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ORIGINAL RESEARCH

Infrastructure-related challenges in implementing connected and automated vehicles on urban roads: Insights from experts and stakeholders

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Abstract

The introduction of connected and automated vehicles (CAVs) has the potential to bring numerous advantages to urban mobility. However, many challenges for road infrastructure need to be overcome before those benefits can be achieved. This study addressed multiple dimensions of the implications of CAV deployment for road infrastructure through a comprehensive survey with 168 experts from different sectors and regions around the world. The issues are grouped into five categories: (1) key challenges of accommodating CAVs in existing urban transport networks; (2) infrastructure improvement required for shared CAV models; (3) maintenance aspects of infrastructure for CAVs; (4) implementation time of infrastructure support for CAVs; and (5) financing infrastructure upgrades to facilitate CAVs on the roads. The outcomes of the research show that there is still no consensus among the stakeholders on what should be considered to maximise CAV benefits for society as a whole. This indicates the necessity for cooperation between stakeholders to achieve the safe and efficient operation of CAVs. Overall, this study provides in-depth insights for decision-makers and transport planners to form policies, regulations, and guidelines regarding the future implementation of CAVs for roads before their commercialisation phase.

1 | INTRODUCTION

Recent advancements in software, hardware and information and communication technologies have propelled the development of Automated Vehicles (AVs), which are no longer mere hype or science fiction but a gradually introduced technology in the automotive market [1, 2]. The classification of AVs based on their capabilities has been subject to various schemes [3], with the widely used six-level classification by the International Society of Automotive Engineers (SAE J3016) reflecting the progressive transfer of driving responsibilities from humans to vehicles [4].[1] Level 4 AVs, in particular, hold the potential for transformative changes in transportation and urban landscapes [5], as they can operate autonomously in various scenarios and geographic areas while still offering the option for human control in exceptional circumstances [6]. Beyond automation, the connectivity aspect of vehicles plays a vital role [7, 8], enabling the exchange of safety and mobility information,[2] overcoming limitations of onboard sensors and improving reliability in challenging conditions [9–11]. The integration of connectivity and automation, known as Connected and Automated Vehicles (CAVs),[3] offers unique advantages that cannot be achieved independently [12, 13].

It is a common view that in the early stages of deployment, the safe operation of CAVs at full capacity will mainly depend on the quality and consistency of road infrastructure [14–16].

[1] No automation (Level 0; hereafter, L0), driver assistance (L1), partial automation (L2), conditional automation (L3), high automation (L4), and full automation (L5).

[2] Connected vehicle technology enables wireless communication between vehicles (V2V), road infrastructure (I2V), and other components (V2X), facilitating the exchange of safety and mobility information.

[3] In this study, the term "automated driving" is used to describe the technology where automation of the driving task, vehicle connectivity, and data are brought together. Also, the term automated driving and connected and automated vehicles (CAVs) are used interchangeably.

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Several aspects of road infrastructure such as the positioning, height, and size of traffic signs, physical characteristics of road markings, variable sign message systems, warning message systems for work zones, curb areas, and maintenance strategies will likely undergo reassessment based on the capabilities of CAVs. For example, the current automation industry consistently emphasises the significance of well-maintained road surfaces and clearly visible signs and road markings, although a definitive standard has not yet been established. However, as the deployment of CAVs becomes more imminent, addressing these needs is increasingly important [17–19]. Moreover, the variety of road facilities and connectivity capabilities brings new challenges for transport authorities and legislators looking to embed CAVs into road networks. Therefore, the relationship between automated driving and both the physical and digital road infrastructure is an area of active research [18]. Road authorities and road safety organisations around the world are actively investigating potential infrastructure modifications to facilitate CAV operation (e.g. [11, 15, 20–22]). Additionally, few research projects [23–25] have been dedicated to developing classification schemes that categorise the capabilities of road infrastructure to support and inform CAVs and users about the functionalities offered by different road facilities. These efforts aim to enhance the compatibility and interaction between CAVs and the surrounding infrastructure, promoting a safer and more efficient integration of CAVs on public roads.

In parallel, regulatory bodies and organisations worldwide have been actively engaged in formulating and implementing legislation to facilitate the integration and safe deployment of CAVs [26]. Notably, the European Commission has taken a leading role in developing policies and regulations within the European Union to promote CAV deployment. Initiatives such as the European Strategy on Cooperative Intelligent Transport Systems and the European Framework for the Deployment of Intelligent Transport Systems aim to harmonize legal requirements and foster cross-border collaboration. In addition, the United Nations Economic Commission for Europe (UNECE) has played a crucial role in shaping international legislation for CAVs. The UNECE's Working Party on Automated/Autonomous and Connected Vehicles has developed standards and regulations, including the influential UNECE regulation on automated vehicles (e.g. Regulation No. 157). Also, countries such as the United States of America (USA) and the United Kingdom have taken proactive measures to support CAV innovation and deployment. The USA, through entities like the National Highway Traffic Safety Administration (NHTSA), has issued guidelines and regulatory frameworks at the federal and state levels. Similarly, the United Kingdom (UK) has established legislation and initiatives to encourage CAV testing and development, such as the Centre for Connected and Autonomous Vehicles (CCAV) and the Code of Practice for Testing.

However, automated driving technology and automation-enabled mobility services are evolving at a more rapid pace than the understanding of the infrastructure required for them to be efficiently and safely implemented [19]. As such, the number of studies addressing potential infrastructure-related requirements to facilitate CAVs or challenges associated with infrastructure adoption for CAVs is limited. Moreover, existing research on CAV implementation has mainly focused on the consumer or end-user perspective. These studies primarily examine how attitudes and perceptions can influence the intention to adopt or use CAV technology (e.g. [27–30]). However, the implementation and adoption of new technology are not solely driven by consumer demand. It is crucial to acknowledge the involvement of other key stakeholders, such as policymakers, vehicle manufacturers, and academia [31, 32].

On the other side, as noted in Shladover [33], the literature on software and hardware technologies that support CAVs is vast and growing rapidly and becoming obsolete rapidly, too. This rapid development in automation and information and communication technologies has prompted researchers who want to gather information about the latest developments in the field to seek opinions from experts (e.g. [15, 34–37]). Among these studies, for example, Saeed [2] explored the types of changes that may be needed for road infrastructure at the two stages of AV operations (transition phase and fully autonomous phase), based on expert feedback from technology developers and highway agencies in the USA. Similarly, Gopalakrishna et al. [22] have investigated the impact of AVs on highway infrastructure through engagement with highway agencies and interviews with industry members in the USA. In another study, Wang et al. [17] conducted an online survey and follow-up interviews with AV industry members alone in California, USA, to evaluate the transportation infrastructure improvement requirements that can improve AV performance. In Australia, Lim et al. [31] conducted in-depth interviews with experts from the public and private sectors who had direct experience with AVs, exploring various micro and macro environmental factors that could either impede or facilitate AV adoption.

In a similar strategy, but on a global scale, this study aims to gather insights and perspectives from experts and key stakeholders to gain a better understanding of critical factors and challenges related to urban road infrastructure for the successful implementation of CAVs. Through a large survey encompassing various sectors and regions, the study explores the multifaceted dimensions of CAV deployment implications and challenges for road infrastructure that authorities will need to consider both in the early stages of their implementation and the transition phase. The main research questions addressed in this study are as follows:

1. What are the key challenges of accommodating CAVs in existing urban transport networks?
2. How does infrastructure improvement support the shared mobility model of CAVs?
3. What additional maintenance for infrastructure will be required for CAV operation?
4. When should infrastructure improvement for CAVs be initiated?
5. How will the CAV infrastructure be funded?

The main contribution of this paper is to provide an overview of the opinions of members of different stakeholder groups that

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may affect or be affected by the deployment of CAVs, on several issues that are contested or lacking in the literature. Particularly, it provides an understanding of priority issues that need to be considered for the successful implementation of CAVs on public roads by identifying the points of convergence and divergence of stakeholders. These insights inform the formulation of policy recommendations to guide decision-makers in navigating the complex landscape of CAV implementation. To the best of the authors' knowledge, while there exist some reports that address the challenges associated with infrastructure adoption for CAVs based on stakeholder engagements, no other study has examined or compared the views of various stakeholder groups internationally on the multiple dimensions of the CAV deployment implications for road networks. Another contribution is to examine the issues that need to be considered for the readiness of the current road infrastructure to accommodate emerging technologies. In this regard, this study can be considered as an addition to reports that identify infrastructure-related requirements of CAVs for safe and efficient operation or research that identify challenges and opportunities for CAVs adoption in road networks.

