, highlight that the road environment and infrastructure are important parameters for testing the safety of AVs (Khastgir et al., 2021; Riedmaier et al., 2020).

In this regard, examining the infrastructure-related requirements of AVs will play an important role in assessing the readiness of the existing road network and preparing the plans to help facilitate the seamless integration of AVs into the future road network. Although automated driving technologies are still under development, some of their basic requirements on the physical and digital infrastructure are already clear. To assess these requirements and present them to decision makers as a whole, a few review papers (e.g. Farah et al., 2018; Liu et al., 2019) and expert opinion-based exploratory research (e.g. Nitsche et al., 2014; Lu, 2018) were conducted. Nonetheless, given the rapid growth in AV-related publications in recent years, some knowledge gaps presented in previously limited research are closed partially. In addition, technological development and field studies have brought additional criteria to be considered in the transition period for AVs or reduced the importance of some requirements for automated driving. Therefore, additional reviews are needed to capture the new knowledge produced in this growing field and complement the findings of the previous studies on infrastructure requirements of AVs.

From this motivation, this research seeks to address what the implications of automated vehicles will likely be for the physical road environment by comprehensively reviewing the current literature. Unlike previous studies (e.g. Farah et al., 2018; Rana and Hossain, 2021; Liu et al., 2019), this issue was investigated by framing two broad questions: 1) What are the potential impacts of automated vehicles (AVs) on road infrastructure and 2) What do AVs require from road infrastructure for safe driving. Although different, these

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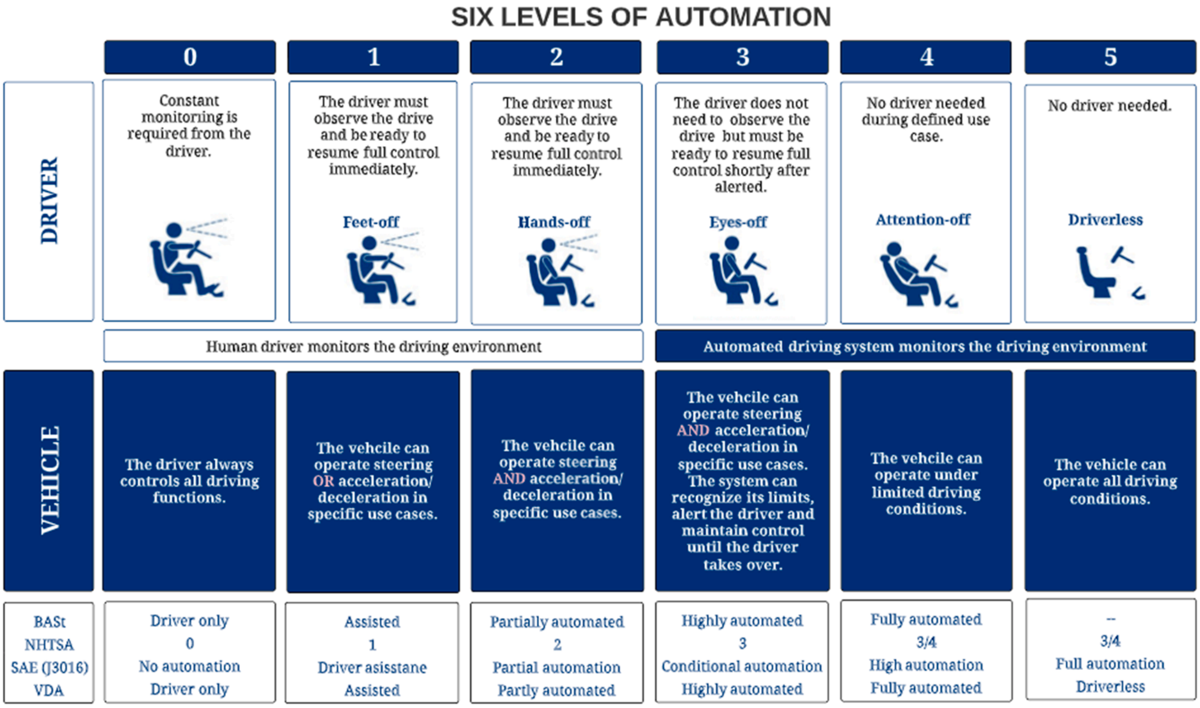
[1] IOOs include agencies, such as state and local departments of transportation, toll operators, and transit authorities, that own and operate infrastructure used for transportation (Gopalakrishna et al., 2021).



SIX LEVELS OF AUTOMATION

	0	1	2	3	4	5
DRIVER	Constant monitoring is required from the driver.	The driver must observe the drive and be ready to resume full control immediately. Feet-off	The driver must observe the drive and be ready to resume full control immediately. Hands-off	The driver does not need to observe the drive but must be ready to resume full control shortly after alerted. Eyes-off	No driver needed during defined use case. Attention-off	No driver needed. Driverless
	Human driver monitors the driving environment			Automated driving system monitors the driving environment		
VEHICLE	The driver always controls all driving functions.	The vehcile can operate steering OR acceleration/ deceleration in specific use cases.	The vehcile can operate steering AND acceleration/ deceleration in specific use cases.	The vehcile can operate steering AND acceleration/ deceleration in specific use cases. The system can recognize its limits, alert the driver and maintain control until the driver takes over.	The vehcile can operate under limited driving conditions.	The vehicle can operate all driving conditions.
BASt	Driver only	Assisted	Partially automated	Highly automated	Fully automated	--
NHTSA	0	1	2	3	3/4	3/4
SAE (J3016)	No automation	Driver asisstane	Partial automation	Conditional automation	High automation	Full automation
VDA	Driver only	Assisted	Partly automated	Highly automated	Fully automated	Driverless

Figure 1. Levels of on-road vehicle automation, adapted from SAE International (SAE J3016).

two questions are often discussed together in the literature and are highly interrelated. Indeed, Amelink et al. (Amelink et al., 2020) emphasise that AVs will have an infrastructure impact in two ways. First, AVs themselves may differ in their characteristics and behave differently than human-operated vehicles, causing changes in the vehicle's impact on infrastructure. The second way is that IOOs and other stakeholders can make changes to road infrastructure due to their need to provide operational design domains (ODD)[2] for automated vehicles. According to some researchers, the impacts on the physical road environment associated with ODDs are expected to be much more significant than the effects of the first type (Ulrich et al., 2020). Therefore, this study can be considered as a supplement to reports identifying the infrastructure-related requirements of AVs for safe and efficient operation, or research identifying the potential effects of AVs adoption on the physical road environment. The study has several target audiences, which are summarised as: researchers who are new to the field; the authorities who own, maintain, and operate the infrastructure; policymakers; and organisations engaged in national or international activities to define the road infrastructure requirements for successful implementation of AVs.

The rest of the paper is laid out as follows. Section 2 provides an overview of the vehicle automation and deployment paths, and road classification efforts for automated driving. Section 3 presents the review technique adopted in this study. Section 4 illustrates the general findings on the implications of AVs for the physical infrastructure-related attributes and interpretation of the current literature. Section 5 provides a discussion and summary of the issues identified and their practical implications for further research. Finally, Section 6 presents conclusions.

2. Background

2.1. Levels of on-road vehicle automation

Several classification schemes have been defined to distinguish between automation levels to guide industry and consumers in establishing safe operating principles for fully automated vehicles. The German Federal Highway Research Institute (BASt) and the

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[2] ODD is the set of driving conditions for a given automated driving system under which it is designed to operate. These driving conditions may include weather conditions, road infrastructure components, and vehicle-related conditions (SAE International, 2021).

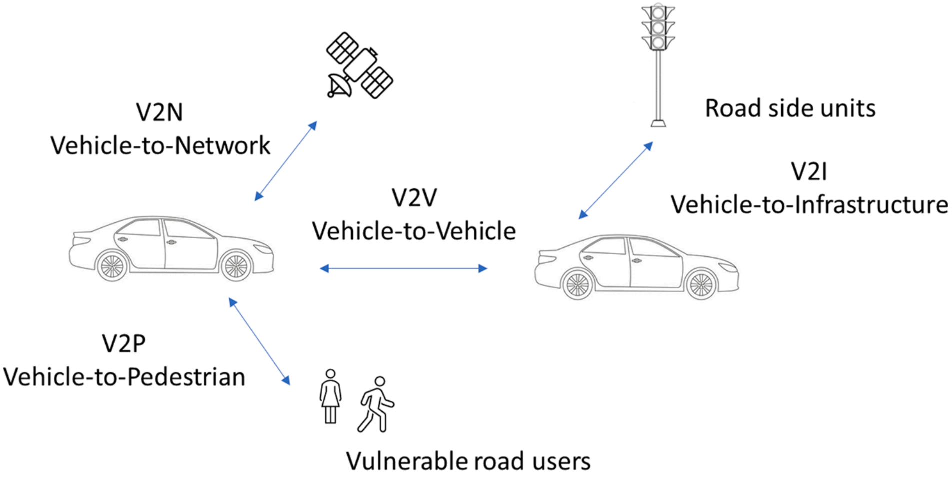

Figure 2. Vehicle communication types.

German Association of the Automotive Industry (VDA), the U.S. National Highway Traffic Safety Administration (NHTSA) and the International Society of Automotive Engineers (SAE) in the United States have introduced levels of automation that differ based on the extent of human driver involvement. The six-level SAE classification (SAE J3016) has the most comprehensive and precise descriptions (SAE International, 2021), and the European industry has agreed to use this classification for a common understanding of automated driving (Mocanu et al., 2015).

The five levels of automation reflect the gradual process of vehicle automation, beyond Level 0 where the driver performs all the direct driving tasks (see Figure 1). At Levels 1-2, the driving assistance systems provide the driver with longitudinal or/and lateral vehicle motion control in the form of adaptive cruise control and lane-keeping assistance. However, at these levels, the driver must supervise the driving system continuously and is responsible for monitoring the environment. For automation Levels 3, 4 and 5, an automated driving system (ADS) performs the entire dynamic driving task (DDT) while the system is engaged. Level 3 is defined as *"the sustained and ODD-specific performance by an ADS of the entire DDT under routine/normal operation with the expectation that the DDT fallback-ready user is receptive to ADS-issued requests to intervene, as well as to DDT performance-relevant system failures in other vehicle systems, and will respond appropriately"*. The difference between Level 3 and Level 4 automated driving is whether the driver (DDT fallback-ready user) is expected to be available for the takeover of the vehicle or not. At Level 4, ADS is expected to handle the fail-safe situation autonomously, but the ODD would still be limited. When an automated vehicle is able to drive in all driving modes which means that its ODD is unlimited, it will be defined as a Level 5 vehicle – this level is often referred to as *autonomous* or *self-driving* in the media (SAE International, 2018).

Apart from the automation capability levels, the distinction between automated and connected implementations is another important dimension of the classification of these emerging systems (Shladover, 2018). When integrated with connectivity, automated driving systems give rise to the connected and automated vehicle (CAV). Although connection and automation technologies have been developed independently initially, they now seem to be converging (Shladover, 2018; Timmer et al., 2015) as in combination they offer many advantages that cannot be achieved on their own (He et al., 2019; Schoettle, 2017). Connected vehicle (CV) technologies allow a vehicle to communicate wirelessly with the surrounding road infrastructure (V2I), vehicles (V2V), other road users such as pedestrians and cyclists (V2P), or many elements in the vehicle's surroundings (V2X), see Figure 2. The limitation of CV technology is that it relies entirely on message exchange for mutual awareness (He et al., 2019). On the other hand, AVs rely on their onboard sensors, embedded software and artificial intelligence in vehicles so that they do not need additional external infrastructure or communications. However, AD technologies are not fully reliable yet and face problems in situations such as extreme weather or unpredicted road conditions (Favarò et al., 2018; Zang et al., 2019). Over the longer term as higher levels of automation is developed, it will be increasingly important for the automation systems to be connected to overcome some of the limitations of AD technologies and, more importantly, to gain transportation system benefits through cooperation (Shladover, 2018). But some argue that it will probably not be possible for all road networks to meet the infrastructure required for connectivity (Madadi, 2021). Reviews of these communication and AD technologies are given in many studies such as (Coppola and Morisio, 2016; Huggins et al., 2017; Sarker et al., 2020; Shladover, 2018; Wevolver, 2020).

