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Infrastructure requirements for the safe operation of automated vehicles: Opinions from experts and stakeholders

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ABSTRACT

The need to future-proof road transport networks is becoming increasingly urgent in order to take full advantage of automated vehicles (AVs). It is now vital to understand the basic road infrastructure requirements of AVs in order to assess the readiness of the existing road network and prepare the roads for the safe operation of these vehicles. However, current literature on this subject is limited. As such this research seeks to understand the desired infrastructure-related requirements of highly automated vehicles (SAE Level 4) for safe operation based on a survey with experts and stakeholders. On the basis of 168 expert responses from 29 countries, this study presents stakeholders' views on: (1) deployment paths of Level 4 automated driving, (2) the concept of road certification for automated driving, (3) basic road infrastructure elements for the safe operation of automated driving, and (4) factors affecting safe operations of Level 4 automated driving. The findings show that different types of stakeholders (e.g. academics, infrastructure owners and operators, and vehicle and information technology developers) have broadly similar views on most criteria requiring consideration in the early stages of automated driving implementation. However, there is no clear consensus on issues regarding operating constraints on road networks and some are 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.

1. Introduction

Automated vehicles (AVs) along with electrification and shared mobility, are currently recognised as one of the three ongoing revolutions in road transportation (Jaller et al., 2020). However, enabling AVs to travel on public roads might require some infrastructure upgrades or adjustments based on the needs of automated driving technologies (Manivasakan et al., 2021). Current road infrastructure and the surrounding environment are designed and built for human drivers and may not be able to deal with the integration of vehicles with high levels of automation (Lengyel et al., 2020; Liu et al., 2019). In other words, it is not known whether they are ready for the safe and efficient operations of AVs during the initial phase of implementation (Johnson, 2017). Also, there are significant differences in the quality, nature, and maintenance standards of roads in the same country and between countries. This gives reason to hypothesise that some roads or zones will likely be less suitable for AVs than others, and therefore the appropriate ones should be prioritized to ensure the highest levels of safety in the early phases of deployment. Hence, with the transition from human-driven vehicles to automated vehicles, the demand for future-ready road networks will likely become more important.

The role of infrastructure in vehicle automation clearly depends on AV capabilities. The six-level classification (SAE J3016) of on-road automation capabilities of vehicles is widely used in academia: no automation (Level 0; hereafter, L0), driver assistance (L1), partial automation (L2), conditional automation (L3), high automation (L4), and full automation (L5). This driving automation spectrum (L0-L5) demonstrates the increasing automated driving capabilities based on the gradual shift of responsibility for dynamic driving tasks (DDTs) from a human driver to computer-based systems. Among these levels, L4 and L5 are the main automated stages, which are fail-safe situations where drivers have sufficient warning or do not need to concentrate on their driving tasks at all (SAE International, 2021). Major benefits of AVs are expected at these stages (e.g. increasing accessibility of people with limited ability of transportation provisional or allowing users to be engaged in other activities in vehicles etc.), therefore this study focused

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on L4 and beyond.

For the transition period to full automation, studies point the safe operation of L4 vehicles at full capacity will heavily depend on the type of infrastructure they encounter (Evas and Heflich, 2021; Huggins et al., 2017; Madadi et al., 2018). Automated driving trials have been disengaged many times due to factors related to the road environment and infrastructure, such as poorly marked and inconsistent road markings (Favarò et al., 2018; Ye et al., 2020). Europe's leading road safety authority (EuroRAP) highlights some potential problems that AVs are likely to encounter given the current infrastructure deficiencies (Lawson, 2018). It is therefore important for road authorities and agencies to know how ready their road infrastructure is for safe automated driving operation (Zenzic, 2019). However, current academic literature and field reports are lacking on this subject (Farah, 2016). Few studies have attempted so far to investigate the role of infrastructure in automated driving (e.g. Amelink et al., 2020; Ehrlich et al., 2016; Gill et al., 2015; Gyergyay et al., 2019; Huggins et al., 2017; Johnson, 2017; Transport Systems Catapult, 2017a) and the number of pilot projects (e.g. Konstantinopoulou et al., 2020; Marr et al., 2020) addressing infrastructure challenges for AVs is limited. Particularly, the number of studies addressing potential infrastructural requirements to facilitate AVs remains substantially limited (Lu et al., 2019; Nitsche et al., 2014; Wang et al., 2022). In short, the literature points to the need for research to assess what infrastructure needs are to contribute to facilitating AVs in the built environment.

This research aims to fill this gap by identifying the potential infrastructure-related requirements of automated driving using a survey to get the views of experts in the field. Another key contribution is to identify (any) differences in perspective between regions and sectors from which experts come, and to provide clear directions to transport authorities based on opinions elicited. In this context, the study focused on the near future to assess the readiness of road infrastructure in the early stages of L4 automated driving applications, which will likely be introduced to roads at a remarkable level within the coming decade (ERTRAC, 2019). The term 'automated driving' is used to describe the technology where automation of the driving task, vehicle connectivity, and the data are brought together (Shladover, 2018).