The organisation of the remaining paper is structured as follows: Section 2 presents the methodology adopted in this study and provides information about the participants. Section 3 illustrates the descriptive results of survey responses and the main interpretation of findings, including the comparison between grouping variables. Finally, Section 4 concludes the paper with recommendations for transport authorities and policymakers toward to integration of automated driving in cities.

2 | METHODS

2.1 | Survey content and participants

Given the sheer diversity of stakeholders involved in the implementation of forthcoming CAV technology, this study narrowed its focus to three distinct categories of supply-side stakeholders (for a detailed examination of stakeholders, refer to [32]). These stakeholder groups can be briefly classified as follows:

1. Agency: This group comprises organisations responsible for road networks, including national, regional, and local government entities, and policymakers who make crucial decisions regarding the regulation of technology, road networks and users and the allocation of funding. Additionally, it includes infrastructure owners and operators who bear direct responsibility for the management and maintenance of roads and engineering companies providing consultancy services.
2. Technology and vehicle industry players: This group encompasses a wide range of companies operating in the automotive and technology sectors. These companies are involved in various aspects such as vehicle manufacturing, the development of artificial intelligence and sensors, the provision of vehicle components, or the sale of data related to connected and automated driving.
3. Academia: This group represents universities, research institutes, and other educational organisations involved in conducting research and providing expertise in the field of connected and automated mobility.

To get the opinions of these key stakeholders, the research employed a semi-structured online survey consisting of a mixture of closed (e.g. multiple-choice and scaling) and open-ended questions. The questionnaire was developed based on an extensive literature review [38]. The methodology adopted in this study is briefly illustrated in Figure 1. While there are other methods that can be effective for gathering such views, such as stakeholder interviews or focus groups, surveying experts on an international scale is more cost-effective and practical to obtain quantifiable data that can be analysed. Another advantage of conducting a survey is that it is anonymous, making respondents feel more confident and secure in sharing their views and expectations about the questions [39, 40]. This is especially important for industry participants because they may not wish to share information publicly about the capabilities and limitations of their products. In addition, such expert surveys give respondents time flexibility so they can respond at any time and pick up where they left off. In the scope of this research, the topics discussed are grouped into five categories: (1) key challenges of accommodating CAVs in existing urban transport networks; (2) infrastructure improvement required for shared CAV models; (3) maintenance dimension of infrastructure for CAVs; (4) implementation time of infrastructure support for CAVs; and (5) financing of infrastructure upgrades to facilitate CAVs on the roads. However, this study is part of a large survey including other research questions related to Level 4 automated driving [41].[4]

The recruitment process involved the distribution of the survey link to potential experts who were identified through various channels, including relevant past conferences, seminars, and research. For this purpose, the link was sent to the E-mail address of more than 800 individuals and also shared on social networking sites dedicated to topics such as vehicle automation, automotive industry, and transportation groups. Additionally, participants were encouraged to forward the survey link to other potential respondents within their organisations through emails and newsletters, which resulted in several successful referrals. The data collection process began in mid-October 2021 and concluded by the end of November 2021. During this period, the survey was distributed to a wide audience, reaching ≈4600 individuals. To assess the eligibility of respondents, the first part of the survey focused on the type of respondents' organisation, area of expertise, work experience, the relevance of their work content to CAVs, and country of residence to gain insight into the profile of the participant. After this step, 168 valid responses were obtained. This limited number of responses can be attributed to the specific expertise required in the field of automated driving and the nature of a comprehensive survey,

[4] The survey was conducted as part of the first author's Ph.D. research on the road readiness index for automated vehicles and only a relevant part of the data obtained from the survey was used in this research (Ethical approval protocol no: LTTRAN-142).

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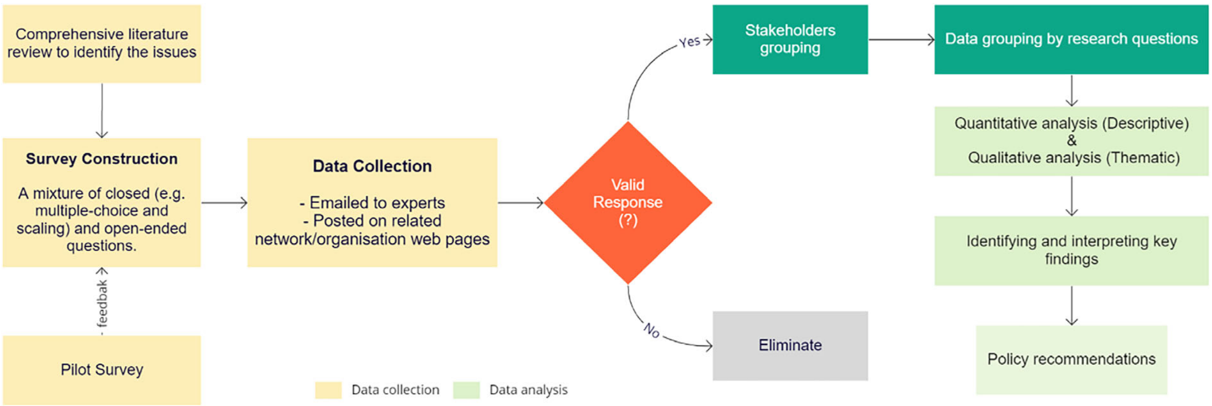

FIGURE 1 The steps of methodology adopted in this study.

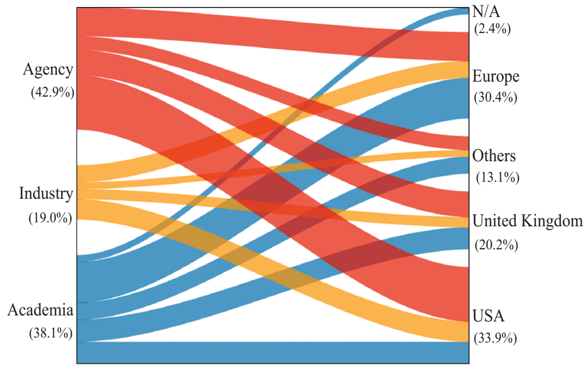

FIGURE 2 Schematic distribution of participants by organisations they represent and place of residence.

encompassing numerous questions from diverse topics. Despite this, it is worth noting that the number of experts surveyed in this study represents one of the largest samples of its kind compared to previous research in the literature.

Responses were collected from a diverse range of sectors, and were grouped into three main stakeholder groups as delineated earlier: (i) Agency (comprising local/regional authorities (9), national authorities (12), road agency/administration/operators (27), consultancy/engineering (24)); (ii) Industry (consisting of vehicle industry (15), technology developers (9), service providers and suppliers (4), research and development companies (3), insurance companies (1)); and (iii) Academia (encompassing universities (39), research institutes and organisations (25)). The composition indicates that the survey respondents well represented the key actors of automated driving. Figure 2 illustrates the proportion of respondents by type of organisation they represent and place of residence.

The study included participants from a diverse range of twenty-nine countries,[5] with a notable majority (54.1%) originating from two countries: the UK and the USA. In addition, the respondents have an average of 17 years of work experience, with over 70% of participants possessing a minimum of 10 years of professional experience in their fields. Predominantly, the respondents belonged to the agency and academy groups, accounting for 81% of the total participants. This trend may be attributed to the inherent reluctance of the vehicle and information technology industries to disclose their existing operational and capability constraints, given the highly competitive nature of the industry [24].

2.2 | Data analysis

This study used a mixture of quantitative and qualitative methodological approaches for the analysis of the responses. For the quantitative data gathered, descriptive statistics were displayed graphically. In response to the open-ended questions, a range of responses from experts and stakeholders was elicited. The thematic analysis of these responses was done using the qualitative data analysis software NVivo. First, word clouds were generated to identify the most frequently used words in the responses. This allowed us to identify emergent themes against the question [42]. After repeated reading of the responses, we coded these verbatim responses into a relatively small set of meaningful categories in order to examine key issues and check how often respondents refer to a particular issue [43]. Lastly, results were tabulated based on the groups by using the crosstab feature in the software. Some missing responses in the survey were acceptable since we expressly requested participants to skip topics that they did not want to answer or those where they believed they did not have the technical expertise to comment on. So, the total number of responses may not reach 168 for some questions.