2.2. Role of infrastructure on deployment paths of automated driving

While automated driving is expected to provide various benefits for mobility, safety and the environment beyond those possible with manual driving (Bagloee et al., 2016), there are many uncertainties regarding the path of transition to full automation (Aigner et al., 2019). The European road transport research advisory council (ERTRAC) has introduced to *"Automated Driving Roadmap"* which provides descriptions of the automation systems and the expected date of their possible deployment, considering differing use cases and mobility models (ERTRAC, 2019). The report estimates that Level 4 AVs will be on the road in the next decade. Similarly, several studies have attempted to explore the market introduction and evolution of penetration rates for AVs through questionnaire surveys or interviews with experts (Saeed, 2019), but the actual rate of development of AVs and the precise nature of the transition path remains unclear (Milakis et al., 2017). The International Transport Forum (2015) points out that two incremental paths toward full automation are being followed by the industry. These two approaches are simply described as "*something everywhere*" and "*everything somewhere*".

The first path "*something everywhere*" strategy is generally embraced by traditional vehicle manufacturers and is largely consistent with SAE automation levels (International Transport Forum, 2015). The goal here is to gradually improve the capabilities of ADS in existing conventional vehicles and shift more dynamic driving tasks from drivers to ADS over time with the maturity of technological progress. Currently, most automakers use automated technology as a support for the driving task, resulting in Level 1 and 2 systems being widespread in the existing vehicle fleet (Robinson et al., 2017). However, driving automation Level 3 (e.g. traffic jam pilot), where responsibility can be exchanged between human and vehicle, can be particularly difficult to implement in terms of the timing of the transition (Lücken et al., 2019) and may require significant user experience for design and engineering. This is because when faced with a situation that the system cannot cope with, the driver is expected to be ready to take control of the vehicle control shortly after the alerted (Merat et al., 2014; Calvi et al., 2020). Although Level 3 has been recently regulated by authorities (e.g., UNECE Regulation No. 157), it raises many controversial questions about how the process can be managed if drivers do not respond. Another criticised point is that in the case of a failure or out-of-ODD, the number of vehicles making a minimal risk condition can be quite large, and their stopping would practically put the whole road to a standstill. Therefore, some studies have noted that stopping in a lane as the minimal risk manoeuvre should be strongly avoided (Ulrich et al., 2020; Transport Systems Catapult, 2017).

To avoid operational challenges in Level 3, technology companies (e.g. Waymo) are making significant progress and focusing on designing and manufacturing self-driving vehicles by completely bypassing intermediate automation levels. Also, some traditional automakers support a similar pattern and have announced that they will not follow the development of Level 3 systems (Bigelow, 2019; Martinez, 2019). This strategy refers to the second path "*everything somewhere*" which involves deploying vehicles without a human driver and gradually expanding vehicle operation to more contexts (International Transport Forum, 2015). In other words, this path is aiming at full automation within a limited ODD (e.g., a specific geofence or defined road types) and makes an effort to expand this domain with more complex driving situations (Madadi, 2021). However, it does not seem possible in the short term to engineer automated driving technology that can operate on all existing roads without requiring any infrastructure upgrades (ERTRAC, 2019). Therefore, reliance on AD technology alone without infrastructure support may jeopardize the potential safety and efficiency gains of AVs.

From the above discussion, it can be concluded that road infrastructure is a determining factor for both approaches and can either facilitate or prevent higher automation capabilities (Madadi, 2021). For the transition period to full automation, many studies highlight that the safe operation of levels 3-4 at full capacity will largely depend on the condition and type of infrastructure they encounter (Huggins et al., 2017; Madadi et al., 2019). It is therefore important for road authorities and agencies to know how ready road infrastructure is for safe automated driving.

2.3. The concept of road classification for automated driving

The idea of road certification for automated driving has been specified by some researchers (Huggins et al., 2017; Issac, 2016; Zhang, 2013; Cheon, 2003) to achieve the maximum benefits of AVs and get safer roads for all users. In this context, many initiatives are investigating cost-effective ways to prepare road infrastructure to enable the transition process in which conventional and automated vehicles coexist, and they are putting out significant effort to produce collaborative and complementary approaches (ERTRAC, 2019). Among these efforts, a recent project in Europe (INFRAMIX) has proposed a simple classification scheme to classify and harmonize the capabilities of a road infrastructure to support and guide AVs (Carreras et al., 2018). Within this framework, five levels (A-E) of infrastructure support for automated driving (ISAD) are defined and suggest that these levels can be assigned to parts of the network to guide AVs and their operator on the "readiness" of the road network for these emerging technologies.[3]

However, the idea is mostly based on digital infrastructure for roads, and connectivity alone might not enough to define how ready

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[3] Levels E and D are called conventional infrastructures and Levels C–A are termed as digital infrastructures. Simply, the classification is based on the availability and types of digital information provided to the AVs.

a road section is to host automation. Physical infrastructure, environmental conditions and other relevant aspects of dynamic elements should be considered in detail. For this reason, some organisations have focused on the concept of road classification and proposed alternative frameworks for service level classification for automated vehicles, considering the ODD and ISAD requirements (García et al., 2021; Poe, 2020; FTIA, 2021). On the other hand, some argue that the requirements of these concepts can be idealistic, expensive, and difficult to meet for all roads. In other words, large investments may be unnecessary, especially for low-volume road types such as rural roads and small city streets that serve primarily to provide access to origin and destination points (Madadi, 2021). Therefore, in the early stage of deployment, these concepts will likely be important for sections of highways rather than entire road networks to configure the various support that the infrastructure can provide to automated vehicles.

3. Materials and method

The study undertakes a comprehensive review of the literature on automated vehicles to address the key research questions: (1) what are the potential impacts of AVs on physical road infrastructure and road design concept, and (2) what do AVs require from road infrastructure? To address these questions, a semi-systematic approach was followed in the literature acquisition process. Studies were identified from academic databases (TRID, Scopus and Web of Science) by searching the following keywords and terms: ("safety assessment" OR "road safety" OR "road infrastructure" OR "road design" OR "physical infrastructure") AN D (autonomous OR automated OR driverless OR self-driving) AND (vehicle OR car). The reviewed documents include scientific journals, conference proceedings, book sections, technical reports, and white papers. Only documents in English published until 2022 were included. The obtained studies' titles and abstracts were screened based on their relevance to the research aim. For the eligibility part, full-text papers were skimmed and evaluated for whether they were relevant to the research question. The general criteria adopted for the document selection were that the studies focused on both the field of AVs and had at least one of the following contents:

- Discussion on potential physical infrastructure requirements or upgrades needed for the introduction of AVs;
- Presenting any challenges or limitations of automated driving caused by road infrastructure or road environments;
- Discussion of possible impacts of vehicle automation on existing road infrastructure and/or possible change in road geometric design.

Then, additional papers were identified and included through the cross-referencing of selected studies and other sources (e.g. organisations' web pages, Google Scholar, etc.). However, the findings of this study may be influenced by the following limitations. The methodology was undertaken based on the qualitative methods without any automated analysis technique and selected keywords may not cover all studies relevant to the research objective. Moreover, the combination and integration of physical and digital infrastructure are necessary for the safe operation of AVs and road traffic. However, within the scope of this literature review, digital infrastructures such as traffic management and control systems and localisation systems are not covered in this study. An overview of the digital infrastructure side of vehicle automation can be found in various studies such as (Coppola and Morisio, 2016; Eskandarian et al., 2021; Huggins et al., 2017; Shladover, 2018; Amelink et al., 2020).

4. Findings and interpretation of the identified literature

In the light of the eligibility criteria mentioned in the previous section, a total of 57 studies were identified from the existing literature (see Appendix A). The descriptive analysis of these studies regarding their year of publication revealed an increasing interest in this field due to technological advances and legislative changes around the world. These figures demonstrate similar trends to previous review studies (Farah et al., 2018; Liu et al., 2019) which confirm the growing interest in understanding the role of road infrastructure in the AVs deployments over the past few years. In the next sections, it will be seen that the available information comes not only from research, but also from grey literature, including government and industry reports, and online articles from technological institutes and websites. However, the findings of the existing studies are mainly based on subjective stakeholder opinions and literature review. The number of studies based on empirical data is quite limited. While studies have generally focused on the effects and requirements of the Level 4 or 5 automated driving system, approximately 37% of the studies identified did not clearly specify which level AVs were focused on in their research. Europe and the USA are the leading regions of origin of these studies, reflecting the fact that academic institutions and researchers from these two continents have significant interests in this topic.

Regarding physical road infrastructure, a total of thirteen key features of infrastructure have been identified in the existing literature regarding vehicle automation operation that should be considered either in the initial phase of deployment or during the transitional phase to full automation (see Figure 3). In determining infrastructure attributes, the study sought to answer the question of which elements of road infrastructure are relevant to vehicles while travelling on a particular road segment. The following sections summarise these critical attributes briefly.

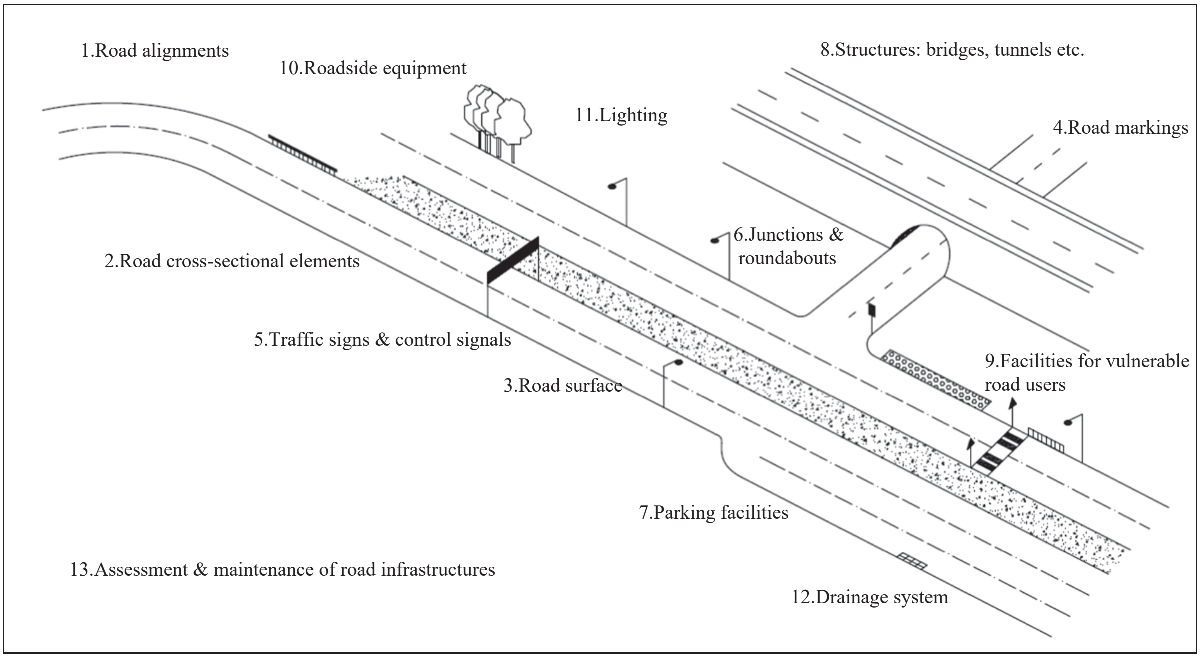

Figure 3. Examples of physical road infrastructure considerations discussed in the study for AVs, adapted from (Lyon et al., 2017).

4.1. Road alignments

Geometric design principles for roads have evolved through years of research and practical experience. Organizations such as the American Association of State Highway and Transportation Officials (AASHTO) are constantly updating their models and recommendations, taking into account newer evidence and data (AASHTO, 2011). However, most of the design manuals are based on the characteristics of human drivers. For instance, the driver’s perception-reaction time, eye height, and other human-related behaviours are the major factors that influence the design of road geometric elements (Othman, 2021). One of the views in the literature is that current road geometric standards may still apply to AVs if they can recognize the risks of driving faster than or equal to conventional users through sensors, scanning, and connectivity systems (Intini et al., 2019; Colonna et al., 2018). On the other hand, many researchers emphasize that as the penetration level of AVs increases in the market, road design parameters involving a direct relationship with the characteristics of human drivers need to be reconsidered (Washburn and Washburn, 2018; Khoury et al., 2019). In other words, the road geometric design philosophy and related specifications and guidelines should be revised as some driver-based requirements may lose their importance by shifting from conventional driving to automated driving (AASHTO, 2017). Parallel to this change, the impact of AVs on highway design is an emerging area of research. However, few studies have so far investigated the impact of AV on highway geometric design elements (Intini et al., 2019; Othman, 2021; Khoury et al., 2019) since current literature mainly focuses on effects on traffic flow and road capacity. The identified literature on this subject is summarised in Table 1, including their main findings and focused design elements.