The rest of the paper is organised as follows. Section 2 presents the methods adopted for data collection and analysis and describes the profiles of the stakeholders surveyed. Section 3 illustrates the descriptive results of survey responses and the main interpretation of findings, including a comparison of opinions between various types of stakeholders. Finally, Section 4 summarises the main findings and gives future research recommendations.

2. Methods

Despite some recent works, there is a general lack of published material on basic road infrastructure requirements for automated driving, as noted in the introduction. The intense competition between automotive and information technology companies for gaining a dominant market position leads to the careful preservation of industry expertise, too (Shladover, 2018). Therefore, little information is available in the public domain regarding precise infrastructure-related vehicle requirements. The AV community, on the other hand, is fast evolving, and aside from highly guarded development projects, there is substantial knowledge in academia, OEMs, and public trials. Under this circumstances, expert consultation appears as an appropriate research method to understand the requirements and implications of AVs for road infrastructure. While there are several options available to seek expert opinions, such as conducting individual interviews or focus groups, these can be time-consuming and costly. On the other hand, questionnaires are more cost-effective and provide more quantifiable data that can be easily analysed. Qualitative methods are generally favoured due to their ability to gain more detail by collecting information about people's views on a given question (Taylor et al., 2015). A mixture of quantitative and qualitative methods, on the other hand, can allow for more diverse insights to be drawn from the results (Thomas et al., 2020). Therefore, this research used a semi-structured questionnaire comprised of a mixture of closed (e.g. multiple-choice and scaling) and open-ended questions to gain an insight into the opinions of experts from various backgrounds.

2.1. Survey instructions and questionnaire content

The draft questionnaire was created using Online surveys (onlinesurveys.ac.uk), a web-based survey tool after identifying from the literature potential factors that affect the safe operation of automated driving. It was subsequently modified and refined based on the outcome of the pilot survey with 5 researchers in the field, before being delivered to the target experts. The final version of the questionnaire consists of 27 questions divided into 5 parts, excluding the instructions for participants. These are.

- Part 1 focuses on the type of respondents' organisation, area of expertise, work experience, relevance of their work content to AVs, and country of residence to gain an insight into the profile of the participant and assess their eligibility for the study. This also allows for the evaluation of a correlation to be formed between the profile-based attributes and the attitudes towards questions.
- Part 2 covers general questions about AV deployment and its potential impacts.
- Part 3 includes a set of questions about participants' views on physical road infrastructure requirements and road evaluation for AV-specific functionality and safety, including questions regarding the concept of road certification.
- Part 4 covers questions about digital and communication infrastructure requirements for automated driving.
- Part 5 focuses on the importance level of thirty potential road safety assessment factors or infrastructure elements that can affect the safe operation of L4 automated driving.

2.2. Participants and data

The survey focuses on three key stakeholder groups who will affect or be affected by the infrastructure for automated driving: academia (e.g., universities and research organisations), industry (e.g., technology developers, vehicle manufacturers, and service providers), and government agencies and related institutions which are responsible for infrastructure investment, regulations, and policy formulation (e.g., national authorities, local authorities, road agencies, and consultancy firms). Although road users have been identified as one of the key stakeholders in many studies (Hamadneh et al., 2022; Lu et al., 2019; Saeed, 2019), they were not considered as we mainly focused on technology and related road infrastructure requirements. After receiving an ethical approval form the University of Leeds Ethics Committee (LITTRAN-142), the questionnaire link was e-mailed to potential experts and stakeholders identified from relevant conferences, workshops, and research. They were also asked to forward it to other possible respondents within their organisations via e-mails and newsletters and several did so. Reminders were sent out to recipients approximately three weeks after the original email date. In addition to the target contacts, the survey link was also shared on social networking sites related to vehicle automation and transportation organisations.

Data collection began in mid-October 2021 and ended at the end of November 2021. A total of 168 valid responses were received from experts and stakeholders, making it one of the largest studies of such experts to participate (compared to Farah et al., 2018; Gopalakrishna et al., 2021; Madadi et al., 2018; Nitsche et al., 2014; Saeed, 2019).[1] Participants came from twenty-nine different countries, but more than half were from two countries: the United States of America (USA) and the United Kingdom. Participants have an average of 17 years (SD 10.8) of work experience, and more than 70% of respondents have at least 10 years of experience in the field. Most are from agency (43%) and academy (38%) groups, with the rest working in the industry (19%). Table 1 shows the detailed breakdown of the respondents' backgrounds.

Table 1
Number and proportion of respondents by type of organization they represent, total work experience, and place of residence. [a], [b].

			Number of Respondents	Percentage share [%]
Organisations	**Academia**	Universities	39	23.2
		Research institutes and organisations	25	14.9
		Total	**64**	**38.1**
	Industry	Vehicle industry	15	8.9
		Technology developers	9	5.4
		Service providers & suppliers	4	2.4
		R&D companies	3	1.8
		Insurance companies	1	0.6
		Total	**32**	**19.0**
	Agency	Local/regional authorities	9	5.4
		National authorities	12	7.1
		Road agency/ administration/ operators	27	16.1
		Consultancy/ engineering	24	14.3
		Total	**72**	**42.9**
Work experience		0–9 years	45	26.8
		10–19 years	44	26.2
		20–29 years	46	27.4
		>30 years	30	17.9
		N/A	3	1.8
Place of residence		United Kingdom	34	20.2
		Europe	51	30.4
		USA	57	33.9
		Others	22	13.1
		N/A	4	2.4

[a] Number of participants by country of residence - USA: (57), United Kingdom: (34), Germany: (9), Italy and Australia: (6), The Netherland 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).