3 | RESULTS AND FINDINGS

This section summarises the findings and interpretation of the opinions of experts and stakeholders on five topics presented in the introduction, including the rationale of the research questions.

[5] Number of participants by country of residence—USA: (57), United Kingdom: (34), Germany: (9), Italy and Australia: (6), The Netherlands and Turkey: (5), Canada, Finland, and Ireland: (4), France and Korea: (3), Albania, Austria, Japan, and Switzerland: (2), Brazil, Croatia, Denmark, Greece, India, Indonesia, Israel, New Zealand, Poland, Singapore, Slovenia, and South Africa (1), Prefer not to state (4).

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3.1 | What are the key challenges of accommodating CAVs in existing urban transport networks?

3.1.1 | Rationale

The imminent introduction of CAVs presents new challenges and opportunities for transport authorities and decision-makers looking to incorporate these technologies into the built environment. In general, studies (e.g. [44–46]) emphasise that four primary pillars play a crucial role in assessing the readiness of countries or jurisdictions for CAV operation: policy and legislation, technology and innovation, infrastructure, and user adoption. While all these aspects are vital in establishing a conducive road environment for emerging vehicle automation, the relative difficulty of achieving each pillar has not been extensively discussed. Therefore, the survey posed a question to stakeholders regarding the perceived difficulty of each key aspect and identified major barriers to accelerating CAV deployment in urban networks. Additionally, there are numerous challenges associated with CAVs within the mentioned pillars and other essential factors in adopting this emerging technology [46–48]. For this reason, the survey also asked stakeholders for their views on the main challenges of accommodating CAVs in existing urban transport networks[6] and how road authorities and policymakers can meet these challenges.

The research specifically focused on the urban road network for several reasons. Firstly, previous studies have mainly concentrated on highway automation, as controlled and well-maintained road environments are seen as potential early operational areas for CAVs. Therefore, by shifting the focus to the urban road network, the study aimed to contribute to the understanding of the unique challenges and their potential countermeasures specific to urban areas. Secondly, CAVs are expected to have significant and multifaceted impacts on urban areas, which encompass diverse environments, land uses, road types, and road users [49, 50]. The complexity and variation in urban road networks present specific challenges that need to be addressed before the commercialisation of CAVs. Additionally, since the survey also focuses on the shared mobility service of CAVs, concentrating on the urban road network can be seen as a logical approach for acquiring comprehensive interpretations.

3.1.2 | Findings and interpretation of responses

The responses ($N = 166$) show that the policy and legislation option is the relatively dominant choice among the options. About one-third of respondents (34.3%) stated that policy and legislation regarding CAVs are the most difficult milestone to accomplish to accelerate the deployment of these technologies in urban networks. The second most frequently mentioned option by respondents was vehicle technology and innovation, corresponding to 22.9% of responses. These are followed by physical road infrastructure (14.5%) and consumer acceptance (13.3%), with almost a similar ratio. On the other hand, a minority of participants (6.0%) believe that digital infrastructure will be the most difficult turning point for accelerating CAV deployment in urban networks.

Figure 3 highlights a consensus among stakeholders regarding the significance of policy and legislation as the primary bottleneck in the adoption of CAVs. This alignment reflects the recognition that automated driving will bring and/or require substantial transformations in policy and legislative strategies. Policymakers and legislators are faced with the challenge of regulating complex CAV technology, including sensors, artificial intelligence, and communication networks. Furthermore, safety assurance, liability considerations, ethical dilemmas, interoperability, standardisation among manufacturers, and the adaptation of existing laws add further complexity to this milestone.

However, other factors show some variation among stakeholder groups and regions. For instance, the academy group prioritise physical infrastructure as the second most challenging milestone after policy and legislation, whereas the agency group assigns it relatively less importance. The role of stakeholders and their country's current level of infrastructure, technology and legislation also influence responses. For instance, those in the UK believe that vehicle technology and innovation will likely be less important issues compared to other regions.

Notably, respondents (predominantly UK respondents) selecting the "other" option emphasise the interdependence of all the milestones, highlighting the need for coordination between technology, infrastructure, and policy timelines. They stress that these milestones are interconnected and crucial for accelerating CAV deployment in urban networks. Some respondents underscore the importance of societal desirability and the need for proper discussion in addressing these challenges.

Table 1 presents the heatmap of responses regarding the challenges of accommodating CAVs in urban networks and ways to overcome these. The main challenges cited by the experts surveyed are the safe and efficient management of mixed traffic, consisting of both CAVs and human-driven vehicles, and interactions between CAVs and vulnerable road users (VRUs) such as pedestrians, cyclists, and e-scooter users. Another major issue mentioned is the environmental complexity and conflicts in the urban road network. Some respondents point out that the road network is becoming more and more diversified in urban, thus increasing the complexity that CAVs must cope with. This is due to various factors such as dense traffic, unpredictable pedestrian behaviour, complex road geometries, and the need to interpret and respond to a wide range of dynamic situations. In this context, technological reliability, as well as infrastructure are key components that need to be addressed. On the infrastructure side, participants also point out the necessity of regulatory guidance to ensure consistency across all jurisdictions and uniformity.

[6] The urban road network refers to the interconnected system of roads and streets within urban areas or cities, facilitating transportation within the urban environment. It includes various types of roads, intersections, and infrastructure designed for vehicles, pedestrians, bicycles, and public transit.

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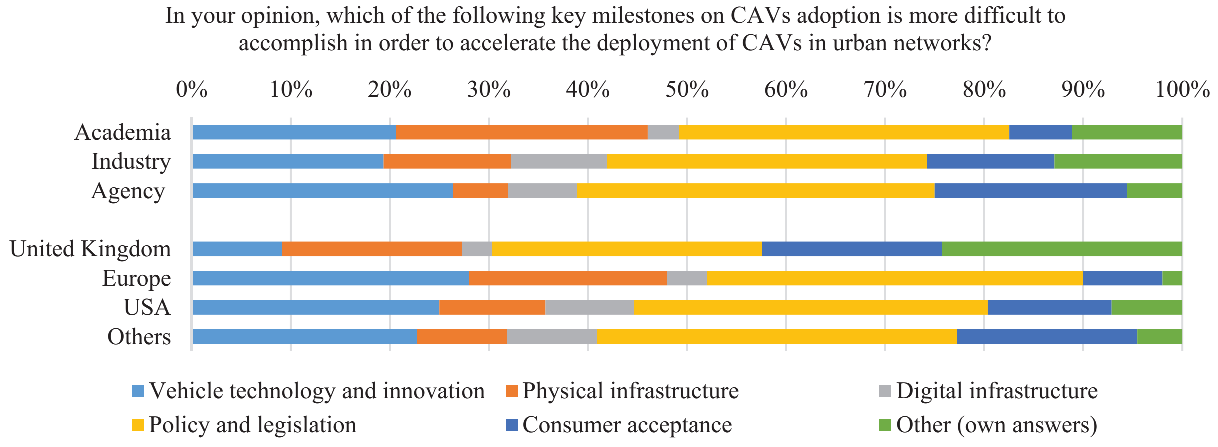

FIGURE 3 Responses to the question about the key milestones that should be accomplished for the acceleration of connected and automated vehicles (CAVs) deployment by type of organisation and place of residence (%).

It is a common expression among many responses that current CAV capabilities and technological developments are insufficient in terms of safety and reliability for societal acceptance. Further evolution of CAV technology is necessary to effectively integrate it into existing urban road networks. A group of participants advocates for the maturation of CAV technologies to prove they are safe enough before large-scale commercialisation. In this context, they highlight the significance of paving the way for CAV trials as a means to develop reliable technology over time. Respondents also note that the physical and digital infrastructure that supports the CAV operation on a large scale today does not exist or that existing provision is not suited to the needs. Limited investment budgets in CAV-focused infrastructure are stated as the main barrier to deployment. Therefore, many experts surveyed, particularly from the industry groups, emphasise the need for funding and incentives to provide the facilities that CAVs require on physical and digital road infrastructure (e.g. digital mapping and communication systems). Suggestions include implementing access-controlled lanes or roads for CAVs during initial deployment stages and establishing low-speed zones in urban areas to address safety concerns in mixed-traffic environments. However, some participants argue that CAVs should operate on existing road networks without requiring additional support beyond conventional vehicles.