Studies have mainly explored possible changes in geometric design elements in response to full Level 4-5 AV fleet penetration and evaluated these changes in comparison to traditional design outputs. Due to differences in perception abilities between human drivers and AVs, studies have mainly focused on stopping sight distance (SSD) and decision sight distance (DSD) criteria, which are key elements in designing road alignments. While human drivers mainly use their eyes to perceive their surroundings, AVs are expected to have a wider sensing range and a shorter perception and reaction time than human drivers as AVs use data from more sensitive and diverse sensors (e.g. lidar, radar and camera) to extract useful information specific to their purpose (Ye et al., 2021). Therefore, AVs will have significantly lower SSD (see Figure 4) and DSD. The SSD is the main factor influencing the lateral clearance on horizontal curves, so AVs can significantly reduce the required lateral clearance (Othman, 2021; Khoury et al., 2019). Furthermore, the drivers’ characteristics such as eye height and reaction time are the main factors that affect the required vertical sag and crest curve length (Aryal, 2020; Ye et al., 2021). Studies underline that AVs can significantly reduce the required curve length.

However, Garcia et al. (García et al., 2019) point out that findings can vary significantly depending on the design guideline being considered, as each design guideline assumes certain values of eye and object height above the roadway surface and deceleration rate. Also, since the height of the sensors' positions differs between vehicles, the characteristics of the AVs affect the results (Khoury et al., 2019; García et al., 2019). Therefore, international standardization of these parameters is needed. On the other hand, studies suggest that most of the geometric elements will not change in the era of AVs, especially those related to physics and comfort-based parameters. For example, the required curve radius or ramp terminals will be similar for both human-guided vehicles and AVs, as it depends on the driving dynamics and passenger comfort, not the characteristics of human drivers (Aryal, 2020).

Moreover, some authors believe that without connectivity, AVs will not outperform humans in situations where the sightline is limited such as detecting objects behind a vertical crest curve (Washburn and Washburn, 2018). Regarding the effect of road alignments on AV operation, studies reveal that both horizontal and vertical curvatures of the road have an effect on the operation of automated driving systems, such as the ability to detect lane markings (Marr et al., 2020; Tao, 2016), precise localisation of vehicles (Reid et al., 2019), and path planning control (Eskandarian et al., 2021; Xu and Peng, 2020). An experimental study on the market-available (Level-2) vehicles emphasises that the driver assistance function is often disengaged or causes drivers to feel unsafe in sharp curves (García et al., 2021; Taylor et al., 2018). Similarly, experts have noted that sharp curves influence the safe operating of ADS such as lane assistance systems, collision avoidance systems and speed control systems (Nitsche et al., 2014). Mainly, sharp horizontal curves and crest vertical curves pose challenging situations for AVs as the visibility range of the machine-vision sensors is limited. To mitigate the possible risks of this challenge, some studies proposed a new speed concept, automated speed, as the maximum speed that an AV can achieve at a specific road element such as horizontal curves (García et al., 2020) and vertical curvature (Gouda et al., 2021). Therefore, it is not expected any change in road alignments during the initial phase of AVs, but revision can be seen on dedicated roads or lanes for safe operation.

4.2. Road cross-sectional elements

4.2.1. Lane width

The dimensions of the cross-sectional elements (e.g. lanes and shoulders) are generally defined in standards based on road type, importance, traffic volume and context (Intini et al., 2019). Current road design standards specify the width of roadway and lanes depending on the width and length of the vehicles, while also providing a tolerance for driver behaviour. The tolerance for driver behaviour takes into account the change in the horizontal position of the vehicle in the lane and the space required to make any turn on the road without entering the opposite lane (García and Camacho-Torregrosa, 2020; Amelink et al., 2020). Typically, cars are about 2 m wide and trucks about 2.5 m, while standard lane widths can range from 2.5 to 3.7 m (Amelink et al., 2020). With the development of positioning technology, one of the common ideas is that AVs will likely have accurate steering control and track more precisely within a lane, which could allow lanes to be narrowed (Lyon et al., 2017). If this could result in fitting an additional lane to be placed in the carriageway, the efficiency of the road will increase without the construction of a new lane. The paved width of current carriageways can be easily retrofitted to achieve this by reconfiguring the lane markings significantly (Saeed, 2019; Amelink et al., 2020).

Besides, when designing new roads, the total road width could be likely reduced for AVs than in the case of traditional roads (Intini et al., 2019). This is generally positive, among the other reasons, for saving land and agency funds for construction and maintenance of the paved surface. Considering the urban street where the speed limits are low, AVs can potentially help to promote more efficient use of land in cities and facilitate new forms of streetscaping. Reduced lane widths for AVs result in more space for vulnerable road users so these spaces could be used for better pedestrian and bicycle facilities or emerging new transport modes (Johnson, 2017). Thus, this can create new opportunities to increase urban attractiveness (Chapin et al., 2016; Stead and Vaddadi, 2019).

As with other road design features, lane width has been found to affect the operation of current vehicles equipped with lane keeping assist (LKA) systems (Reddy et al., 2020; Reid et al., 2019). García and Camacho-Torregrosa (García and Camacho-Torregrosa, 2020) conducted an experimental study to understand the effect of lane width on partially automated vehicle (Level 2) performance and revealed that the LKA system tends to fail in narrow lanes. The test results showed that the threshold value for the safe operation of the automatic lateral control is a 2.75 m lane width. Similarly, Marr et al. (2020) underline that lane width narrower than 2.8 m is challenging for the machine vision systems of vehicles, especially in the absence of edge lines. On the other hand, several studies in the literature conclude that AVs have the potential to reduce the required lane width to 2.4 m with high communication between AVs (Othman, 2021).

However, the configuration of lane widths on curves will need to be handled more carefully due to vehicle turning paths and vehicle overhangs (Saeed, 2019). Sight distance would also be affected by lane reconfiguration. Therefore, it is not clear yet how the narrow lane width will affect road safety. Given mixed fleet conditions with different levels of automation on the same road, lane width reduction during the transition period may not be possible unless a dedicated lane is allocated for high-level AVs. This is because recent experimental studies on partially automated vehicles (Level 2) currently on the market have revealed that the positioning stability of the vehicles differs significantly (Taylor et al., 2018; Russell et al., 2018). This variation between vehicles may pose an issue for driver confidence and safe function within narrow lanes. Taylor et al. (2018) emphasize that either certified vehicles must prove capable of remaining within a minimum given lane width, or roads must only be certified as suitable for vehicles when a safe minimum lane width is met.

4.2.2. Shoulders and emergency bays

Shoulders are important design considerations for roads and provide additional space for visibility or, in emergencies, for recovering after lane departure or manoeuvring to avoid collisions. Furthermore, emergency vehicles need shoulders to reach incident sites to bypass the traffic congestion. More importantly, shoulders and emergency bays are used by all vehicles in case of vehicle breakdowns for the safety of road users and the prevention of traffic jams. In a recent survey with road agencies in the USA, 35% of respondents expect reduced shoulder widths in AV operations due to more precise driving and better handling of road conditions than human-driven vehicles (Saeed, 2019). However, it is mentioned in multiple studies that AVs will need shoulder and frequent safe harbours during the transitional period to full automation (PIARC, 2021; Transport Systems Catapult, 2017; Gopalakrishna et al., 2021). According to some, with the prevalence of AVs on the roads, shoulders will be needed more than ever in order for vehicles experiencing software or hardware failures to have a safe harbour (Saeed, 2019).

Regarding vehicle automation, Level 4 systems can operate without any driver involvement within a specific ODD, but once the vehicle leaves that ODD (e.g. due to adverse weather conditions, work zones etc.), drivers need to take control. It is possible that the driver is not ready to take control of the vehicle, in this situation the vehicle needs a safe area to stop/park and wait for the driver to be ready, or wait for conditions to improve to the extent where the automated control system is able to proceed (Transport Systems Catapult, 2017). Therefore, there is likely a need to have wider shoulders and emergency bays at regular distances to act as safe harbours to stop AVs in case of the temporary ending of the ODD. Emergency refuge areas and wide enough shoulders for stopping a vehicle safely are widely available already on most highways. However, there is no shoulder available in many locations, such as bridges, tunnels, or many two-lane highways, so additional requirements will need to be considered at these locations (Nowakowski et al., 2016). Furthermore, on some highways, paved shoulders have been modified so that all lanes are running or open to traffic at peak times via indicators on overhead signage (Transport Systems Catapult, 2017). Therefore, the suitability of using the shoulder as a safe harbour needs to be carefully assessed depending on the road situation (Amelink et al., 2020).

4.2.3. Median (central reservation) and barriers

Median refers to the road infrastructure that separates the opposite directions of the travelled way and it is highly desirable for high-speed carriageways (AASHTO, 2011) as it helps prevent head-on crashes across the entire road segment and provides a recovery area for out-of-control vehicles (Kim et al., 2017). In addition, median barriers and side guardrails mitigate the negative consequences of road departure of human-driven vehicles (Konstantinopoulou and Ljubotina, 2020). In urban areas with low-speed roads, the function of the median is also to provide an open green space, a refuge area for pedestrians crossing the street, and control the location of intersection traffic conflicts (AASHTO, 2011). In the long term, many studies suggest that medians could be removed or narrowed since a safety buffer between traffic in opposing directions may no longer be needed for L4-5 AVs. The space saved can be used to accommodate additional lanes or other modes of travel (serving as sidewalks or bike lanes), or even converted into parking space (McDonald and Rodier, 2015; NACTO, 2020; PSC and CAR 2017).

In the transition period, the mixed traffic era, it is likely that medians and barriers will still be needed for road safety due to the availability of human-driven vehicles. In addition, many studies point to the importance of dedicated lanes to ensure safe and efficient operation during the initial phase of implementation (Ye and Yamamoto, 2018). However, it is unclear how much buffer would be adequate for separating AVs from human-driven vehicles (Saeed, 2019), and extra efforts will be required to design and operate dedicated lanes in terms of safety and efficiency (Razmi Rad et al., 2020; Guhathakurta and Kumar, 2019). An experimental study revealed that the proximity of the line-markings to concrete safety barriers, which have similar properties to lines from a machine learning perspective made it harder for AV systems to identify them (Konstantinopoulou et al., 2020). Similarly, Kim et al. (2017) stated that flexible median barriers such as wire rope barriers can present difficulties, as AVs may have difficulty detecting smaller objects. Therefore, it is asserted that the design requirements of barriers and their types would be different for AVs (Pape and Habtemichael, 2018). Besides, design loads for barriers may need to be reconsidered due to the effect of truck platooning (Huggins et al., 2017; Lawson, 2018).

4.3. Pavement/road surface

As previously stated, AVs are likely to have more precise steering control allowing them to maintain a lateral position in the centre of the lane (Lyon et al., 2017). However, the more precise positioning enabled by lane-keeping technology results in reduced wheel wander distance, so repeated single-point loading can significantly affect pavement condition and cause rapid pavement deterioration (Chen et al., 2016; Yeganeh et al., 2022; Zhou et al., 2019; Lutin et al., 2013). Rutting, the permanent load-induced deformation on a flexible pavement surface, is one of the potential effects of this and needs to be carefully considered in the pavement design as it can

Table 1
A summary of the identified literature on the impact of AVs on road geometric design.