[b] Pearson's Chi-Squared test was carried out to assess whether grouping variables are correlated. Based on the results, no association was found between groups: for organisations and work experience ($\chi2$ (6) = 11.934, p = 0.063); for organisations and place of residence ($\chi2$ (6) = 8.663, p = 0.193); for place of residence and work experience ($\chi2$ (9) = 5.790, p = 0.761).

2.3. Analysis method

A mixed methodological approach was adopted in this study. Statistical analysis of the collected quantitative data was performed using Excel and SPSS, and descriptive statistics were presented using graphics. Some missing responses were valid, as we specifically asked participants to skip questions that they did not want to answer or that they thought did not have the technical knowledge on the subject. The responses of the participants were tested with the Kruskal-Wallis H test, which is suitable for testing the statistically significant differences of the variables where preference scales were used (Liljamo et al., 2018; Marusteri and Bacarea, 2010). Lastly, qualitative data analysis software NVivo was used for the thematic analysis of the open-ended responses to the survey questions.

3. Results and discussions

The research questions in this study are grouped into four main categories: (1) deployment paths of L4 AVs, (2) concept of road certification for automated driving, (3) basic road infrastructure elements for the safe operation of automated driving, and (4) factors affecting safe operations of L4 automated driving. In light of these four topics, the analysis and interpretation of opinions of experts and stakeholders are presented in the following sections, including the rationale of the research questions.

3.1. When, where and which model of level 4 AVs are expected to be widely available?

3.1.1. Rationale

In recent years, most vehicle manufacturers have adopted automation technology as a support for the driving task, and as a result, L1-L2 systems have become commonplace in the existing vehicle fleet (Robinson et al., 2017). Considering the L3 systems, it raises many controversial questions about how the process can be managed if drivers (DDT fallback-ready users) do not respond when the occurrence of a failure or out of operational design domain (ODD)[2] condition – which is referred to as a minimal risk condition.[3] To avoid this challenge in L3 AVs, technology firms and some conventional automakers are focusing on developing and manufacturing L4 automated driving (Bigelow, 2019). In L4, system is expected to handle the fail-safe situation autonomously within the certain ODDs. For this reason, L4 AVs are of great interest in both academia and industry and are currently being tested on real roads in many cities around the world, albeit on a small scale (Farah, 2016; KPMG International, 2020). Several documents have been published that provide descriptions of automation systems and the expected date of their possible deployment, taking into account different use-cases and mobility models (Aigner et al., 2019; ERTRAC, 2019; Litman, 2020; Transport Systems Catapult, 2017b; Zenzic, 2019). Studies predict that, in general, L4 AVs will be on the road in the next decade, but the actual deployment path of AVs and the precise nature of the transition path remain unclear (Milakis et al., 2017). However, to prepare and evaluate

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[1] This online survey was conducted as part of the first author's PhD research on the road readiness index for automated vehicles. Only a part of the data obtained from this survey was used in this research.

[2] SAE International defined the ODD as *"operating conditions under which a given driving automation system or feature thereof is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics"*.

[3] According to the BSI (CAV Vocabulary BSI Flex 1890 v4.0), "minimal risk condition" defined as: *"stable, stopped condition to which a human driver or automated driving system brings a vehicle after performing the dynamic driving task fallback in order to reduce the risk of a collision or other loss when a given trip cannot be continued"*. For example, at Level 3 if the human driver fails to respond to transition demand, a failure mitigation strategy follows, such as stop-in-lane.

the future-ready roads, understanding the deployment paths of L4 automated driving is essential. Therefore, this section presents the results of the questions asked to get participants' views on when, where and which models of the L4 AV will be generally available to the public.[4]

3.1.2. Findings and interpretation of responses

The first question in this regard concerned the deployment time of L4 automated driving, which is considered safe enough to be allowed for public use. Responses show that there is no dominant choice among the options (N = 165). About one in six respondents (17.6%) were very optimistic about the deployment time and believe that L4 AVs will be available for public use in the next 5 years (starting with 2021). Relatively more participants (27.3%) stated that this technology will hit the road and be safe enough in the next 5–10 years. The second-highest proportion (19.4%) was the option of in the next 10–15 years. Only a minority of participants (7.9%) have stated that L4 AVs will not likely be considered safe enough to allow for public use before the next 20 years. To examine the differences of opinion among stakeholders, Fig. 1 illustrates the proportion of responses based on the type of organisation respondents represent, their total work experience in the relevant field, and their place of residence. The figure shows that the participants from the USA, and those with relatively little work experience generally have a very positive attitude towards the deployment time of AVs. More than half of the responses in both groups indicated that L4 AVs would likely be safe and on the road in the next decade.