Clearly defining the operational constraints of CAVs is another measure often cited by respondents to reduce the potential risks from the limitations of technological capabilities. However, this will be possible by establishing safety testing protocols for CAVs, including both software and hardware systems of vehicles. As noted in Shladover and Bishop [47], this issue has two dimensions, each with different challenges: determining the safety requirement and verifying that the particular vehicle system meets the safety requirement. To address these challenges, there is widespread agreement that collaboration between stakeholders (e.g. legislators, transport authorities, telecommunication, original equipment manufacturers etc.) is vital and essential to achieving success in this area. This is also important for the standardisation and harmonisation of regulation activities such as registration, licensing, and testing of CAVs.

Also, the reliance of CAVs on data and technology raises a wide range of new legal issues such as data protection, cybersecurity, and privacy. In addition, there is a lack of evidence on how the technology is ethically appropriate, and the moral hazard side of CAVs is seen as a main concern. Lastly, liability and insurance issues regarding CAVs are seen as one of the main challenges by many participants. Regarding this issue, there are many questions that need to be addressed. For example, where a vehicle is highly or fully automated, how will liability for road accidents be shared between the manufacturer and the driver, or what if a design flaw, a cyberattack on digital hardware or software, or an internet outage causes an accident? In short, the main challenge is to clearly define who will be responsible for what. To address the liability and insurance challenges arising from CAVs, there is a need for new regulations and insurance systems for both this emerging technology and related infrastructure. Despite this, some experts surveyed mentioned that regulators are generally under-skilled in technology to be able to meaningfully regulate the technology companies developing CAVs. Therefore, they suggest that road authorities and policymakers need first to be educated on what is CAV.

Briefly, all these challenges can be seen as major obstacles to public trust and acceptance. This is also the main reason for the reluctance of decision-makers to take the initiative in the commissioning of CAVs, as can be interpreted from the quote: *"Without a large public drive/need, why would a politician take the risk and legislate in this area? And where is the public push to move away from current (human-driven) taxi/bus models?"* (agency respondent). Therefore, as some respondents have pointed out, gradual (a process that is carried out incrementally with implementation planning from year to year) and integrated (a process that includes various aspects and cross-field expertise) planning is required for CAV implementation. Road authorities and policymakers can overcome these challenges by following a roadmap describing the proposed activities to be undertaken in terms of technology, infrastructure, policies and socioeconomics.

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TABLE 1 Thematic representation of responses on key challenges of connected and automated vehicles (CAVs) adaptation in urban road network and potential countermeasures.

	Survey respondent				Survey respondent				
	Agency (72)	Academia (64)	Industry (32)	Total (168)	UK (34)	Europe (51)	USA (57)	Others (22)	Total (164)
Key Challenges									
• Environmental complexity and conflicts in the urban road network	8	5	0	13	3	6	3	1	13
• Inadequacy of technological developments (limitations on CAVs capabilities)	10	10	3	23	10	5	6	2	23
• Interaction between CAVs and VRUs (e.g. pedestrians, cyclists)	9	14	3	26	4	13	6	3	26
• Lack of physical and digital road infrastructure to support CAV operation	12	12	5	29	8	11	9	1	29
• Liability and insurance of CAVs	15	6	5	26	5	6	11	4	26
• Limited investment budget in CAV-focused infrastructure	4	2	1	7	2	1	3	1	7
• Management of mixed-traffic situations (CAVs and human-driven vehicles)	11	15	4	30	6	13	6	5	30
• Policy and legislation barriers	11	4	2	17	2	4	8	3	17
• Societal, economic, and environmental challenges in the adoption CAVs	4	7	2	13	5	2	2	3	12
• Trust, acceptance, and willingness to use CAVs	15	4	1	20	6	6	6	2	20
Ways to overcome barriers/challenges									
• Access controlled lanes and roads for CAVs (Segregation)	6	1	3	10	2	4	2	2	10
• Addressing data management and privacy issues (data protection and cyber-security)	5	2	0	7	1	1	4	1	7
• Clearly define operational constraints of CAVs (Attributes of ODDs)	4	1	1	6	2	2	2	0	6
• Collaboration between stakeholders (legislators, IOOs, OEMs etc.)	12	4	5	21	4	4	8	5	21
• Education of the public on automated driving technologies	5	2	0	7	0	3	3	1	7
• Establishing safety test protocols for CAVs (proof of safety)	8	4	3	15	5	5	2	3	15
• Introduction of urban low-speed zones for CAVs operation	4	1	2	7	3	2	2	0	7
• Investments to support road infrastructures for CAVs (digital and physical)	9	12	9	30	5	11	10	4	30
• Maturation of automated driving technologies	3	4	3	10	2	2	4	2	10
• Paving the way for CAV trials	7	2	0	9	0	4	3	2	9
• Policies mitigating negative impacts and promoting socially benefit models of CAVs	5	1	0	6	3	2	1	0	6
• Registration, licensing, and testing of CAVs	5	2	2	9	2	2	4	1	9
• Standardisation and harmonisation of activities related to CAVs	6	8	1	15	2	7	6	0	15
• CAVs must be developed to operate on existing road networks without any support.	3	2	3	8	1	1	5	1	8
Total number of respondents (unique)	**70**	**56**	**29**	**155**	**33**	**44**	**57**	**20**	**154**

Abbreviations: VRUs, vulnerable road users; IOOs, infrastructrue owner and operators; OEMs, original equipment manufacturers.

3.2 | How does infrastructure improvement support the shared mobility model of CAVs?

3.2.1 | Rationale

Existing studies [51] reveal that, despite some negative consequences that may arise with shared CAV services (e.g. increasing vehicle miles travelled and security or privacy concerns of users), it has the potential to bring many benefits to the whole community (e.g. increasing accessibility and complementing mass transit systems). Therefore, the transition to automated driving must be carefully managed with policies that will promote the most sustainable forms of travel [52]. Activities for shared mobility models of CAV need to be supported by local and

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TABLE 2 Thematic representation of responses on infrastructure improvement for shared connected and automated vehicles (CAVs) adaptation in urban road networks.

	Survey respondent				Survey respondent				
	Agency (72)	**Academia (64)**	**Industry (32)**	**Total (168)**	**UK (34)**	**Europe (51)**	**USA (57)**	**Others (22)**	**Total (164)**
Expectations of infrastructure improvement for shared mobility models of CAVs									
• Access controlled dedicated lanes or roads for CAVs operation	8	13	3	24	4	6	9	5	24
• Facilities and measures for vulnerable road users to reduce interaction and conflict with CAVs	5	3	0	8	1	1	6	0	8
• Implementation of cameras and sensors for traffic control and management system	3	3	1	7	0	2	2	3	7
• Initiatives for consumer acceptance of sharing and integrating CAV into the Mobility as a Service platform	3	4	0	7	2	2	3	0	7
• Maintenance of physical infrastructure features and reconsideration of roadway design for safety improvements	2	3	3	8	0	3	4	1	8
• Parking facilities for CAVs e.g. pick-up and drop-off points, parking lots	11	6	4	21	7	1	11	2	21
• Providing high-definition mapping service—digital twin	6	8	1	15	2	8	3	2	15
• Reconsideration of lane width and speed limit for CAVs operation	3	2	0	5	0	3	2	0	5
• Reducing complexity in junctions and providing connected traffic light control systems for CAVs	7	9	3	19	2	7	6	4	19
• Regular checks and measures on and surrounding the roadway to improve visibility	2	1	1	4	1	2	1	0	4
• Standardisation, investment and maintenance on machine-readable road markings and traffic signs	20	10	9	39	8	8	15	8	39
• Supporting communication infrastructure (DSRC, Cellular network etc.)	21	13	10	44	5	17	18	4	44
• Supporting the localisation function of CAVs	2	3	1	6	1	3	1	1	6
• No need to significant changes in infrastructure for CAVs	5	0	6	11	2	3	5	1	11
Total number of respondents (unique)	**59**	**45**	**25**	**129**	**22**	**36**	**53**	**18**	**129**

government authorities and preparing proactive plans for these technologies will likely have a key role in public acceptance. Among these activities, supporting CAV-compatible infrastructure will likely be a key factor for the safe introduction of CAV mobility services by operators in cities. However, the public knowledge and academic literature available on the infrastructure side of vehicle automation are lacking. So, the opinions and suggestions of experts in the field on this subject are important in terms of giving a preliminary idea to the decision-makers and transport authorises. The survey, therefore, asked stakeholders a question about what infrastructure improvements could support the shared use model of CAVs in urban areas without compromising the needs of human drivers.