References	Considered design elements or criteria	Design guidelines	Comments / findings
Washburn and Washburn (2018)	Vehicle performance (acceleration and deceleration rate), Sight distance (crest of vertical curve, horizontal curve, and gap acceptance at two-way stop-controlled intersection).	N/A	An exploratory approach to the subject. As safety and comfort will still be decisive factors, the authors do not expect a tremendous change in roadway design based on the vehicle performance assessment. Considering the sight distance, V2X connectivity will promote economic design for new roads.
Khoury et al. (2019)	Stopping sight distance (SSD), Decision sight distance (DSD), Length of crest vertical curve, Length of sag vertical curve.	AASHTO	Potential economic and environmental improvements through the reduced cut and fill volumes of the new design (based on the elimination of human driving) and the flexibility to use shorter vertical curves. The length controls for sag and crest vertical curves would need to be revised to accommodate the AV's required SSD.
Saeed (2019)	SSD, Acceleration lengths for entrance terminals with flat grades.	AASHTO	The road geometry design will not undergo any drastic revisions that could make the ride uncomfortable for the AV occupants. Regarding the acceleration lengths, reducing the merging manoeuvre length is only possible if the AVs are electric as they can accelerate faster than a gas combustion engine vehicle.
Intini et al. (2019)	Length of tangents and curves, Radius of circular curves, Transition curves, Road design consistency, Grades, Radius of vertical curves, Consistency of horizontal and vertical alignments, Sight distance, Speed concepts, Road friction, Lane and shoulder width.	Focus on internationally valid design concepts	Human-based requirements can greatly change in the case of the roads used only by AVs, but other requirements may still apply. Compared to current design standards, they suggest more relaxation would be expected for the design of alignments, speeds, and sight distance.
Welde and Qiao (2020)	SSD, Length of crest vertical curve, Length of sag vertical curve.	AASHTO	A significant reduction in SSD is due to changing design elements related to human characteristics and vehicle performance (e.g. perception and reaction time, deceleration rate and height of sensors), hence the minimum length of the crest and sag curves is expected for both scenarios (human drivers with a level 3 vehicle automation, and AVs without a human driver). This results in shorter curves that are more economical.
García et al. (2019)	SSD, Crest vertical curves, Speed concepts	AASHTO Spanish guidelines	International standardization is needed for related parameters as the findings might significantly change depending on the considered design guideline as well as the used AVs because each design guideline assumes specific values of the height of the eye and object above the roadway surface, and the deceleration rate is different among vehicles.
Aryal (2020)	SSD, Passing sight distance (PSD), Intersection sight distance (ISD), Length of crest vertical curve, Length of sag vertical curve, Lane width.	AASHTO	The geometric design parameters could be optimized, and this brings a reduction in the minimum required geometric design value for the AVs along with the reduction in net earthwork volume, pavement material volumes, and environmental impacts.
McDonald (2021)	SSD, Length of crest vertical curve, At-grade rail crossings, Ramp terminals.	AASHTO	The author emphasizes that as long as human-driven and controlled vehicles are part of road traffic, roads should continue to follow traditional design guidance for human-guided vehicles.
Guerrieri et al. (2021)	SSD, Maximum straight length, Horizontal circular curve design, transition curve: design criteria for the clothoid, Gradients, Crest vertical curve design, Sag vertical curve design	Italian guidelines (D.M. n. 6792. 5/11/2001)	AVs proved to need much shorter SSD (calculated in function of the design speed and the slope) than those today required by manually guided vehicles. This may eliminate many speed limits along with some motorway segments, due to visibility obstacles (e.g. small radius curves and the presence of safety barriers).
Ye et al. (2021)	SSD, Length of crest vertical curve, Length of sag vertical curve, Complex combined horizontal and vertical alignments.	AASHTO	AV-based design controls on vertical curves are more tolerant than those based on human drivers; and the dominating criterion of sag vertical curve design control is comfort for AVs, versus required SSD for human drivers.
Othman (2021)	SSD, DSD, Lateral clearance on horizontal curves, Length of crest vertical curve, Length of sage vertical curve, Lane width, Horizontal curve design, Spiral curve design, Maximum length of straight segments on horizontal alignments.	AASHTO	AVs can substantially reduce: 1) the required lateral clearance due to having lower SSD and DSD; 2) the required vertical curve length because of having faster reaction time and the differences in sensor height.

cause vehicles to skid and drivers to lose control of the vehicle (Yeganeh et al., 2022). Chen et al. (Chen et al., 2016) investigated the potential effects of AV deployment on the long-term service performance of asphalt pavement using large-scale finite element modelling. Specifically, the pavement rutting performance by the possibly changed behaviours, such as the vehicle's wheel wander, lane capacity, and traffic speed were examined. The study showed that there are varying influencing factors that will counterbalance AVs' effects on the pavement. While the decreased wheel wanders and increased lane capacity could bring an accelerated rutting potential, the increase in traffic speed would negate this effect. Therefore, whether the net effect is positive or negative depends on the practical road and traffic conditions.

On the other hand, Carsten and Kulmala (2015) stated that AVs could be programmed to drive more evenly across the whole width of the driving lane to reduce pavement wear. Besides, there are some more "radical" ideas that there is no need for vehicle lanes on the roads in a fully automated environment (Malekzadeh et al., 2021). AVs can adjust the distances among them intelligently without following vehicle lanes. These ideas could prevent increased damage from precise positioning, but it also means that the lane width could not be narrowed. Zhou et al. (2019) investigated the different lateral wandering pattern impacts on the pavement by modelling with the Texas Mechanistic-Empirical Flexible Pavement Design System (TxME). Results showed that the AVs with smaller lateral wandering (compared with human-driven vehicles) would shorten pavement fatigue life by 22% and increase pavement rut depth by 30%, which leads to a much higher risk of hydroplaning (Zhou et al., 2019). On the other hand, they estimated that the use of AV optimal pattern – designed for wider wheel wander with uniformly distributed traffic loads - can be beneficial and decrease the rutting depth by 24% and extend the pavement life cycle by 16%.

Similarly, Noorvand et al. (2017) suggested that if properly controlled, automated trucks can be quite useful for pavement design and will be most effective when the penetration of automated trucks is larger than 50%. The potential benefits stemmed from the ability to control the positioning of automated trucks more systematically and more uniformly using the available pavement surface. On the other side, in the absence of proper control, especially by repositioning trucks in the same location, the amount of damage can be quite harmful and noticeable effects can occur at automated truck volumes as low as 10% (Noorvand et al., 2017). Unlike previous research, Yeganeh et al. (Yeganeh et al., 2022) estimated the impacts of dedicating a reduced lane width to AVs on pavement rutting performance using finite elements. The study finds that dedicating a narrower lane for AVs could significantly influence the flexible pavement's rutting performance. Using dedicated lane widths of 3 m and 3.25 m for AVs with uniform-wander distribution would increase the total rutting depth of the pavement by 20.48% and 7.31%, respectively, compared to the lane width of 3.5 m.

Given the reported discussions, the net impact of vehicle automation on pavement structure is difficult to predict precisely as it depends on many variables (e.g. traffic speed, road capacity, lane width etc.). However, in urban areas with low-speed limits and narrow lane widths, the negative impact of AVs on the pavement is expected to be greater, so certain areas below the AV operation track may need to be strengthened (Johnson, 2017). Additionally, more efforts will likely need to focus on the balance between thresholds (e.g. speed limit, lane width, uniform wandering strategy etc.) and a detailed cost-benefit analysis should be done to examine the optimum solutions.

4.3.1. Skid resistance on the road surface

Skid resistance relates to the force developed when a tyre that is prevented from rotating slides along the pavement surface (Konstantinopoulou and Ljubotina, 2020; Zhao et al., 2021). Although many vehicles today have electronic stability control, which is a system designed to help drivers to avoid crashes by detecting and reducing skidding or loss of traction as a result of over-steering, drivers are normally unaware that a skid will occur until it starts (Weeratunga and Somers, 2015). Several car accidents on rural roads are currently caused by a loss of friction. Therefore, vehicle automation shows great potential for reducing this accident type since AVs will likely be able to forecast the skidding before it happens, based on friction estimations (Montanaro et al., 2019; Colonna et al., 2018). However, the failure to estimate friction on the road might result in roadway departure crashes. This would need to research not only the requirement for the coefficient of friction skid resistance but also speed and maximum values of acceleration and deceleration of AVs. Zhao et al. (2021) evaluated the driving safety of AVs concerning pavement friction and suggested that there is no

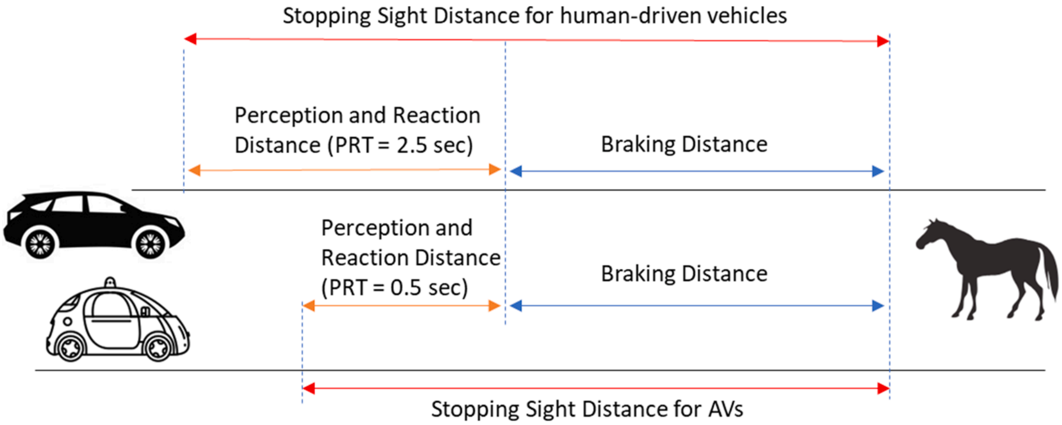

Figure 4. The stopping sight distance for human-driven vehicles and AVs, adapted from (Othman, 2021).

urgent need to increase pavement friction requirements concerning rear-end crashes involving AVs. In addition, AVs can adjust their speed more predictively through communications with roadside units (V2I) or vehicles (V2V) to avoid sharp braking (Johnson, 2017). The requirement for the coefficient of friction, so materials with less skid-resistance in the surface layer can be used in the future (Liu et al., 2019). Nonetheless, AVs will continue to use rubber wheels and drive on paved or concrete surfaces, so friction is still a crucial factor in design (Washburn and Washburn, 2018). Apart from that, Zhou et al. (2019) stated that significant efforts are necessary to evaluate how pavement skid resistance decreases with the applications of multiple AVs under different lateral wandering widths and various distribution patterns.

4.4. *Road markings*

Road markings are one of the most prominent research areas among physical road attributes since current and near-future advanced driver assistance systems (e.g. LKA) highly rely on road markings in order for positioning the vehicle within the section of the road (Gupta and Choudhary, 2018). AVs use sensors, cameras, and artificial intelligence to detect the edges of the roads and identify lane markings on the roads to complete the tasks of driving and navigation (Easa et al., 2021; Kuutti et al., 2018; Meneguette et al., 2018). However, improper delineation of road markings poses challenges for vision sensors of AVs to predict where the vehicle is in the lane (Konstantinopoulou et al., 2020). Many trials of automated driving have failed or been disengaged due to the poorly marked and inconsistent road markings (Favarò et al., 2018). As such various studies have been conducted in order to develop algorithms that allow for real-time recognition of lane boundaries and vehicle guiding (Eskandarian et al., 2021; Xing et al., 2018). However, most of the research has concentrated on the phenomena from a hardware and software standpoint (i.e. image recording devices and detection algorithms). The infrastructural component, on the other hand, plays an important part in this phenomenon (García et al., 2021).

In the last few years, there has been a growing interest in scientific committees to evaluate the optimum requirements and conditions of road markings (see Figure 5) for the safe operation of AVs (Ambrosius, 2018). In this context, studies have attempted to identify performance characteristics of road markings that could affect the ability of machine-vision systems to recognise markings (Marr et al., 2020; Konstantinopoulou et al., 2020). However, as sensor technology and software capabilities evolve, the minimum requirements for road marking conditions for AVs will likely change as well. For example, findings of a recent project, using 360-degree imagery and computer vision techniques showed that the width of lines was as not as important as the condition of the line itself (Konstantinopoulou et al., 2020). On the other hand, optimum requirements of road markings for vehicle automation are difficult to determine precisely as it depends on many variables (e.g. operating speed, road surface condition, lane width etc.). A recent experimental study highlights these factors and outlines the desired conditions and configurations of road markings for AVs (Marr et al., 2020).