Considering the comments stated in the "other" option (10.9% of respondents), participants generally highlighted the role of ODDs and specific controlled environments in assessing the deployment time of L4 automation. Most of these respondents expect L4 AVs with the carefully defined ODDs will likely be available for public use within the next 5–10 years and, but only on a small part of the network specifically maintained for successful operation. Most of the network will likely be suitable in more than 20 years and entirely dependent on technological advances that negate current challenges. Moreover, some stressed that deployment time largely depends on what use-cases are considered. In this context, they point out that in a very restricted ODD, L4 vehicles like robotaxi, heavy-duty trucks, shuttles, and small robot delivery services are already operating on some public roads and sidewalks by giving examples. However, many have the same opinions that current L4 AVs are still under development and not safe enough for citywide operation, therefore at-scale commercialisation of L4 AVs will take much longer.

In the next question, stakeholders were asked for their views on what types of roads should be considered safe for the operation of L4 automated driving during the initial stage of deployment. For this, by giving their definitions, respondents were asked to choose five different road types commonly adopted in the UK.[5] Multiple responses were allowed to this question, and a total of 313 responses were collected from 168 participants. The results show that over 60% of respondents believe motorways with or without active traffic management systems will likely be considered safe road types for the early operational phase of L4 AVs. The second most frequently selected option was minor roads, corresponding to 26.2% of respondents. This indicates that participants might have an opinion that minor roads will be more suitable for low-speed AVs operation from a safety point of view. Considering A and B roads, only 10% of respondents had an opinion that these roads would be safe for L4 operation. On closer inspection, the findings show that there is no remarkable difference in opinions between the groups (see Fig. 2). However, various explanations were made by the participants in the "other" option (17.3% of the total participants). These are.

- A group of respondents noted that the type and intended use of the L4 vehicle will be directly related to the areas in which it could safely operate, and most developers are focusing on a particular type of area for their early deployments. They commented that well-maintained protected environments such as dedicated lanes/roads and areas where pedestrians can be controlled will likely be considered safe road environments for AVs. In addition, some participants mainly from the industry highlighted the importance of the role of infrastructure and road environment in AV capabilities and stated that the initial deployment will take place on networks that prove their safety status. Some of these responses are: "*There is not a safe option, the environment needs to be built to accept these driverless vehicles. Until there is a sufficient level of control over the environment, it will not be safe. The environment also needs to be sure of an excellent standard level of maintenance*" and "*It depends less on the type of road than on the level of infrastructure development*".
- Some experts believe that AVs will only operate on limited-access motorways due to safety reasons. One respondent specifically stated that controlled long-distance motorways sections only be safe for the operation of AVs. Similarly, few respondents have a pessimistic view of AV technology on minor roads, commenting, "*We have very mixed modal traffic in the cities, which I do not think the AVs would be able to handle sufficiently well*" and "*There are unresolvable problems for the safe operation of L4 AVs in urban environments*". However, another group believe that for the early stage of deployment, low-speed models of L4 AVs will be available on private roads or geo-fenced areas (e.g. university campuses, theme parks, airports, manufacturing plants, etc.) rather than public roads for avoiding high risks.
- Unlike previous views, some academy participants argued that it depends on the safety assurance of the vehicles and one stated that *"If the vehicles can be assured to handle the specific hazards associated with each road type, then it may not matter. How can city authorities control which AVs might be used on their roads?"*.

The last question was about the deployment model of L4 AVs. In this context, we asked the opinions of the stakeholders about three models that are likely to be encountered with the emergence of L4 automation technologies.[6] Responses (N = 167) indicate a relatively dominant choice among the options. Half of the respondents (49.7%) stated that the public transport L4 AV service model will likely be available for public use firstly compared to other models. This opinion corresponds to around 60% of the UK respondents (see Fig. 3). When the private (18.6%) and shared (19.2%) L4 AV models are considered, there is not any remarkable difference of opinion among the participants. However, closer inspection shows that respondents from the agency and industry groups do not have the same opinion about these two models compared to the academia group. They asserted that privately-owned L4 AVs will likely be generally available firstly compared to shared models. On the other hand, academia respondents chose the shared L4 AV model almost twice as many as the private L4 AV use model.

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[4] Relevant definitions and schematic representations of vehicle automation levels in accordance with SAE J3016 were also given in the survey to evaluate similar technology and eliminate the misconception about L4 AVs among the participants.

[5] These are: *Motorways* that are high-traffic access-controlled roads where non-motorized vehicles and pedestrians are prohibited; *Smart Motorways* that employ active traffic management techniques to monitor and respond to fluctuating traffic conditions; *Radial roads (A-roads)* which are high-density traffic roads that connect motorways to distributor roads or urban centres*; Distributor roads (B-roads)* that connect A-roads with minor or local roads and generally have low to moderate capacity; and lastly *Minor roads (local roads)* that provide access to residential areas and other local developments.

[6] These are: 1) Privately owned L4 AV - You own the vehicle but will use the auto mode on certain road types and conditions; 2) Shared L4 AV - You do not own the vehicles, but you will/(not) share rides with strangers in certain areas; 3) Public transport L4 AV - Such as bus services on private lanes and certain routes.