3.2.2 | Findings and interpretation of responses

In the survey, a range of responses from stakeholders ($N = 129$) regarding the actions on infrastructure that could support the shared models of CAV was elicited. Table 2 summarizes the responses thematically by stakeholder groups and the frequency of responses. As shown in the table, most of the requirements are not only for shared models but also crucial for the safe operation of many CAV use cases. The most mentioned physical infrastructure improvement is the necessity of the standardisation, investment and maintenance of machine-readable road markings and traffic signs. This is because current CAV deployments, either vision-based or sensor fusion-based systems, depend heavily on clear, uniform, and visible road markings and traffic signs to safely perform driving tasks. Participants claim that high contrast, reflective, and well-painted lane markers and road edges are the most effective infrastructure technology that universally benefits CAVs, regardless of the manufacturer. In this regard, some experts surveyed have emphasized the importance of the consistency of these road characteristics between jurisdictions. Therefore, it is underlined that international harmonisation and standardisation on road markings and traffic signs are needed, including relative to the location of the roadway.

Another frequently cited improvement on physical infrastructure is the implementation of dedicated lanes that could help to realize the full benefits in specific locations while operations remain in the mixed-use case. Regarding this, some respondents suggested that dedicated lanes for public transport vehicles can

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be allowed during the transition period. Additionally, a few participants mentioned that special lane markings such as magnetic markers can be considered for these lanes in dense urban zones to support the basic operation of CAVs. In connection with this improvement, facilities and measures should also be taken into account for VRUs to reduce interaction and conflict with CAVs. Pedestrian fences along the sidewalks and physically separated lanes for bicycles or micro-mobility users such as e-scooter are some of the examples stated by respondents for this improvement in dense urban zones.

In addition, the accommodation of shared mobility models of CAV in the urban network will require the reconsideration of parking facilities. There was a wide consensus among stakeholders that the dedicated curb area for passenger pick-up and drop-off and CAV-compatible parking lots will support the efficient operation of CAVs. There were also some radical ideas for parking practices, such as removing on-street parking from all commercial corridors and replacing them with pick-up and drop-off zones, and introducing high-cost or limited parking for private single-occupant vehicles. This will also encourage potential users to accept shared mobility by providing a more convenient service. This seems to be important because some experts surveyed point to the necessity of initiatives for consumer acceptance of sharing CAVs. Moreover, maintenance of physical infrastructure features, reconsideration of roadway design for safety improvements, and regular checks and measures on and surrounding the roadway to improve visibility are less frequently mentioned than other previously stated physical infrastructure improvements.

Concerning the digital features of road infrastructure, the importance of supporting short-range and long-range communication infrastructures for the efficient and safe operation CAVs is stated mainly by respondents. Therefore, uninterrupted telecommunication networks (i.e. good cellular network coverage) or implementation of roadside units (e.g. dedicated short-range communication) at critical locations along the road network will likely play an important role for CAVs in receiving critical operational information such as road conditions, work zones, incidents, or lane closures. However, their effectiveness relies on the availability of traffic control and management centres, and information systems that provide up-to-date data by road agencies or city authorities. Road condition sensors and cameras need to be implemented to provide continuous data from the road environment. Some participants stressed the need to allocate space for retrofitting the physical components of digital infrastructures. Additionally, some participants expressed that internet-based cloud systems for sharing such data in real-time or in advance (e.g. information about work zone plans) will be important for the safe operation of CAVs. Another frequently mentioned support for connectivity is the implementation of traffic light control systems that can communicate with CAVs to share traffic signal information (e.g. Signal Phase and Timing and Green Light Optimal Speed Advisory). This can be crucial not only from a traffic efficiency perspective, but also for safe operation, especially where traffic signals are difficult to detect by automated driving technologies. More information on the facilities of these communication services for automated driving can be found in the reports [11, 53, 54]. Besides, standardisation of intersection layouts or adjustment of traffic rules such as some restrictions on CAV manoeuvres to reduce complexity is mentioned by participants to be able to support CAVs in urban networks. Lastly, according to some the most helpful infrastructural improvements would be high-definition digital twins of city areas and road networks.

On the other hand, some agency participants expressed concerns about uncertainties in CAV deployments and technology capabilities, making it challenging to determine common requirements for authorities in their investment plans. For example, one of these participants emphasised this uncertainty by stating, *"We do not know yet exactly what CAV will actually require."* Another participant explained the industry's diversity by stating that different CAVs under development require various roadway features for operation. This includes preferences for high reflective striping, reliance on signage or base mapping, and the need for communication systems. Agencies face a significant dilemma in preparing for the wide variety of CAVs due to the lack of standardisation in their operation. Also, some participants claim that no significant physical infrastructure changes should be made until the market is more mature, and the focus should be on the digital side until the new business models for CAV's matures. This is because for CAVs to become mainstream, they must be able to share roads with human-driven vehicles—and most are being developed to do so. Therefore, infrastructure improvements or changes should be minimal.

3.3 | What additional maintenance for infrastructure will be required for CAV operation?

3.3.1 | Rationale

Deployment of CAVs will likely pose new challenges in maintenance and asset management systems for cities and road authorities to ensure their roads are safe and compatible with all road users. In other words, with the adoption of CAVs instead of human-driven vehicles, different infrastructure maintenance requirements are likely to be needed [55]. Many studies in recent years have underlined the importance of road infrastructure maintenance in the initial phase of CAV deployment [22, 36, 56, 57], rather than dramatically changing infrastructure [58]. For example, the frequency of maintenance of road infrastructures, which may be critical to CAVs, and current winter maintenance strategies can change drastically as sensor-based vehicles hit the roads [59]. A recent survey of AV industry members in California highlighted that the performance of automated driving systems will improve with well-maintained infrastructure [17]. Therefore, CAVs can probably be expected to require stricter rules for maintenance. In short, a change in the approach to road maintenance and asset strategies may be required to facilitate the safe operation of CAVs. In addition to the statements mentioned in the available literature, to understand the stakeholders' opinions on the maintenance aspects of road infrastructure, in the survey, we asked two questions: *1) Do*

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you think the parameters of maintenance and current asset management strategies will change? 2) What additional maintenance for infrastructure will be required for CAV operation?

3.3.2 | Findings and interpretation of responses

In the survey, about half of the participants ($N = 85$) expressed their opinions directly regarding the change in maintenance and asset management strategies that could support the safe operation of CAV. Most of these respondents ($n = 57$) believe that maintenance parameters and current asset management strategies will change drastically because the AD technology requirements from the infrastructure will be different. Regarding this, one general view is that parameters will likely expand to include additional supportive equipment (e.g. roadside devices) that will need to be maintained that is different from traditional infrastructure. Another more optimistic view is that reliance on physical infrastructure will decrease as technology advances. Some of these participants argue that anything that needs a change in current asset management strategies should be moved to digital platforms. As such, it will likely require a different maintenance approach. However, according to some experts surveyed, although a change in existing procedures is needed, the funding and time necessary to develop and implement a national infrastructure with standardised traffic control devices are at least a generation away. On the contrary, a small group of respondents ($n = 17$) mainly industry representatives argue that most infrastructure required for CAVs is essential and desirable for all users, so maintenance needs will likely not change dramatically. Some also point out that regardless of the CAVs, parameters for maintenance and asset management are continuously changing based on experience and knowledge. As was mentioned multiple times, some respondents argue that CAV manufacturers should be encouraged to improve capabilities within existing infrastructure provisions. According to these stakeholders, the less external infrastructure is needed outside the vehicles, the better, because they believe that all other scenarios will not become fundable. Lastly, a relatively small group of respondents ($n = 11$) did not have a clear view of the subject and expressed that they are unsure until the technology is ready.