In general, research points out that ideal road marking should be “readable” by both human drivers and machine-vision systems (Huggins et al., 2017; Nitsche et al., 2014; Transport Systems Catapult, 2017; Lawson, 2018). In Europe, it is recommended that a good road marking should have a minimum performance level of 150 mcd/lux/m^2 in dry conditions and have 150 mm width for all roads, while it should be 35 mcd/lux/m^2 for wet conditions (EuroRAP and Euro NCAP, 2013; ERF 2013). Also, it is widely accepted in the literature that high-quality and frequent maintenance of road marking can help overcome the challenges of camera vision technology. However, road markings are not always clear in natural environments, numerous factors such as shadows from trees affect their clarity (Ye et al., 2018). Moreover, the most frequently cited issue from the AV industry regarding road infrastructure opportunities to support AV deployment is the lack of uniform implementation of markings and signs around the world. In Europe, for example, non-standard road markings are cited as a major problem facing current drivers and confuse AVs (Johnson, 2017; PIARC, 2021; EuroRAP and Euro NCAP, 2013). To deal with non-standard, damaged, or poor-quality markings, AVs may need to use other sensors or systems or supplementary information via high-definition maps that provide a better position estimate (Van Brummelen et al., 2018; Marr et al., 2020). Additionally, there are various road layouts and situations (e.g. road works) where lane marking is not available. The development of the V2I communication technologies might become the key solution for these marking issues. Furthermore, new applications such as magnetic materials, which have been embedded on the road to improve the navigation and positioning of the AVs, might be potential solutions for AVs (PIARC, 2021).

According to the Transport Systems Catapult (Transport Systems Catapult, 2017), it is possible that as vehicles use digital infrastructure and mapping to localise and navigate, the issue of road markings will become less critical; however, current technologies rely on road markings, and at least some highly automated systems are expected to rely on them for some time. Furthermore, physical markings will be required as part of the road infrastructure until human-driven vehicles are completely removed from the road network. Apart from this, AVs can benefit from a “hybrid” combination of both physical road markings/signs and their digital twins in digital maps, thereby increasing the robustness of their operational capabilities (Ulrich et al., 2020). Also, some argue that HD maps will likely not be available for many cities during the early stage of implementation. Briefly, as human drivers will be able to take control of the vehicles until fully AVs are commonly adopted, road markings will continue to represent an important infrastructure element (Ambrosius, 2018) and will play a vital role for the foreseeable future (Department for Transport, 2015).

4.4.1. Rumble strips and road studs

Rumble strips are important physical road attributes for road users' safety due to having the potential to reduce road accidents. Rumble strips are commonly used to delineate the centre and shoulders of paved roads (Department for Transport, 2019) and take a few different forms. For example, they can be produced by cutting grooves within the pavement surface, or by adding plastic ribs to the road. Research has shown that shoulder and centre rumble strips can significantly reduce serious run-off-road and head-on crashes on single carriageways (Biehler et al., 2009). Also, the profile of the marking within the rumble increases the night-time visibility of markings, particularly under dark and wet conditions (see Figure 6). However, considering the current literature, the role and effectiveness of rumble strips on AVs and their potential impact on the operation of machine vision systems are not clear yet.

Another important road attribute for the delineation of the lane boundary is the application of road studs. Road studs provide visibility for drivers to keep the vehicle in the lane and prevent it from running off the roads. Retroreflective road studs, also known as cat's eyes are significantly important for drivers, particularly in wet and rainy conditions where puddles and fog inhibit vision (Pike et al., 2019). The presence of cat's eyes on a road has the potential to improve the readability of lane markings by providing a reference point with a much higher reflectance. This may enable more robust detection and classification of pavement markings by machine vision systems (Shahar et al., 2018). Recently, solar-powered, connected road stud sensors have been launched as part of the Internet of Things (IoT) to support autonomous traffic management systems. These wireless sensors collect data about vehicle movement, physical objects and road surface conditions (Browne, 2020). Similarly, Singh and Islam (Singh and Islam, 2020) propose to use raised pavement markers with a chip installed inside to provide the smooth movement of AVs in work zones.

4.5. Traffic signs and control signals

Traffic signs and control signals are also well-researched topics among road features because AVs, like human drivers, need to detect, read and understand traffic rules in order to navigate safely. Current traffic sign recognition technology works through built-in cameras that see and interpret the traffic sign's colour, shape, message etc. (Bruno et al., 2018). However, this technology has not yet reached the desired level (Nowakowski et al., 2016). For example, false positives and false negatives are both a problem for the safe operation of vehicles (Shladover and Bishop, 2015; Koopman, 2019). For this reason, scientific committees show great effort to develop more robust and reliable traffic signs and signal recognition systems (Chen and Huang, 2016; Jensen et al., 2016). However, for this to be successful, the traffic signs have to be visible to both the human eye and the machine vision technology that is reading them (Lyon et al., 2017). While there are standards for signs and signals, many road features, including traffic signs, differ from jurisdiction to jurisdiction (Huggins et al., 2017; EuroRAP and Euro NCAP, 2013). This variability will likely be challenging for automated driving, so there is a need to understand what types of signs, markings, and devices are currently "easy" for AVs. For example, variable message signs (VMS) are often difficult to read with cameras because they are using technologies and control systems designed for the human eye (PIARC, 2021; Roper et al., 2018). Moreover, rural and remote areas might pose significant challenges to the functionality of AVs, as they often lack the necessary infrastructure and communications network for road operation. There is a need for low-cost machine-readable static signage that can fill the gaps in the infrastructure. For example, markings such as "QR codes" may be intelligible to machines, but they would be challenging for humans (Ozan, 2019). Therefore, the collaboration between industry and authorities is becoming urgent to develop standards that could assist both AV and human drivers.

A recent project in Europe analysed approximately 1000 km of roads across Croatia and Greece to assess the readability of traffic signs for AVs by using 360-degree imagery and mobile lidar (Konstantinopoulou et al., 2020). According to the assessment carried out as part of this study, about 11% of the five main types of signs (predominantly speed signs) in Croatia were not detected using computer vision techniques on undivided roads. On the other hand, this was nearly 25% on divided roads. In Greece, these were around 5.4% and 4.1%, respectively. Based on the initial findings, the project points out that the adoption of harmonised regulation and standardisation of sign types, symbols used, shapes, heights, locations, and orientations are required to increase the readability of traffic signs (Konstantinopoulou et al., 2020). Moreover, the need for regular and consistent maintenance is particularly important for AVs as they rely on delineation and signs (Huggins et al., 2017).

In the future, although most of the safety-critical information for AV navigation is expected to be able to be sent wirelessly, in the absence of a connection, traffic signs will still play a prominent role in informing the decisions an AV needs to make (Transport Systems Catapult, 2017). In addition, there is still no guarantee that the information transmitted by temporary signs, such as those used in road works or temporary deviations, will be wirelessly transmitted to the vehicle or and therefore they remain necessary. Apart from that, some infrastructure requirements can be relaxed by using a high-definition (HD) map that can assist the vehicle with a safe motion plan (Ulrich et al., 2020). But some researchers believe that all road networks will not be covered in the geographical database in the early stage (Mocanu et al., 2015). Nonetheless, the need for traffic signals and signs is expected to potentially decrease gradually with the maturity of digital support (Liu et al., 2019).

4.6. Junctions and roundabouts

Junctions are complex traffic situations and represent bottlenecks in the traffic flow (Montanaro et al., 2019). They can be classified into two groups: intersections and interchanges. The main distinction is that interchanges are two roads that cross over and under one other, whereas intersections are two roads that meet at the same level. Interchanges use ramps to connect the roads for often seamless traffic flow, while intersections usually employ a set of rules or a system (e.g. traffic lights) to direct traffic flow and prevent crossing paths (Paulsen, 2018). AVs are expected to improve these bottlenecks significantly with the help of new connectivity technologies that allow cooperation between vehicles or infrastructure. In line with this motivation, extensive research has been conducted on the effects of connected and automated vehicles on traffic flow at intersections to date (Elliott et al., 2019). Simulations have shown that AVs contribute to increasing the efficiency of traffic flow, thereby increasing junction capacity and reducing fuel consumption and waiting time at intersections (Atkins, 2016). However, many articles have highlighted that AVs without connectivity may not provide these benefits.

From a safety perspective, although junctions represent a small part of the road system, a significant amount of fatalities occur in the area shared by crossing streets, and these fatalities are in part due to human error (Montanaro et al., 2019). For example, statistics show that during the 10 years from 2007 to 2016, over 35% of the fatalities on UK roads occurred at junctions (European Commission, 2018). Similarly, current AV trials in mixed traffic conditions show that intersections are the most challenging road sections for AVs since 89% of the reported AV accidents (mostly rear-end crashes involving manually driving vehicles) happened at intersections (Favarò et al., 2017). Problems arise for AVs in these areas as traffic conditions are complex and there are many things to detect and monitor. Also, high speeds and sensor range limitations can cause problems at intersections. Much of the research focuses on digital infrastructure and how V2V and V2I can address these challenges. In this context, vehicle-to-network communication has also gained momentum in recent years (Martínez-Díaz et al., 2019). However, the solution does not just come from vehicle automation and connectivity, but the serious effort is also needed to upgrade infrastructure during the transitional period. Particularly, it is necessary to understand which types of intersections are safe to facilitate automated driving, and what special rules and physical requirements must be considered for intersection types to ensure AVs can safely accommodate, including platooning of vehicles. According to expert opinions, motorway exit/entrance, unsignalised intersections and roundabouts with bicycle lanes are the most dangerous and challenging road situations for AVs (Lu et al., 2019) because they are considered a complicated areas for AVs in terms of dimensions, visibility, and other issues (Amelink et al., 2020).

While few studies suggest that as the number of AVs on roads increases, signalised intersections will gradually be replaced by roundabouts as they are likely more efficient for AVs (Gill et al., 2015), many studies point out that signal-controlled junctions and crossings might be easier for AVs to handle than other forms of junctions (Transport Systems Catapult, 2017; Lawson, 2018). It is suggested that signalised intersections may be safer for AVs than roundabouts, mainly because they provide the more predictable elements of a stop-and-go manoeuvre and provide more closely defined turning manoeuvres. A recent simulation-based study by Morando et al. (Morando et al., 2018) shows that AVs might reduce the number of conflicts by 20% to 47% with penetration rates of between 50% and 100% at signalised intersections, while for the roundabout the number of conflicts is reduced by 29% to 32% with the 100% AV. Consequently, solutions for junctions are an area of active research, and will primarily need connectivity with likely minor changes to the physical infrastructure. In the long term, considerable changes can be expected at intersections thanks to vehicle coordination. For example, intersections could be made more compact (Huggins et al., 2017). However, in this case, the intersection

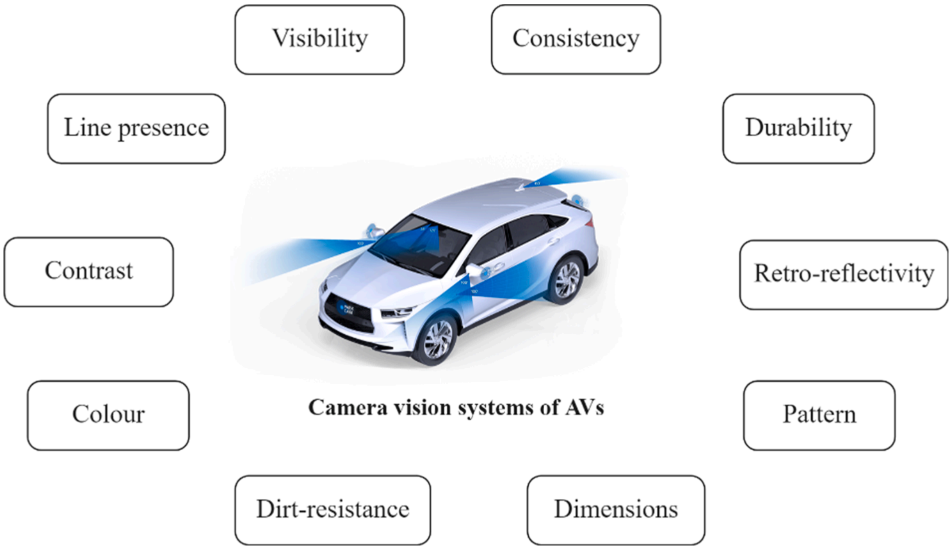

Figure 5. Requirements and conditions of road markings for camera vision systems of AVs. Picture of the vehicle is taken from: https://www.mobileye.com/solutions/super-vision/.

sight distance (visibility) models should be checked for safety, and design specifications may need to be revised as they are based on driver behaviour rather than vehicle and road capacity (Aryal, 2020; Wang et al., 2021). In addition, some studies reveal the necessity of redesigning the geometry of intersections in order to implement seamless flow (Chen et al., 2021; Lin et al., 2021).