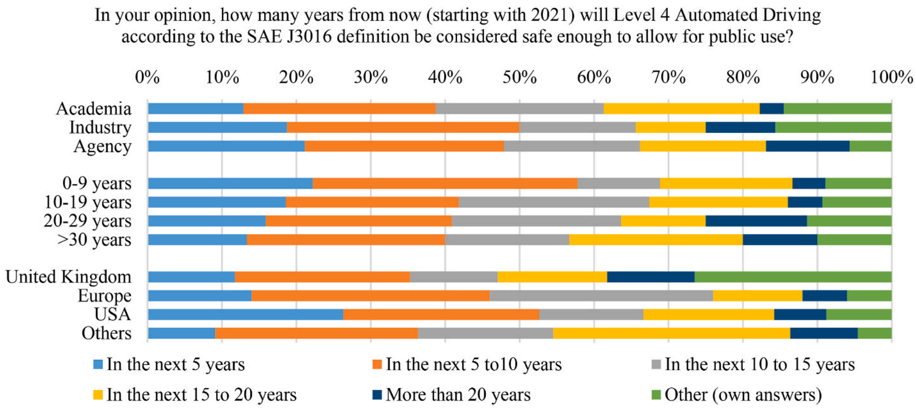

Fig. 1. Responses to the question regarding the deployment time of L4 AVs for public use, by type of organisation, work experience, and place of residence (%).

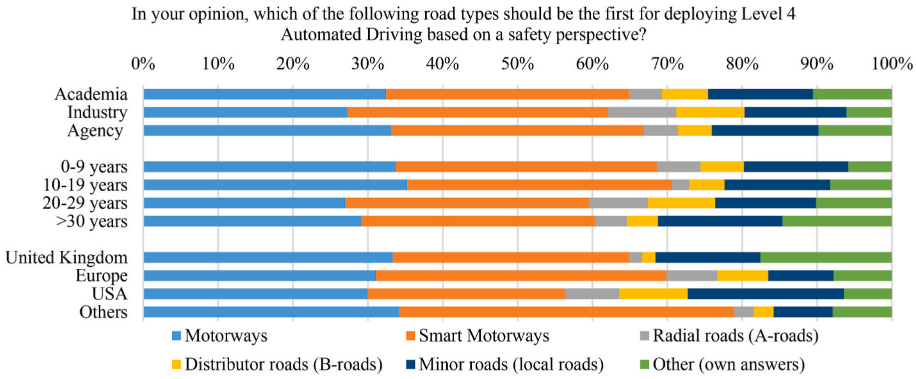

Fig. 2. Responses to the question regarding the road types for the safe operation of L4 AVs, by type of organisation, work experience, and place of residence (%).

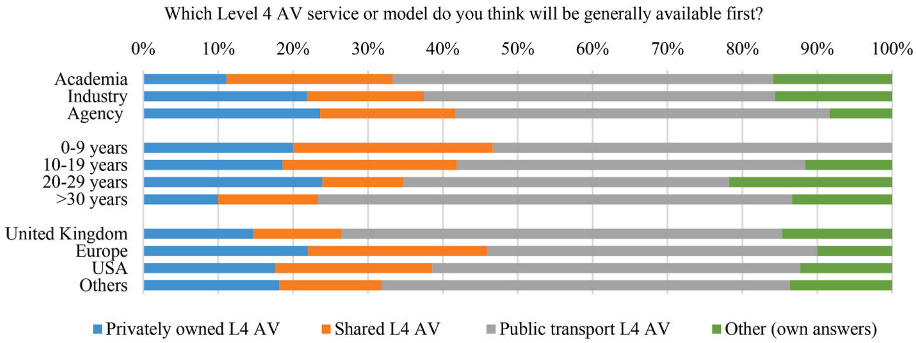

Fig. 3. Responses to the question regarding the deployment model of L4 AVs, by type of organisation, work experience, and place of residence (%).

In addition to the use-cases given in the question, looking at the opinions expressed in the “other” option (12.6% of respondents), respondents highlight automation in freight transport such as L4 automated freight trucks or commercial vehicles should not be overlooked. They suggested that commercial trucking owned by a company would probably be generally available first. In addition, some express that several models of L4 will likely be available on the market simultaneously.

3.2. Do we need to certify roads for automated driving?

3.2.1. Rationale

There has been a growing literature in recent years recognising the importance of road infrastructure for the safe operation of automated driving. 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 for collaborative and complementary approaches (ERTRAC, 2019). Among these efforts, a recent project has proposed a simple classification scheme to classify the capabilities of a road infrastructure to support and guide AVs (Carreras et al., 2018). In this context, five levels of infrastructure support for automated driving are defined and suggesting 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 the coming motorway automation era. Similarly, the concept of road classification (García et al., 2021; Poe, 2020) or certification (Cheon, 2003; Huggins et al., 2017; Issac, 2016; Zhang, 2013) has been specified by some researchers, however, the idea is mostly based on the digital infrastructure for motorways. Besides, the requirements of this concept can be idealistic, expensive, and difficult to meet for all roads, especially low-volume road types such as small city streets (Madadi, 2021).

Given the current ADS technologies, AVs capable of operating on all existing road networks in various environmental conditions are not expected to emerge in the short term, at least at an affordable price (Shladover and Bishop, 2015). Reliance on vehicle technology alone without infrastructure support may jeopardize the potential safety and efficiency gains of AVs. Therefore road certification or assessment of road infrastructure might play an important role in demonstrating suitable routes for the safe operation of AVs, as well as ensuring the safety of all road users in the early stages of deployment. This issue was handled in the survey by asking questions about the necessity of road assessment and the concept of road certification. This section presents the findings of the responses to these questions.