With respect to the necessity of additional maintenance on the infrastructure for CAV operation, a range of responses from stakeholders ($N = 128$) was elicited. In general, the responses of stakeholders are consistent with outlined maintenance requirements for CAVs in the current literature. Many participants ($n = 54$) pointed out the importance of the quality and consistency of physical infrastructure and surrounding road environment for CAV operation. It is expected that CAVs will require higher and more frequent infrastructure maintenance compared to the current maintenance schedule for human-driven vehicles. The rationale is that human drivers have a good ability to detect and react when road infrastructure deteriorates or is not up to standards. However, current automated driving systems have limited capabilities to perform driving tasks when faced with gaps in the infrastructure, thus needing data fusion from different sensors or external supporting information via connectivity. In short, the degradation of road infrastructure will pose a challenge to the safe performance of CAVs. Therefore, respondents believe that keeping infrastructure more compatible and detectable for vehicle sensors will be crucial in the transitional phase. In this context, assessing the readability of road markings and traffic signs (e.g. painting, cleaning), repairing road surface conditions (e.g. potholes, rutting), providing proper road lighting, controlling traffic loading on long-span bridges due to platooning effects, or channelisation of pedestrian crossings and intersections are some of the examples in maintenance that need to be considered. Also, roadside environments such as plants and trees that are constantly growing during the spring and summer months should be regularly maintained because onboard sensors of CAVs see them as obstacles and they affect the sight lines of vehicles. In addition, locations with extreme weather (e.g. snow, flooding) have significant impacts on the roadway system, so asset management and maintenance will be critical to ensure the safe operations of CAVs. Therefore, some respondents ($n = 6$) underline the importance of the necessity of new adverse weather maintenance strategies for CAVs.

In fact, nearly all mentioned precautions related to physical infrastructure are also important and beneficial for human-driven vehicles in terms of safety. The main expected difference is that more frequent maintenance will play a critical role in the CAV adoption in road networks. In this context, frequently recorded road views or monitoring the road conditions with sensors might be necessary as well as some communication equipment might help CAVs learn the new road conditions. However, present road maintenance and inspection methods necessitate extensive manual surveying work on the part of agencies. According to some participants, a paradigm shift from traditional human judgment techniques to more objective tracking and assessment techniques based on the technology will be necessary for road maintenance. Additionally, there is potential to leverage the CAVs' cameras and sensors to be able to collect and share inventory and conditions data for the road. However, there are many uncertainties about whether the data provided by CAVs will be accurate and appropriate. Furthermore, CAVs can offer this information in real-time, but this raises concerns about how this data can be managed and how hurdles to supplying such data can be overcome without jeopardising cybersecurity and data privacy.

In addition to the current physical road infrastructure attributes, the maintenance and control of newly introduced digital infrastructure (e.g. communication units and sensors) and their physical components will need extra consideration from authorities or service providers ($n = 59$). As frequently mentioned by participants, current road infrastructure uses long-cycle maintenance. However, with more electronic equipment installation on roads, the maintenance cycle will need to be much shorter and much more time-sensitive, and thus more budget will be required for more teams, more spare parts' stock and so on. Some respondents ($n = 4$) emphasise that agencies and city authorities will need personnel with higher qualifications to maintain these electronics. Lastly, digital mapping will likely be needed for road safety features and conditions

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to allow rapid treatment and mitigation of priority items in road networks. Furthermore, a few experts ($n = 3$) point out that infrastructure maintenance plans and execution should be part of the certification process for roads and controlled by independent audits.

3.4 | When should infrastructure improvement for CAVs be initiated?

3.4.1 | Rationale

There has been a growing literature in recent years recognising the importance of the quality and consistency of road infrastructure in the safe operation of CAVs [58]. Similarly, the findings of the previous section show that maintenance of road infrastructure will be crucial to maintain a high level of road quality so that CAVs can operate safely. However, there is uncertainty about when the necessary infrastructure-related improvements for automated driving and connectivity will be introduced to meet the emerging market needs [60]. This uncertainty may remain until the marketplace further matures. Therefore, to get a preliminary idea of the subject, we asked stakeholders a question: *"What is the minimum level of market penetration for road agencies and operators to start reorienting their road infrastructure to accommodate CAVs?"*

3.4.2 | Findings and interpretation of responses

Looking at the distribution of responses, there is no dominant choice among the stakeholders ($N = 162$). About one in four respondents (22.2%) expressed that when about less than 10% of vehicles on roads are CAVs, road agencies and operators should start to re-orient their road infrastructure for CAVs. Relatively more participants (25.3%) believe that this should be started when about 10–25% of vehicles on roads are CAVs. This indicates that about half of the participants (47.5%) express that when less than 25% of vehicles on the roads are CAV, necessary infrastructure improvement should be considered. Conversely, around 30% of the respondents suggested that improvements should be contemplated once the market achieves a specific threshold of penetration, such as exceeding 25%. For closer inspection, Figure 4 illustrates the proportion of responses based on the grouping variables. The data in the figure clearly show that the participants from academia and industry groups have relatively more favour for infrastructure improvements in the early stage of the CAVs to accelerate the adoption. A similar trend can be seen in the respondents from Europe. On the other hand, agency participants are more in favour of waiting for the technology to mature or until it proves beneficial to overall community goals and then acting on the infrastructure needs.

Moreover, nearly one-fourth of respondents (23%) selected the "other" option to share their views regarding the question. Considering the comments expressed here, there is no distinction between stakeholder groups on views and three different views can be underlined:

- The first group is in favour of taking proactive action in advance of the widespread implementation of CAVs, recognizing the crucial role of road infrastructure in automated driving. They believe that without some upgrades to an existing roadway and higher levels of maintenance, it might not be obtained higher automation levels on roads. These respondents emphasise that many of the infrastructure improvements for CAVs will also make roads safer for all users. Therefore, national plans are required for infrastructure to facilitate automated driving.
- The second group is more cautious in this regard and favours the gradual implementation of necessary improvements as the market matures. They point out that maintaining the minimum standards on roadways (e.g. improving lane markings) will be necessary for the early stage of CAVs, but substantial maintenance needs to occur further down the track. That is, the type of infrastructure change depends highly on the degree of penetration. However, some participants argue that comprehensive orientation such as changing lane width might require nearly 100% adoption. Participants also stated that for the transition period, different areas should be zoned as CAV and non-CAV.
- The third group argues that CAVs should be designed to adapt to existing roads, so there should not be major changes in the physical road infrastructure, but rather the digitisation of the mobility system, which is relatively inexpensive compared to the physical infrastructure. However, these respondents anticipate that there may be changes on the physical roads for use cases of CAV with societal benefits such as buses and shuttles.

3.5 | How will the CAV infrastructure be funded?

3.5.1 | Rationale

Numerous studies (e.g. [47, 57, 61, 62]) and some official reports [63] indicate that new funding and incentives are needed to provide the facilities that CAVs need for physical and digital road infrastructure. However, there has been limited research in the available literature focusing on the financing requirements for infrastructure-related investments, maintenance, and operation expenses [60, 64]. Government revenue, budget and financial institutions should conduct a thorough review of how revenue streams may change as a result of automation and supporting legislation [1, 65]. Krechmer et al. [66] have discussed a set of individual scenarios with corresponding upgrade cost estimates that might be paid for by public or private organisations in the USA. However, there is a lot of uncertainty around this issue and a lack of evidence on how to measure the potential impact of CAV adoption on financing plans and, more importantly, what the approach of stakeholders from different groups is. Moreover, developing new business models for financing infrastructure improvements will likely be needed for different jurisdictions. This is because, as noted in Shladover and Bishop [47], approaches that fit well within one country's established