4.7. Parking facilities: pick-up and drop-off locations, service stations

The impacts of Level 4-5 AVs on parking demand and related effects on urban forms have been extensively studied in the literature, particularly in the context of shared AVs (Stead and Vaddadi, 2019). It is widely accepted that as AVs become widespread, there is a potential that private car ownership will decrease, so parking space requirements will decrease significantly (Litman, 2020; Johnson, 2017; Gill et al., 2015). However, this scenario will likely be possible when the adoption of shared mobility models is high (Currie, 2018), otherwise, the need for parking will continue and or even increase (Duarte and Ratti, 2018).

Regarding automated driving, parking assist systems are already available on the market, but with the automated valet parking (AVP) systems, cars will park in parking lots or garages after the driver or passenger leaves the vehicle (Shladover, 2018), which will bring both challenges and opportunities (Transport Systems Catapult, 2017). For the opportunities, many researchers point out that in areas where land is expensive, parking spaces can be redesigned to be more compact, making it possible to use other purposes (e.g. recreational), or placed further away from the buildings they serve (Stead and Vaddadi, 2019; Shladover and Bishop, 2015). On the other hand, it is predicted that curb frontage loading areas need to be expanded to accommodate pick-up and drop-off points (Lutin et al., 2013). These points in urban areas will likely become increasingly valuable, especially those within walking distance of transport links (Huggins et al., 2017). Also, existing car parks are not designed to support self-parking facilities (Liu et al., 2019), so their infrastructure needs to be improved in many aspects. The majority of parking spaces in urban areas are located underground where GPS signals are not strong, which will cause difficulties in navigating the vehicle (UK Autodrive and Gowling, 2018). Moreover, the Transport Systems Catapult (Transport Systems Catapult, 2017) has stated that many car parks do not use standard road markings because they are privately operated, making the markings difficult to read by onboard sensors. In short, a serious effort will be required in many aspects such as the implementation of proper toll systems, standardization of lane markings and traffic signs to design AV-compatible parking lots.

4.7.1. On-street parking

Street parking is popular in many countries, but this imposes a huge restriction on traffic flow. In fact, this situation may leave insufficient space for two-way traffic in many places. In this case, drivers can decide among themselves who goes first, and this can often be communicated by a hand gesture or a flash of the headlights (Transport Systems Catapult, 2017). However, during the transitional phase, AVs may have trouble on these roads to operate. To enable AVs to operate on these roads, several options may need to be considered, such as removing street parks or converting streets into one-way operations (Transport Systems Catapult, 2017). According to current guidelines on traffic signs (e.g. in the UK (Department for Transport, 2019)), centreline marking is not required on roads with a carriageway width of 5.5 m or less – most residential roads are in this category. This might cause a significant challenge for AVs to navigate and localise on these roads with the presence of on-street parking. Current lidar and camera integrated L4 AV trials

Figure 6. Night-time visibility of line marking within the rumble strip, taken from (FHWA, 2015).

with HD mapping in the USA show that parking on the street may not be a major problem for AVs navigation, even in the absence of road signs. However, it is not yet clear how AVs will operate safely in countries with narrower roads such as the UK.

4.8. Structural elements

4.8.1. Bridge design

Many studies suggest that AVs will have an impact on existing bridges and may require revision of design standards in light of the potential future scenarios (Huggins et al., 2017; Liu et al., 2019; UK Autodrive and Gowling, 2018). This is because the current bridge load models and bearing capacity guidelines have not considered the possibility of additional lanes and vehicle platooning. Contemporary bridge design standards make assumptions about the number of vehicles likely to be on the bridge at any given time, as well as other physical characteristics such as vehicle mix, axle spacing and loadings (Ulrich et al., 2020). However, the potential impacts of AV platooning, particularly groupings of heavy goods vehicles (with small headways and little lateral offset) on these design standards need to be explored further (Paulsen, 2018; Yarnold and Weidner, 2019; Tohme and Yarnold, 2020; Sayed et al., 2020; Thulaseedharan, 2020). Platooning of AVs can change the loading on the bridge deck, and this poses a great risk, especially for existing bridges with long spans. Therefore, on routes for heavy truck platoons, structural recalculation of bridges needs to be carried out, potentially resulting in the need for strengthening measures (Amelink et al., 2020). Additionally, if the lane width decreases due to the precise movement of vehicles and the right of way are sufficient for reconstruction, the total lanes on the bridge might be increased (see Figure 7). It should be considered whether this effect will be significant and whether the load models used in the design of the structures will be sufficient for this change.

Previous research has found that the spacing between trucks in a platoon is a crucial factor that has a significant impact on bridge safety (Tohme and Yarnold, 2020; Thulaseedharan, 2020). As a result, increasing the spacing between vehicles in platoons before reaching might be a strategy for managing or mitigating the impact of platoons on existing bridges. However, traffic volume will be affected in this case. There is no research in the literature to explore how the load capacity limit of bridges that can allow the maximum number of vehicles in a platoon will affect road capacity. On the other hand, to prepare for the future, newly constructed bridges must take truck platooning into account, and new bridge design standards must be created. A recent report of an EU-funded project covers this issue extensively, and the effects of automated freight vehicles are thought to depend on future load capacities rather than automation (Ulrich et al., 2020). Also, bridge design standards/guidelines are different in each country, thus standardization on future platooning scenarios might be required globally.

4.8.2. Tunnels and underpasses

Similar to underground parks, tunnels and underpasses might be an obstacle to the safe operation of AVs in two ways. The first is that satellite signals may be weak or blocked, making location accuracy problematic within these road sections (Wevolver, 2020). As a result, specialised positioning infrastructure for the functioning of AVs will be required (Huggins et al., 2017), such as roadside beacons or landmarks for positioning assistance (Kulmala et al., 2020; PIARC, 2021). The second is that illumination might be an issue for AV vision-based systems. Roads around underpasses and tunnels may require more or different lighting than they currently do, as a recent project found that image-based line recognition cannot detect lines in tunnels due to low light levels (Konstantinopoulou et al., 2020). Another potential issue is that AV vision-based systems may fail to detect approaching tunnel entrances or exits or may become completely blind as a result of rapid changes in surrounding illumination (see Figure 8) (Rosique et al., 2019; Taylor et al., 2018). However, this might be mitigated by mapping and real-time information may also be needed to support AVs at these critical points. Briefly, lighting and positioning are two topics discussed in the literature for the safe operation of AVs in tunnels.

4.9. Facilities for vulnerable road users

Vulnerable road users (VRUs) such as pedestrians, pedal cyclists, motorcyclists, or users of new micro-mobility modes such as e-scooters are the biggest obstacle to the success of collision avoidance systems due to the high risk of injury and fatality when involved in vehicular accidents. For example, VRUs have the highest accident rate in terms of casualty rate per billion passenger miles by road user type in the UK (Department for Transport, 2018). Interestingly, pedestrian fatalities have increased recently in many countries such as the USA, although vehicles are increasingly equipped with more sophisticated safety and anti-collision technology (Elliott et al., 2019). Despite this, advances in AD technology are expected to substantially reduce the fatalities of VRUs by eliminating accidents caused by human error (Lawson, 2018).

However, before AVs can be widely accepted for use in urban environments, convincing demonstrations must be made that AD technology can detect and safely respond to the VRUs (Shladover and Bishop, 2015; Parkin et al., 2016). For this reason, this issue is receiving increasing attention from researchers, OEMs and road agencies (Vissers et al., 2016; McDonald et al., 2018). In this context, there are many crucial issues to examine such as how pedestrians and cyclists interact with AVs that have no human driver or to what extent AVs will be able to detect a cyclist on the road ahead when lighting and weather conditions are adverse (Vissers et al., 2016;

Stanciu et al., 2018). A recent study finds that current detection technologies vary widely in their potential to detect and avoid fatal collisions with pedestrians, from less than 30% (visible-light cameras alone) to over 90% (combination of cameras, lidar and radar) of preventable fatalities (Combs et al., 2019). This means that cameras, the most affordable detection technology, are unlikely to be effective alone in substantially reducing pedestrian fatality. Nonetheless, it is believed that advancements in artificial intelligence will help increase the onboard scene recognition capabilities of AVs (Gwak et al., 2019). So better scene recognition leads to safer decisions on the part of the automated driving system (International Transport Forum, 2018).

Clearly, the road infrastructure should enable and support AVs to make safe progress on roads with VRUs (Johnson, 2017). In the transitional period, physical road design changes will likely be needed for junctions and crossing to better accommodate AVs among human-driven vehicles (Kulmala et al., 2020). However, care will need to be taken to consider pedestrian and cyclist movements in any innovative design (Huggins et al., 2017). Johnson (2017) states that unless AVs are to operate on completely separate, dedicated infrastructure, other road users will need to be separated from or educated in and adapt to the behaviour of AVs in different ways. Based on expert opinion, Nitsche et al. (2014) suggest that pedestrian and bicyclist protection and shielding at urban intersections are needed for the safe operation of AVs. In addition, Transport Systems Catapult (2017) points out that infrastructure-mounted sensors and V2I communication to AVs can help, but must be developed to provide robust, mission-critical, fault-proof information rather than advisory information. Pedestrian crossings also are one of the most challenging locations for operating AVs in urban areas. The report also suggests that zebra crossings may need to be replaced with signalled crossings that are much more deterministic for pedestrians (Transport Systems Catapult, 2017). Road markings at pedestrian crossings are also well maintained and be good service quality to easily detected by on-boar sensors (Lawson, 2018).

4.9.1. *Speed limit adaptation*

Speed has been identified as a key risk factor for road users and greatly affects both the risk of traffic accidents and the severity of injuries from accidents (Konstantinopoulou and Ljubotina, 2020). With the introduction of AVs, it is expected that accidents caused by unsafe speed will be eliminated or significantly reduced. This is because AVs will likely travel at a safe speed under harsh conditions with the help of their onboard sensors as well as I2V communication and accurate map data with speed limits (Nitsche et al., 2014). There is a potential for to AVs dynamically adapt their speed based on the legal speed limit or external factors such as road alignment, congestion and weather conditions to reduce accidents caused by unsafe speed. Therefore, speed ranges will be within the permitted speed limits for each road category as AVs are expected to follow the rules (Amelink et al., 2020).

From the road infrastructure point of view, a revision or necessity of speed-related infrastructure measures needs to be reconsidered for a fully automated environment. For example, traffic calming, speed bumps, radar-imposed speed restrictions, and related engineering measures, primarily concerned with reducing the negative impact of motor vehicles in built-up areas, will likely lose their importance with the deployment of AVs. In addition, since AVs have the potential to adapt vehicle speed according to road design characteristics, relevant design parameters in the specifications need to be reconsidered (Intini et al., 2019).

Given the operating aspect of AVs, current automated driving systems are not yet ready to safely perform all driving tasks at high speeds (Schwall et al., 2020). While sensors normally see better than people, and a human cannot match a computer's response, humans are often considerably better at reading traffic and detecting potentially dangerous situations. High-speed traffic is difficult for computers to understand and predict situations happing driving environment (Pendleton et al., 2017). At higher operating speeds, automated vehicles need to perceive and react more quickly – e.g. detection of the environment by the sensors, the processing of the sensor data by the software or the achievement of a control decision (Campbell et al., 2010). Higher speeds and therefore less response time increase the complexity of ADSs as they require much faster computation time and higher computational resources (Soteropoulos et al., 2020). Therefore, different speed limits will likely be vital for the functional use of different AVs during the transition period. For example, some AV use cases such as low-speed shuttles and robotaxis may not be operated safely on high-speed roads based on the current sensor and software solutions. Additionally, depending on weather conditions, the operation speed of AVs can be changed according to their capabilities. So different speed limits may be considered for different use cases of AVs, but the effects on the traffic and management side should be considered. However, it is unclear in the current literature how different speed limits can be applied on the same roads according to different use cases or capabilities of AVs.