3.2.2. *Findings and interpretation of responses*

The first question was whether AVs should be allowed to operate on all public roads or only certain subsets of the road network. Just over half of respondents (53.7%) stated that AVs should be allowed to operate on only certain subsets of the road network (N = 162). Unlike this view, 46.3% of the participants argued that AVs should be allowed to operate on all public roads. This indicates that there is no dominant view from the participants regarding the question. Fig. 4 shows that only stakeholders from the agency group prominently stated that AVs should be allowed to operate on only certain subsets of the road network (61.4%). On the contrary, participants in academia (50.9%) and industry (54.8%) believe that AVs should be allowed to operate on all public roads. Also, those with relatively less work experience have the same view. Considering the residence-based grouping, around two-thirds (64.5%) of UK respondents believed AVs should only be allowed to operate on certain roads of the networks, whereas for other locations there was no clear agreement on this.

Also, we asked an additional question about what difficulties would arise in the implementation of this requirement for those who chose the option “on only certain subsets of the road network”. Based on a review of the 81 responses to this question, the following key statements can be highlighted.

- A group of respondents mentioned that the methodology for selecting suitable road sections and subnets that can meet the requirements for the safe operation of AVs in the network will likely be very difficult and complex. Additionally, some participants emphasize the difficulties of balancing between the investment cost of required road infrastructure and meeting the user demands. Therefore, it would be difficult to support AV travel on all roads as the cost of building infrastructure for a limited number of vehicles operation might be expensive and not be feasible during their initial stages. Experts noted the challenges of how to design AV routes or catchment areas that correspond with the trips people want to make. Low consumer uptake of AV technology could be a problem if it can only be used in certain locations. They added that this would be triggered by the public perception that infrastructure would be only to support the wealthy that can afford the technology.
- Another frequently mentioned problem by participants is the requirement of effective enforcement. These respondents underline that policy development is needed for specific roadways until technology can be applied to any roadway/environment. In addition, few participants pointing out the necessity of public education about the capabilities and limitations of automated driving. Some of these responses are: “*ensuring that all users are aware of where AVs are permitted*”, “*ensuring that AV operators know which roads are available to them and enforcement of those rules*”, “*educating drivers about their responsibilities*”, and “*educating the public about safe operation and the boundaries required until greater acceptance*”.
- Some respondents noted that as an interim step, as automated driving technologies are not yet ready for use on all public roads, well-maintained, very accurately mapped, and controlled subsets of the network will reduce difficulties in deployment. However, according to some, this will require more advanced road quality management and maintenance than is available, and it will also be difficult to provide real-time data for road accessibility. Also they underlined that the difficulties of geofencing in practice and maintaining definitions of allowed zones, accounting for vehicles with different capabilities.
- In the context of geographic limitations, many participants pointed out the importance of clearly defining the boundaries within which the AV can operate safely. These participants mainly noted possible functional difficulties in operating L4 AVs. Some of the responses are: “*Difficulties could arise with these vehicles not being able to get to the full range of destinations they would like*”, “*What happens at the edge of the ODD?*” and “*What to do if the beginning or ending of a trip is outside of the ODD?*”. This is because in the period of transition, not all the networks may be AV ready, so it may be necessary for drivers to take over in areas where the road infrastructure or environmental conditions cannot support L4. For example, one expert noted that “*ODD must be clearly documented and be communicated to the vehicle owner. Violation of operations outside ODD needs to be prevented by technical means*”. However, some worry about managing the transition from automated to manual mode or manoeuvring between subsets and claim that some temporary deadlocks on roads may occur. Therefore, recognition and classification of subsets and ODDs would be difficult and segmented and differentiated driving in mixed usage areas could bring new uncertainties and risk developing new risk scenarios.

The second question in this thread concerned whether the necessity of an approach such as road certification or iRAP star rating[7] to assess the suitability of roads for the operation of AVs. More than half of the respondents either strongly agree (21.8%) or agree (32.7%) with the statement that roads need to be classified or properly evaluated for the AV operation (N = 156). On the other hand, roughly one in seven respondents (14.7%) expressed a negative attitude towards the requirements of road certifications for AVs, and the proportion of those with a very negative attitude was only 4.5%. Moreover, a considerable number of participants (30.8%) have a neutral opinion regarding this subject. The proportions of the responses according to grouping variables are illustrated in Fig. 5. Overall, the results were consistent across stakeholders, with no significant differences detected between grouping variables.[8] However, a prominent finding is that approximately 40% of the industry respondents strongly agree with the road assessment requirements for automated driving, while this is about 20% for academia and agency. Also, those who state that AVs should only be allowed to operate in certain subsets of the road network are more in favour of the necessity of the road certification approach. On the other hand, experts who argue that AVs should operate on all road networks are generally more neutral or negative towards the idea of road evaluation.