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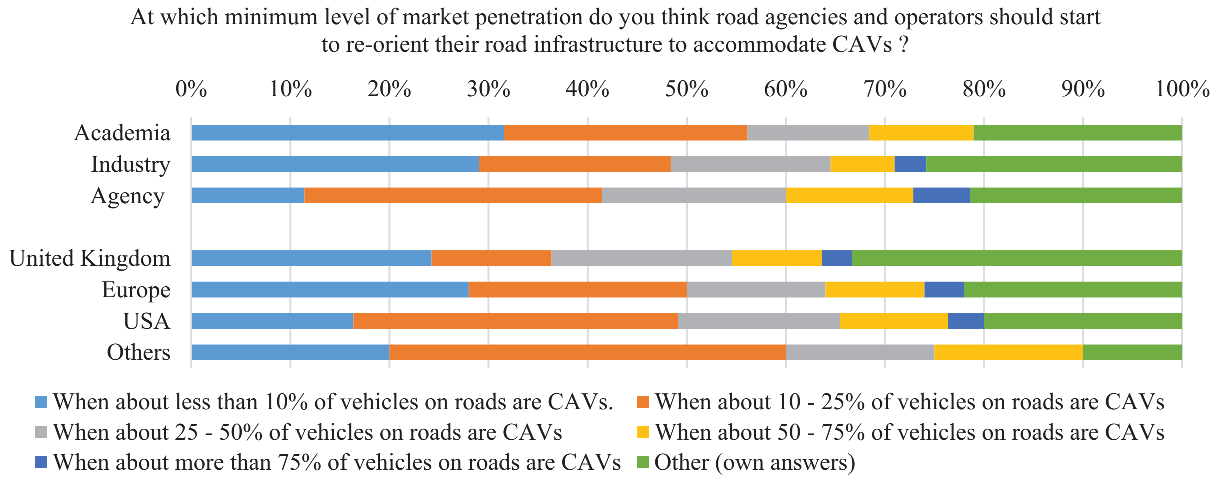

FIGURE 4 Responses to the question about the penetration rate for infrastructure improvement for CAVs, by type of organisation and place of residence (%).

business and legal frameworks may not fit well at all in another. In the survey, we asked stakeholders how road agencies and operators (IOOs) can meet their infrastructure financing needs to accommodate CAVs on the roads to understand the recommendations of the experts on the subject.

3.5.2 | Findings and interpretation of responses

In the survey, a variety of responses ($N = 141$) were received from stakeholders regarding potential actions that could contribute to financing needs for infrastructure-related investments. However, some of the answers (*n = 23 respondents*) were not applicable as they either stated that they had no idea about the question or were related to their expectations and views in the context of automated driving and infrastructure. For infrastructure-related investment, a few respondents ($n = 9$) believe that road agencies and operators, as well as local authorities, can afford their financing requirements through internal funding and budgetary allocations. However, some ($n = 7$) point out that there is great uncertainty about the requirements, as there is currently no agreement on optimal and standard requirements that can facilitate automated driving due to a lack of knowledge. Therefore, road agencies and operators are still unsure what will be needed or how to budget. For example, an agency participant stated this as follows: "*We first need to understand what is needed and develop strategic plans to incorporate the things that will be needed and utilized by CAV technology. This will allow IOOs to spend money wisely and not on things that are not useful.*"

On the other hand, a group of respondents ($n = 13$) argues that the efforts and focus should not be on building and investing in infrastructure specifically for CAVs, but on initiatives that will be beneficial for all road users. Among these experts, as mentioned in the previous sections, some suggest that CAVs should be developed to operate on the existing infrastructure and they need to prove their safety, as well as benefit the whole society. One example of this view is that *"If CAVs need additional infrastructure to operate then the technology is not mature enough."* Therefore, proofs of concept that CAVs are safer than human drivers and finding the proper arguments for public acceptance are required before road agencies and local authorities have any motivation to make the required changes.

Contrary to previous opinions, another group of participants ($n = 13$) believes that road agencies and operators cannot afford these investments alone, so they should not be solely responsible for them. In this regard, participants point to the current financing constraints faced by road and local authorities to keep roads maintained. One of the respondents criticises this situation by commenting: "*For basic, simple things (like painting faded road lines, cleaning road signs, and so on) they often fail to do this well enough, even for human drivers, despite it being a legal requirement.*" This is because funding is a major challenge, particularly for local governments with limited infrastructure budgets. As one participant (from Academia and Europe) commented, *"with limited funding, investments specific only to CAVs might not be justifiable."* For this reason, according to some participants, CAVs that can work on the existing infrastructure will be the best fit with the current state of infrastructure funding. In other words, this view asserts that CAV technology should, at least in the short term, be developed in locations where the need for extra infrastructure support is minimal.

However, considering current technological deployments, it may be unrealistic to expect maximum benefit and social value from CAVs without infrastructure improvements. According to many respondents, roads allowing CAVs to travel must have additional infrastructure elements; thus, unit investment per vehicle must be minimized by starting with major arterials and city centres where we have high traffic volumes. For intercity/rural corridors, these should be the ones with higher commercial vehicle traffic volumes as the commercial vehicle fleet transformation to CAVs can be faster and more fundable. The key consideration is that road agencies and local authorities should not be obliged to invest simply to enable CAVs to get started: the private sector such as technology companies and service providers need to contribute to fund any necessary infrastructure. Therefore, many participants ($n = 20$)

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believe that public-private partnerships will be key to moving forward with ubiquitous infrastructure distribution. Particularly, when it comes to funding large-scale transportation projects that involve design, building, financing, operation, and maintenance in one package for CAV-related facilities, incentives for the private sector by regulatory bodies will likely be critical.

In addition, given the current financial situation of local authorities and road agencies, there will need to be significant government policies in place to better support the use of CAVs before they become mainstream. Many respondents ($n = 34$) emphasise that new business models and strategies need to be identified for CAV-oriented investments. For instance, it requires a large shift to funding maintenance of traffic control devices and new connected technology from pavement management and construction budgets. This will take a paradigm change in legislation and policy ($n = 8$). As commented by one of the respondents these changes should be implemented incrementally, aligning with the advancements in vehicle technology. Moreover, one of the main challenges the authorities will face is that different levels of vehicle automation and use cases can require different infrastructure support and therefore different business investment models will need to be considered. For this reason, participants point out that multilateral cooperation at the levels of producers and road authorities needs to make a decision to use public and international funding.

To date, roadway infrastructure has been designed based on the average human driver criteria. For this reason, identifying the variation between the average human driver and the developing CAVs is essential. Determining where design standards may need to be adapted to accommodate both will allow agencies and authorities to focus funds in areas that will create a longer infrastructure life for the least cost. It is also worth noting that, some of the investments in improving current road infrastructure will be beneficial for both the CAVs and human-driven vehicles, such as well-painted road markings, clear and consistent traffic signs, frequent maintenance of road surfaces and so on. Therefore, the realisation of these improvement investments needs to be made by using public funds that mainly come from the taxation of the car-buying public, fuel taxes, licencing and so on ($n = 16$). This may not be an issue until vehicle technology reaches Level 4 automation, as human drivers will still be required for safe use (i.e. traditional car buying will continue, and revenue streams may not significantly change). But the main challenges begin with Level 4 services where a driver may not be needed in certain operational areas. In this context, the policy options could be around a charging model to provide further funding, but this is a politically tricky thing to do and requires getting the public on board and showing all the potential positive and negative aspects regarding safety, the environment, accessibility and so on. Some respondents ($n = 6$) believe that the cost of infrastructure-related investment can be compensated by the direct and indirect benefits of CAV adoption. However, this will be difficult to handle from the existing budgets of authorities because the initial investment cost will be high and the savings offered are a long way in the future, making the business case hard to predict. According to a group of experts ($n = 19$), a special tax can be issued for certain transportation services for funding purposes. Regarding this, stakeholders mentioned many options for user-based charging, such as tolls on roads, vehicle miles travelled (VMT) fees, congestion fees, additional registration fees for privately owned CAVs and so on. Among these options, some participants believe that mileage-based user fees may be an equitable approach to funding considering the connected direction vehicles are progressing as well as the likely reduction in gas revenue (due to electrification in the vehicle industry). One of the respondents explains this situation by commenting: "*VMT is the only way to make the needed funding possible. The decline in collected funds is affecting the authorities and change needs to be made to include all of the forms of users. The funding currently does not keep up with maintenance let alone the new infrastructure to be implemented.*" However, some argue that introducing a toll system may not be successful since during the transitional phase most vehicles will not be CAV and thus will not pay. Therefore, the system can only be funded through the combination of the general exchequer funding and the collection of taxes/tolls from a certain group of taxpayers (users of automated driving services).

4 | CONCLUSIONS AND POLICY RECOMMENDATIONS

This study engaged a diverse group of experts and key stakeholders to comprehensively explore the various aspects of connected and automated vehicles (CAVs) deployment on urban roads. By analysing and interpreting the feedback collected through an online survey, the research identified areas of agreement and disagreement among stakeholders, resulting in some policy recommendations.