4.10. *Roadside equipment or street furniture*

Automated driving systems not only detect and respond to dynamic objects such as pedestrians, cyclists and animals but also need to perceive the static objects and obstacles across the road like bushes, trees, safety fences, pedestrian barriers, street nameplates, bins, bollards, hydrants, post boxes, bus shelters, grit bins, seating, verge marker posts etc. Soteropoulos et al. (Soteropoulos et al., 2020) emphasize that the complexity for automated driving systems increases as the number of objects increases due to the necessity of detecting, identifying and determining the behaviour of such objects. Thus, the more such objects mean the more complex environment for ADS. Therefore, the vehicle and information technology industries must demonstrate that their systems operate safely in complex road environments. In addition, roadside objects constitute a physical obstacle to the detection task of an automated driving system (Koopman and Fratrik, 2019). Road authorities will likely need to check the roadside frequently and take precautions for objects that may pose a risk to AVs. On the other hand, studies suggest that AVs should have a detailed prior knowledge of the traffic infrastructure and surrounding environments on the planned route before the journey starts (Huggins et al., 2017; PIARC, 2021; Ulrich et al., 2020).

4.11. Road lighting

Adequate illumination of roads especially urban roads during night hours is essential to ensure road safety for all road users (Department for Transport, 2009). According to Shladover and Bishop (2015), improving the visibility of road markings, signals, and signs enabling AVs to operate successfully may require enhanced road lighting, either through greater illumination or more closely placed lights. In particular, critical road sections such as road underpasses and tunnels may require more illumination than they do now, as a recent project shows that image-based line detection is unable to detect lines in tunnels due to low light levels (Konstantinopoulou et al., 2020). Similarly, Reddy et al. (2020) conducted experimental research on LKA-enabled vehicles to estimate the impact of driving environment components on vehicle performance and discovered that driving at night with streetlights and rain resulted in the lowest detection performance for vehicles when compared to other visibility conditions. Lastly, Ye et al. (2021) investigated the patterns and associated factors of AV trials-related road traffic injuries in California and discovered that crashes in poor lighting, even with streetlights turned on, resulted in a much higher number of victims than those in daylight. Consequently, further investment and maintenance in lightning circumstances are required in their operational regions until the AVs can operate safely at night.

4.12. Drainage systems

Drainage systems are one of the main road features that significantly affect road safety, especially in areas with intense rainfall. Insufficient drainage allows water to accumulate on the pavement surface, leading to the phenomenon of partial hydroplaning on curves at higher speeds and also reducing the skid resistance of the surface (AASHTO, 2011). Although the response of AVs to events such as skidding and hydroplaning is expected to be better than that of human drivers, it is unclear how AVs will safely perceive and respond to the environment when the road surface covers water (Johnson, 2017). Regardless of lane marking quality, the ability to read road markings and surface edges is also affected by the amount of water on the road. Inadequate drainage and muddy-filled surface cause difficulties for AVs in detecting road markings (Lawson, 2018). This is a major issue, particularly at night when there is less ambient lighting, and vehicle headlights can produce high-intensity reflections from wet road surfaces (Reddy et al., 2020). Therefore, higher priority should be given to the design and maintenance of the drainage infrastructure (Johnson, 2017). However, the expectation of suitable drainage systems covering all road networks may not be realistic. Many residential roads, low-flow roads, and even parking lots do not have good drainage systems. Therefore, ADSs need to prove their capabilities under such harsh conditions.

4.13. Assessment and maintenance of road infrastructures

Maintenance of the infrastructure is important not only to meet the needs of AV development but also to meet the safety requirements of all road users. Studies point out that the maintenance of road infrastructure will play a key role at an early stage of AVs, rather than dramatically changing infrastructure (Liu et al., 2019). It is mentioned in multiple studies in the literature that AVs are likely to require road infrastructure (e.g. road markings, traffic signs, drainage, roadside, etc.) to be maintained at a much higher level

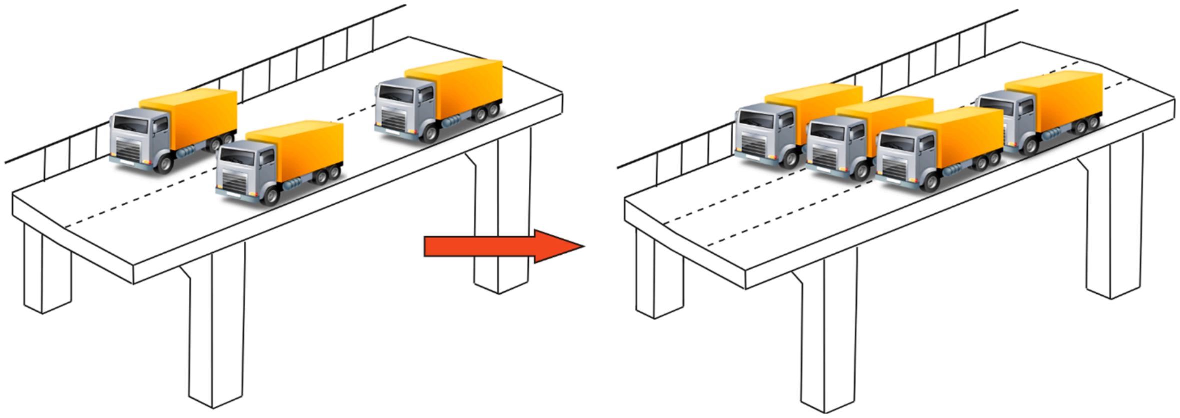

Figure 7. The capacity of the bridges will likely need to be rechecked according to new driving scenarios (e.g. platooning or lane width reconfigurations).

Figure 8. An example of the limitation in vision-based systems on near the exit of the underpasses and tunnels (Google Street View).

and a higher standard than is currently the case (Lawson, 2018; Liu et al., 2019; Johnson, 2017). Particularly heavy vehicle platooning will require a different consideration of maintenance regimes for structures and pavements (Huggins et al., 2017). For this reason, to achieve the desired level of safety, inspection and repair of road infrastructures are important. Therefore, road and city authorities need to start coordinating with the vehicle and information technology industry to develop new asset and maintenance strategies for emerging technology.

However, current road maintenance and inspection methods entail a significant amount of manual surveying effort by transportation agencies. Manual surveying is time-consuming, labour-intensive, inefficient, and prone to errors and traffic interruptions (Gouda et al., 2021; Konstantinopoulou and Ljubotina, 2020). Recently, new technologies have emerged for automated road assessment that can provide high-accuracy data at traffic speed without interrupting the current traffic flow (Urano et al., 2019; Osichenko and Spielhofer, 2018). However, while highways and trunk roads are periodically inspected with specialized vehicles (Department for Transport, 2021), roads maintained by local authorities are relatively less inspected because of a lack of budget and workforce (Urano et al., 2019). This will likely limit the road infrastructure that allows AVs to operate and will trigger several problems in terms of automated driving safety. Improving vertical and horizontal coordination between government levels is needed to foster stronger collaboration in order for improving road safety performance (International Transport Forum, 2019).

In addition, road agencies and operators will need to be allocated sufficient funds to prepare roads for AVs, but it is still unclear how they will be able to meet their infrastructure financing needs. Also, parameters of maintenance and current asset management strategies might be changed as digital infrastructure equipment (e.g. landmarks, roadside beacons, etc.) are also needed to be maintained regularly. So the type and frequency of maintenance efforts necessary for various technologies should be reconsidered. Moreover, AVs are likely to require different winter maintenance strategies (Ødegård and Klein-Paste, 2021).

On the other hand, AVs also have cameras and sensors that can collect inventory and condition data for the road (Osichenko and Spielhofer, 2018). In other words, road maintenance can also benefit from new data sources on road conditions made possible through additional vehicle sensors and V2X communication. The collection of road condition data like potholes, cracks, rutting or skid resistance facilitating sensor technology of AVs through V2X communication would greatly benefit road maintenance (Ehrlich et al., 2016). The application of this technique will allow automated inspection, geolocation and prioritization of roads or areas that may require maintenance and repair, as well as inform drivers or AVs about road safety conditions to prevent accidents. Additionally, road condition data should be made available to service and map providers to increase automated driving safety (Kulmala et al., 2020a). However, so far it remains unclear whether AV sensors will be suitable for providing road condition data. In addition, the correlation between road data from measurement systems and vehicles with ADS is under question. It is not clear whether this data will be of the same quality and usability as data from measurement devices. Also, AVs can provide this information in real time, raising questions about how this big data can be managed and how barriers to providing such data can be overcome without compromising cybersecurity and data privacy (Ehrlich et al., 2016; Osichenko and Spielhofer, 2018). The answers to these questions are important for the further development of road asset management.

5. Summary of findings and recommendations

Technological developments and regulatory reforms are accelerating the adoption of automated driving systems on the roads. However, many uncertainties remain regarding the potential impacts of AVs on physical road infrastructure. As such this research has sought to understand what the implications of AVs will likely be for the physical road environment based on a comprehensive literature review. A total of thirteen features related to physical infrastructure have been identified in the existing literature regarding vehicle automation that should be considered during either the initial phase of deployment or transition to full automation. Based on these features, the following key findings can be highlighted:

- Although horizontal and vertical alignments of roads have been found to affect the operation of existing automated driving systems, no changes are expected in the current road design philosophy for the transition period. In the long term, there are potential economic and environmental improvements for new roadway design due to the elimination of human-based driving characteristics.

However, requirements will vary by AV models and types, therefore international standardisation is needed in geometric road design parameters such as the height of the sensor positions in vehicles.

- Cross-section elements of roads such as lane widths, shoulders, medians and safety barriers are also found to affect the functioning of existing automated driving systems. However, further research is needed to evaluate and validate the effects of the type and configuration of these elements on the operation of AVs. Also, their design needs to be re-evaluated for future scenarios, including vehicle platooning. For example, no studies were found on the impact of AVs on barrier capacity, considering the re-configuration of lane width, shoulder etc. Additionally, there are no empirical studies regarding the implications of reducing the cross-section elements on traffic safety performance.
- Wider shoulders and emergency bays at regular distances will likely be needed for L3-L4 AVs to stop/park in the event of temporary termination of ODD. However, many places, such as bridges, tunnels, or some two-lane highways, do not have shoulders, so additional requirements should be considered from a safety and traffic efficiency perspective at these locations. However, the current literature is scarce on this subject. Therefore, more experimental, and simulation-based research will likely need to investigate possible scenarios and present solutions.
- The effect of vehicle automation on the road surface structure depends on many variables e.g. speed limit, lane width, uniform wandering strategy etc. In urban areas where the speed limits are low and lane width is narrow, the negative impact of AVs on the pavement such as rutting will likely be more pronounced. More field and laboratory research are needed to focus on the balance between thresholds and detailed cost-benefit analyses should be conducted to examine the optimum solutions.
- Road markings and traffic signs are key road features that affect the operation of AVs, but there is presently no formal standard or benchmark to be used by authorities to assess the quality of their markings/signs to support automated driving. It is necessary to set minimum criteria for their conditions and configurations as well as international standardisation. For this, studies are needed to determine their optimum design conditions (e.g. width, location, size, shape etc.) under different road environment conditions. Future research should include evaluating the role and effectiveness of road studs and rumble strips for AVs. Also, one of the questions yet to be unanswered is whether road marking/signs will still be important with the digitalisation of the road environment. Therefore, it is important to start questioning their role and minimum requirements of these elements with the transition to the digitalisation of the road environment.
- With the redesign of intersection layouts and the help of connectivity, there is a potential for achieving seamless traffic on intersections in a fully automated environment. However, available data on accidents involving AVs indicate that intersections are one of the most challenging road segments for the early phase of AV deployment due to the complexity of traffic conditions. For this reason, more research is needed to understand which types of intersections are safe for automated driving, and what special rules and physical requirements must be considered for intersection types to ensure AVs can perform safely, including in the special case of platooning of heavy vehicles.
- AVs will likely present new risks and challenges for existing road structures such as bridges and tunnels. Any new design should consider the impact of the heavy vehicle platoon. More importantly, existing bridge capacities need to be rechecked according to possible scenarios. Also, tunnels and underpasses are likely to need additional investment in positioning and lighting infrastructure for AVs to operate. However, more empirical findings and applications are needed on how AVs can operate safely in these critical locations and what infrastructure support will be needed.
- The transition to full automation will likely be dominated by human factors, so much research focuses on ways to reduce risks for vulnerable road users through technology. However, this may not be possible without additional precautions in physical road environments. Also, it is possible to consider different speed limits for different use cases of AVs or based on the ODD changes, but the effects on the traffic and management side have not yet been studied adequately and rigorously. Simulation-based research is needed to explore how different speed limits can be applied on the same roads according to different use cases or capabilities of AVs.
- More research is needed to clarify how automated driving can operate in improper road drainage systems and what its limitations are. Also, it is not clear whether the current standards on gradient level of roads need to be revised for future road design. This has not been systematically investigated in the literature or practice.
- Road lighting factors such as illumination colour, intensity and location of light can also affect the operation of automated driving performance. However, the available literature on this topic is limited, so further research is required to examine what the main factors are on the operation limitations of AVs and whether standardisation of these elements is necessary.
- Last but not least, it is clear that new asset and maintenance strategies are required for the safe operation of AVs. However, there is currently no official standard or benchmark to be used by transport agencies to assess the quality of their infrastructure that can support both driver assistance systems and automated driving functions. Therefore, government officials need to start coordinating with the vehicle and information technology industry to produce policies and strategies for emerging technology.