The findings of the previous questions suggest that assessing the suitability of roads for AVs is desirable among stakeholders. However, it is also important to discuss who should be responsible for this audit. Responses (N = 159) indicate that the road agencies/administrations option is the relatively dominant choice among the possibilities. About half of the respondents (46.5%) suggest that road infrastructure readiness assessment for AV operation should be conducted by road agencies/

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[7] Star ratings are based on road inspection data and provide a simple and objective measure of the level of safety which is ‘built-in’ to the road for vehicle occupants, motorcyclists, bicyclists, and pedestrians.

[8] According to the Kruskal Wallis H test, p value is greater than 0.05 for all grouping variables. ($\chi^2(2) = 1.948$, $p = 0.378$, with a mean rank score of 81.82 for Academia, 84.02 for Industry and 72.91 for Agency; $\chi^2(3) = 5.865$, $p = 0.118$, with a mean rank score of 73.45 for 0–9 years, 73.51 for 10–19 years, 90.67 for 20–29 years and 69.02 for >30 years; $\chi^2(3) = 0.547$, $p = 0.908$, with a mean rank score of 79.09 for United Kingdom, 80.33 for Europe, 75.80 for USA and 73.05 for Others).

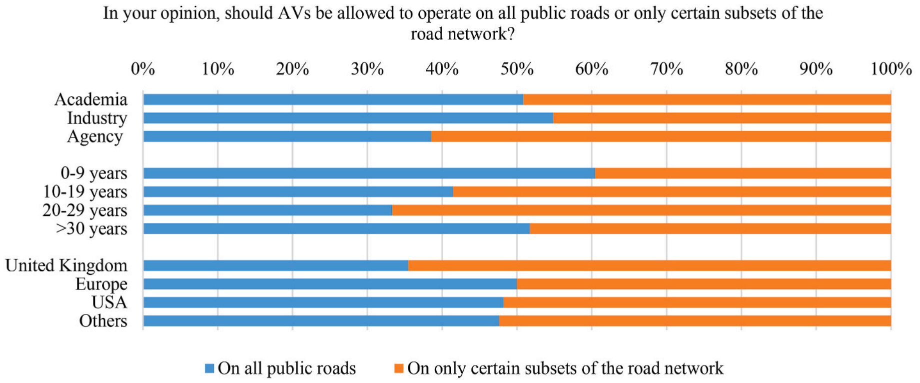

Fig. 4. Responses to the question of allowing AV operation on road networks. by type of organisation, work experience, and place of residence (%).

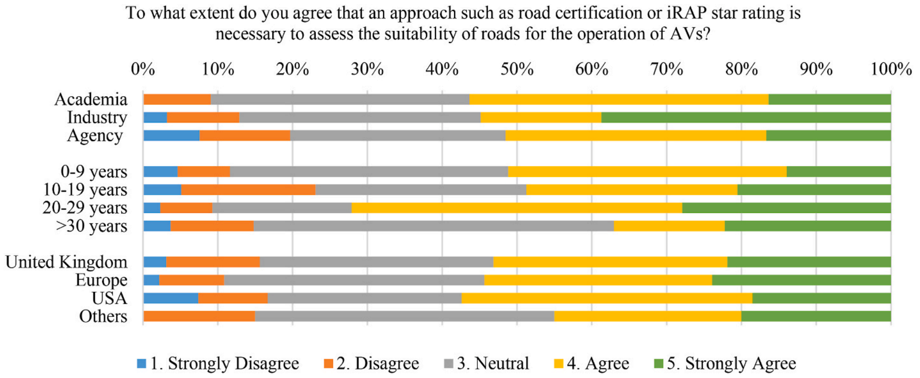

Fig. 5. Responses to the question regarding the road evaluation approach for AVs operation, by type of organisation, work experience, and place of residence (%).

administrations. This is followed by national authorities, which stated by 23.9% of respondents. On the other hand, a minority of participants stated that local authorities (6.9%) and the vehicle industry (5.0%) should be responsible for the assessment of the road infrastructure. Fig. 6 shows the distribution of responses according to the grouping variables for a deeper look at whether there is any difference of opinion among stakeholders. Although the results show that the most preferred option for all stakeholders is road administrations and operators, participants from the academia and industry did not have an explicit decision between the options of road agencies/administrations and national authorities. Similarly, UK and Europe respondents expressed divergent views on who should be responsible for the readiness assessment of road infrastructure, and no option is dominant.

Considering comments given the question (17.6%), most of the respondents underline the importance of collaboration between all stakeholders because they believe that one group is never going to have the funding and expertise necessary. They stated that a combination of organisations should be responsible for the readiness assessment of road infrastructure for automated driving operation. Some of these responses are: "*Should be a partnership between operators, authorities, and industry to fully understand all components of readiness*" and "*There needs to be a process that involves all stakeholders, including citizens (e.g. disability advisory groups). AV should be subjected to societal readiness assessment.*".

Also, some noted that independent and accredited auditors should be responsible for road infrastructure readiness assessments, but that this requires a special assessment body. For example, a respondent from Europe suggests that there should be a system like a type of approval, and it should be in the hands of specific authorities under the responsibility of the transport or infrastructure ministry. Some of the other suggestions by participants are as follows: "*Non-governmental organisations founded by traffic victims and relatives recruiting technical experts*", "*A third party unbiased otherwise countries will try to 'compete' to show they are more ready than others*", and "*It should be done by national authorities and delegated agencies. Self-certification by road operators and compliance checks by public authorities could also be an option*".