One common conclusion emerging from the survey is that stakeholders' attitudes and perspectives on the implementation of CAVs vary based on the types of organisations they represent and their geographic regions. Respondents from Europe, for example, prioritise challenges related to managing mixed traffic situations and interactions between CAVs and vulnerable road users (VRUs). UK respondents, on the other hand, highlight concerns about the adequacy of technological advancements. In contrast, USA respondents mainly underlined liability and insurance issues associated with CAVs. These differences can be attributed to the varying levels of infrastructure, technology, and legislation in each country [44], as well as their unique urban forms. The current state of these factors in each region shapes stakeholders' perceptions and priorities regarding the implementation of CAVs. For example, EU stakeholders commonly emphasise the use of low-speed shuttles in urban streets, reflecting their strategic focus on integrating into public transport systems. In contrast, stakeholders from the USA frequently emphasised the concept of driverless taxis, reflecting a car-focused approach in their strategies for CAV implementation.

While the priorities of each stakeholder in the deployment of CAVs may differ, there was a strong consensus regarding the main barriers to CAV adoption in urban networks. Concerns for the safety of automated driving technologies and deficiencies in

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the development and implementation of policy and legislation are widely recognised as significant challenges. In fact, there are two kinds of challenges awaiting authorities to facilitate the integration of CAVs: the first is the steps to be taken for the successful implementation of CAVs on the existing road network and the second is the problems arising from the implementation. There was widespread consensus that it is not possible to address many of these challenges without concerted cooperation among stakeholders. Therefore, new platforms are vital to provide continuing dialogue between stakeholders. Another commonality was the need for investment in road infrastructures that would benefit the safe deployment of CAVs. The main reason for this is the frequent mention of the lack of physical and digital infrastructure to support the CAV operation on a large scale, regardless of their mobility models.

Nevertheless, the findings of this study indicated the presence of three distinct perspectives among stakeholders regarding infrastructure improvement to support automated driving. According to the first group, mainly from industry and academia representatives, infrastructure investments need to be made “in advance” of widespread consumer adoption of vehicle technologies. The main argument is without any supportive upgrade in infrastructure maximum benefits of automated driving will not be achievable by relying on only vehicle technology. On the other hand, the second group of participants (predominantly legislators and IOOs) are in favour of a “wait to see” stance to take action on this emerging mobility option. This is mainly because uncertainties regarding technological advancement and CAV implementation pose a major challenge for authorities to plan infrastructure upgrades in their short-term agendas. More importantly, their impacts on road transport are still highly uncertain as they will affect many aspects of transport system performance. Therefore, the steps that pave the way for CAV trials will play an important role in the development of reliable technology over time and in evaluating their potential impacts. The third group, however, is more sceptical in this regard and holds that automated driving systems must be able to perform all driving tasks safely on existing road infrastructure. Their argument is that it is neither possible nor feasible to prepare all roads for CAVs. However, achieving the desired level of digital infrastructure in the urban network is commonly seen by many stakeholders as a relatively less challenging step to support the deployment of CAVs. The overall opinion is that digital infrastructure can offer greater potential for short-term benefits compared to physical infrastructure upgrades, by providing cost-effective and adaptable solutions to improve transportation systems.

Contrary to the differences of opinion regarding CAV infrastructure improvement, another common agreement among stakeholders was that CAVs will require stricter rules for maintenance regimes of road networks. This also means that current maintenance and asset strategies will need to be changed significantly. Compared to human-driven vehicles, it is expected that CAVs will require more advanced and frequent infrastructure maintenance to keep infrastructure more compatible and detectable for onboard sensors of vehicles. While there are arguments suggesting that CAVs may collect data for the network themselves, stakeholders have expressed concerns about the quality, consistency, and sharing/storage of such data. Therefore, the development of new technologies for automated road assessment becomes increasingly important to ensure the provision of highly accurate and officially approved data for road authorities [56, 67]. Another consensus was that the maintenance and control of the emerging digital infrastructure (e.g. communication units, road detectors, sensors, cameras, etc.) and their physical components will require separate consideration by the authorities or service providers. With more electronic equipment installed on the roads, the maintenance cycle will need to be much shorter and time-sensitive [55]. This also brings a necessity for personnel with higher qualifications and skills in multiple fields for road agencies and city authorities to operate and maintain these electronics. An interdisciplinary approach and collaboration with other stakeholders will be key to expanding their in-house expertise [22]. Briefly, to facilitate the integration of CAVs, a more proactive approach (i.e. shifting from a repair-as-needed approach to a preventative-maintenance) is necessary for the maintenance of road infrastructure, as stated by Wang et al. [17]. Also, it is necessary to initiate direct and in-depth discussions between the public and private sectors on the standardisation of many digital infrastructure aspects and the determination of task sharing.

There was no widespread agreement among stakeholders on the financial models to meet the needs of infrastructure-related investments, maintenance and operating expenses. In particular, it remains unclear how the authorities will meet the initial infrastructure investments related to CAVs and who should be responsible for them. Moreover, there is substantial uncertainty and information complexity around the minimum and optimum requirements of CAVs. Although the need for standardisation and harmonisation in activities related to road infrastructure and maintenance of infrastructure elements has been highlighted, there are not yet official specifications or agreed guidelines for assessing the readiness of existing infrastructure. The diversity in CAV capabilities and models also poses challenges for authorities to understand and act based on the requirements of emerging mobility trends. Therefore, as a first step, it is necessary to determine the roadway characteristics that allow for a minimum performance at each automation level or within various mobility models. Then, by starting the investments with roadway features that are important for human-driven vehicles, it will likely eliminate disagreements or controversies in the public sphere.

Despite the inherent uncertainty concerning the future, it is argued that decision-makers should be aware of upcoming public finance challenges and take them into account in their agendas. With the introduction of CAVs, it is likely that the revenue streams of both local and central governments will change drastically. Currently, many countries rely mainly on revenue from fuel taxes of vehicle users for investment in road infrastructure. However, with the increasing trend of vehicle electrification due to environmental benefits and regulatory requirements, revenue streams for road authorities are declining. Therefore, CAVs (expected to be electrified) will not directly contribute to road maintenance to a major extent unless

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a new business model is developed for electric vehicles. The tax structure will need to be reconsidered before CAVs begin to dominate the roads, or CAVs' maintenance and infrastructure demands dominate road maintenance costs. This is because there is a common argument that infrastructure owners and operators cannot afford the required investments alone. However, for the early stage of deployment where the operation of CAVs will be limited due to the lack of coherent road infrastructures, the integration of new business models may raise many social and equity concerns among the public. On the other hand, it is not clear how accepting CAVs users will be about paying extra for features that can only be used while driving in wealthier political jurisdictions, as stated in Shladover and Bishop [47]. Therefore, although operating environments are expected to be constrained, commercial fleets are viewed as feasible in the short term [22], with cooperation between the public and private sectors. This seems particularly important because survey findings showed that there is a concern about whether investments in CAVs will benefit all segments of society.

There are clearly further needs for research in specific areas. Firstly, while this study primarily examined experts' opinions of CAV deployment and infrastructure requirements, it is important for future investigations to also consider public opinions, which are commonly incorporated in CAV adoption research [28]. Differences in opinions between stakeholders and the public regarding CAV deployment can offer decision-makers a more comprehensive understanding of the overall landscape. This is because stakeholder opinions and public opinions can differ on the deployment of CAVs, hence the requirements and challenges [68]. Although this study revealed variations in stakeholders' attitudes and perspectives towards CAV implementation, these observations were derived from qualitative analysis of open-ended responses, lacking quantitative validation. Therefore, the findings of this study can be utilised in future research to compare expert opinions across diverse stakeholder groups by using multi-actor multi-criteria analysis (MAMCA). As evidenced by Kroesen et al. [69], expert perceptions have undergone shifts as a result of increased related research in the domain and heightened awareness of CAV technology. The findings can be compared over time to track changes in stakeholders' perceptions of CAV deployment and its impact on infrastructure. Implementing these recommendations will contribute to a more profound comprehension of the perceptions and expectations surrounding CAV deployment and infrastructure.

AUTHOR CONTRIBUTIONS

Oguz Tengilimoglu: Conceptualization; formal analysis; investigation; methodology; resources; software; visualization; writing—original draft. **Oliver Carsten**: Supervision; writing—review and editing. **Zia Wadud**: Supervision; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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