6. Conclusions

This study has gathered and interpreted the perspectives of the existing vehicle automation and infrastructure literature on the potential impacts of AVs on the physical road environment and infrastructure-related requirements for safe operation. The main implication from the identified literature is that many researchers recognise that improved road maintenance and enhanced and harmonised physical road infrastructure, in addition to digital infrastructure, have the potential to improve both driving assist systems and automated driving operations. However, given the uncertainty regarding automation capabilities and requirements, many are concerned about making long-term infrastructure investments. The main reason for this is that there are some unclear points regarding the necessary infrastructure changes, as discussed in the previous section, due to the speed and state of technological development of AVs and the rate of user adoption after commercial deployment of AVs. Also, some argue that AVs are still in the development and testing phase, so it is difficult to predict in advance which technologies will be successful and therefore what infrastructure will be needed.

Another reason is that vehicle and information technology industries are often reluctant to share what they expect from road infrastructure as they are in serious competition for a dominant position in the emerging market, which naturally leads to close protection of industry knowledge. This highlights the value of research, field testing and deployment pilots as well as organised discussion among stakeholders. Particularly, road authorities and policymakers need to start coordinating with the vehicle and information technology industries to evaluate their requirements and expectations and prepare their roads for this emerging technology. They also need to start making changes to the infrastructure where there is enough evidence of benefits. Thus, achieving readiness for automated driving will require a combination of high-level AV capabilities, upgrades to infrastructure, and improved operations and maintenance practices of infrastructure (Somers, 2019).

Otherwise, although it is not mentioned in the literature, the equity gap between societies caused by differences in the quality of infrastructure is inevitable. For example, there is potential for a gap in access to AV services among people living in the same cities due to the variability of the road environment. Therefore, instead of waiting for AVs to be ready for the roads, authorities need to focus on the question of when the driving environment will be ready to permit the use of AVs and where will this disruptive technology work best during the transition period. Also, there will likely be different types of deployments that operate in different areas of the network. Activities should begin by investigating prospective applications and their impact on cost structures, transport, and the environment.

In addition to infrastructure and technological issues, other key issues such as the lack of policies and regulations regarding the implementation of AVs, the uncertainty of societal benefits, and public trust and acceptance of AVs are frequently raised in multiple studies. The impacts of AVs on road transport, especially at high levels of automation, will be diverse, complex, and highly uncertain as it will affect many aspects of transport system performance (Milakis et al., 2017). For this reason, some researchers point out that the most important question of AV implementation is the assessment of whether it would be beneficial for each particular society and place of implementation. Therefore, there appears to be widespread agreement in the literature that the necessity of policies mitigating negative impacts and promoting socially beneficial models of AVs that can provide safe, equitable, and sustainable mobility throughout a community.

CRediT authorship contribution statement

Oguz Tengilimoglu: Conceptualization, Methodology, Writing – original draft, Investigation, Writing – review & editing. **Oliver Carsten:** Writing – review & editing, Supervision. **Zia Wadud:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Appendix A

See Table A1.

Table A1
A summary of the key attributes from the literature on implications of AVs for the physical road environment

No	Ref	Outlet type	Location	Level of automation (SAE) considered	Research type[1]	Road attributes considered												
						Road alignments	Road cross-sectional elements	Pavement / Road surface	Road markings	Traffic signs and control signals	Junctions and roundabouts	Parking facilities	Structures: bridges, tunnels etc.	Facilities for vulnerable road users	Road equipment	Lighting	Drainage system	Maintenance
1	(Alonso Raposo et al., 2017)	Report	EU	U	LR				X	X								X
2	(Amelink et al., 2020)	Report	EU	L4	LR & SV	X	X	X	X	X	X	X	X	X	X	X		X
3	(Aryal, 2020)	Thesis	Sweden	L5	AR	X*	X*	X			X							
4	(Carreras et al., 2018)	Conference paper	Austria, Spain	U	SV				X	X								
5	(CAVita, 2017)	Report	USA, Canada	U	SV					X		X						
6	(Chapin et al., 2016)	Report	USA	L5	SV		X			X	X	X		X				
7	(Chen et al., 2016)	Journal	Sweden	U	AR			X*										
8	(Department for Transport, 2015)	Report	UK	L4-5	LR & SV				X	X								
9	(Ehrlich et al., 2016)	Conference paper	France	U	LR	X		X	X	X								
10	(EuroRAP and Euro NCAP, 2013)	Report	EU	L2	SV				X	X						X		
11	(Farah et al., 2018)	Book section	Netherlands	U	LR & SV	X	X	X	X	X	X		X	X				X
12	(FTIA, 2021)	Report	Finland	L3-4	LR & ER		X	X	X	X	X	X	X	X	X	X	X	X
13	(García et al., 2019)	Conference paper	Spain	L2	ER	X	X											
14	(Gill et al., 2015)	Report	Canada	U	LR & SV		X	X	X	X	X	X	X					X
15	(Gopalakrishna et al., 2021)	Report	USA	L1-5	LR & SV		X	X	X	X	X	X	X	X	X	X		X
16	(Guerrieri et al., 2021)	Journal	Italy	L4-5	AR	X*												
17	(Huggins et al., 2017)	Report	Australia, New Zealand	U	LR & SV	X	X	X	X	X	X	X	X	X	X	X		X
18	(Intini et al., 2019)	Journal	Italy	L5	AR	X*	X	X									X	
19	(Issac, 2016)	Report	USA	L5	LR		X	X	X	X		X		X				X
20	(Johnson and Rowland, 2018)	Report	Australia	L1-5	LR, SV & ER	X	X	X	X	X	X	X	X	X	X	X	X	X
21	(Johnson, 2017)	Report	UK	U	LR & SV	X	X	X	X	X	X	X	X	X	X	X	X	X
22	(Khoury et al., 2019)	Journal	USA	L5	AR	X*												
23	(Kockelman et al., 2017)	Report	USA	L1-4	LR & SV				X	X	X	X				X		
24	(Konstantinopoulou and Ljubotina, 2020)	Report	EU	L3-5	LR & ER	X	X	X	X	X	X	X	X	X	X	X		X
25	(KPMG and CAR, 2012)	Report	UK	U	LR & SV		X		X	X		X						

(continued on next page)

Table A1 (*continued*)

No	Ref	Outlet type	Location	Level of automation (SAE) considered	Research type[1]	Road attributes considered												
						Road alignments	Road cross-sectional elements	Pavement / Road surface	Road markings	Traffic signs and control signals	Junctions and roundabouts	Parking facilities	Structures: bridges, tunnels etc.	Facilities for vulnerable road users	Road equipment	Lighting	Drainage system	Maintenance
26	(Lawson, 2018)	Report	UK	U	LR & SV				X	X	X			X		X		X
27	(Liu et al., 2019)	Journal	UK	U	LR	X	X	X	X	X	X	X	X	X			X	X
28	(Lu et al., 2019)	Conference paper	Netherlands	L4	LR & SV	X		X	X	X	X			X				
29	(Lutin et al., 2013)	Journal	USA	L5	LR		X	X				X						
30	(Lyon et al., 2017)	Report	Australia	U	LR		X	X	X	X	X	X	X	X	X	X		X
31	(Manivasakan et al., 2021)	Journal	Australia	L4	LR & SV	X	X	X	X	X	X	X	X	X				X
32	(McCarthy et al., 2016)	Report	UK	U	LR				X	X		X	X		X			X
33	(McDonald, 2021)	Conference paper	USA	L5	AR	X*	X	X	X	X	X							
34	(McDonald and Rodier, 2015)	Book section	USA	U	SV	X	X				X	X		X				
35	(Mocanu et al., 2015)	Conference paper	Austria	L4	LR & SV	X	X	X	X	X	X	X		X	X	X		X
36	(Nitsche et al., 2014)	Conference paper	Austria	U	LR & SV	X		X	X	X				X	X			
37	(Noorvand et al., 2017)	Journal	USA	L5	AR			X*										
38	(Othman, 2021)	Journal	Canada	L4-5	LR	X	X	X	X	X		X	X			X		
39	(Paulsen, 2018)	Thesis	Norway	L4-5	LR & AR	X	X	X	X	X	X		X					
40	(PIARC, 2021)	Report	-	L3-5	LR & SV	X	X	X	X	X	X	X	X	X	X			X
41	(PSC and CAR, 2017)	Report	USA	U	LR & SV		X		X	X		X		X		X		X
42	(Rana and Hossain, 2021)	Journal	Canada	U	LR	X	X	X	X	X								
43	(Saeed, 2019)	Thesis	USA	L4-5	LR & SV	X	X	X	X	X	X	X	X				X	X
44	(Shladover and Bishop, 2015)	White paper	USA	L2-5	LR & SV		X		X	X		X		X		X		X
45	(Somers, 2019)	Report	Australia	U	LR, SV & ER		X	X	X	X								X
46	(Soteropoulos et al., 2019)	Journal	Austria	L4	LR	X	X	X	X	X	X	X	X	X	X	X		X
47	(Transport Systems Catapult, 2017)	Report	UK	U	LR & SV		X	X	X	X	X	X	X	X				X
48	(UK Autodrive and Gowling WLG, 2018)	Report	UK	U	LR & SV		X		X	X	X	X	X					
49	(Ulrich et al., 2020)	Report	EU	L3-5	LR & SV		X	X	X	X	X	X	X	X	X		X	X
50	(Vujic et al., 2020)	Book section	Croatia	L5	LR				X	X								
51	(Washburn and Washburn, 2018)	Report	USA	L5	LR & AR	X					X	X						
52	(Welde and Qiao, 2020)	Journal	USA	L3 & L5	AR	X*												X
53	(Ye et al., 2021)	Journal	China, USA	L5	AR	X*			X									

(*continued on next page*)

Table A1 (*continued*)

No	Ref	Outlet type	Location	Level of automation (SAE) considered	Research type[1]	Road attributes considered												
						Road alignments	Road cross-sectional elements	Pavement / Road surface	Road markings	Traffic signs and control signals	Junctions and roundabouts	Parking facilities	Structures: bridges, tunnels etc.	Facilities for vulnerable road users	Road equipment	Lighting	Drainage system	Maintenance
54	(Yeganeh et al., 2022)	Journal	Belgium	L5	AR		X	X*										
55	(Zhang, 2013)	Report	USA	L0-5	LR				X	X								
56	(Zhao et al., 2021)	Journal	Canada	L5	AR			X*										
57	(Zhou et al., 2019)	Report	USA	L5	ER		X	X*										
Total number of research covering identified issues.						28	36	35	41	42	28	30	21	24	14	16	7	26

U = Unspecified

1: AR= Analytical research, ER= Experimental research, LR= Literature review, SV=Stakeholder views

X: Provides inference from either the problems that emerged in a real situation or the critical thinking through engineering experience.

X*: An in-depth analysis has been made on the subject

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