However, few respondents point out that rather than road infrastructure-based control, vehicles type approval standards should be needed for early AV deployments. In other words, these respondents are more in favour of vehicle readiness assessments for existing infrastructure. Some of these responses are: "*AV operators need to understand the vehicle ODD and should assess whether the intended deployment area is covered by the ODD*" and "*To approve usage on roads, the vehicle industry establishes an approved ODD at point of type approval meeting national authority standards*".

3.3. What are the basic road infrastructure elements for the safe operation of automated driving?

3.3.1. Rationale

The previous section presents the opinions of stakeholders on the need for road assessment for forthcoming automated driving and who should be responsible for these inspections. However, it is unclear how the evaluation should be conducted and how future technological requirements would be satisfied. These issues were also mentioned by stakeholders regarding difficulties that will arise when determining the suitable subsets of road networks for AV operation. However, current academic literature and field reports on this subject are limited (Tengilimoglu et al., 2023). Therefore, to understand the parameters that are likely to be critical in the assessment framework, we asked what the most important road infrastructure features for the safe operation of AVs are. Also in the next section, we asked the experts to rate possible road evaluation factors that could affect the safe operation of automated driving. Therefore, the findings in this section allow understanding of whether the parameters determined from the literature are compatible

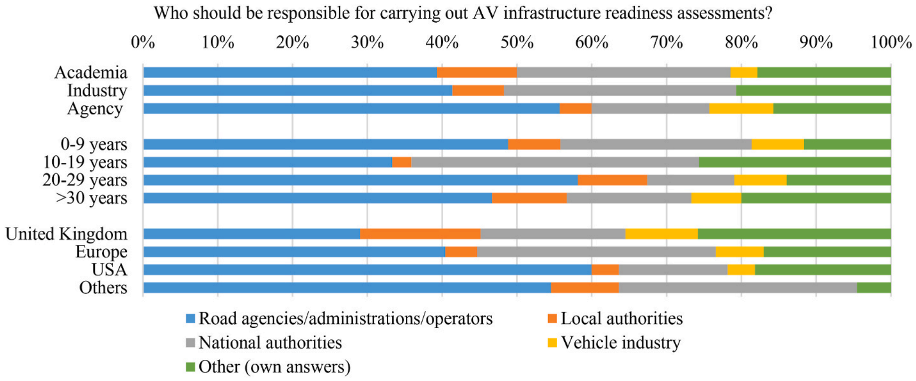

Fig. 6. Responses to the question about who should be responsible for the assessment of roads for AV, by type of organisation, work experience, and place of residence (%).

with the expert opinions.

3.3.2. Findings and interpretation of responses

In response to the questions of what are the three most significant (1) physical and (2) digital and operational road infrastructure attributes for the safe operation of AVs, a range of responses from experts and stakeholders was elicited. Word clouds were generated using NVivo 12 software to identify the most frequently used words in the responses (see Fig. 7). This allowed us to identify emergent themes against the question. Then, we coded the responses of the experts to examine attributes and check how often respondents refer to a particular issue (Feng and Behar-Horenstein, 2019).

Table 2 shows the results by type of organisations represented by experts and frequency of response, created using the matrix encoding feature in NVivo. It is clearly seen from the table that the quality and conditions of road markings, and traffic signs are mostly stated by the stakeholders. Regarding road marking, many respondents underlined the optimum requirements and conditions (e.g. consistency, dimensions, colour, retro-reflectivity etc.) for the safe operation of AVs. Some respondents point out that lanes, pedestrian crossing zones, junctions and roundabouts should be very clearly marked. Similarly, participants expressed their views on how traffic signs should be for AVs. They noted the need to harmonise and standardise sign types (e.g. symbols, shapes, heights, positions, and directions) to improve the legibility of traffic signs. Also, it is widely stated that high-quality and frequent maintenance of road marking/signs can help overcome the challenges of vision technology. Moreover, the quality and consistency of road surface, and separated roads/lanes for AVs in the early phase of implementation are frequently mentioned by respondents. These are followed by the clear and simple configuration of intersections and roundabouts, low-speed limit adaptation and facilities for vulnerable road users' safety. An unobstructed sight line that simplifies the perception task for AVs at intersections and consistent intersection indicators are some of the examples cited by respondents. Furthermore, the importance of assessment and maintenance of road infrastructure is mentioned by some participants.

With regards to digital and operational road attributes, the importance of both short-range and long-range communication infrastructure and its quality and reliability is frequently stated by stakeholders. Some also point out the requirements of international standards and protocols for the communication of vehicles and infrastructures. High-definition (HD) maps with dynamic ground truth information and effective information systems for any roadworks or other temporary modifications follows connectivity in importance. Moreover, experts noted the requirements of clear landmarks and better positioning technologies.

On the other hand, a few participants claim that current roads need to handle AVs. For example, a respondent from the USA who represents the agency group stated that "*AVs need to be capable of working on existing roadways as it is without any dependency on I2V information provided by public agencies*".

Overall, stakeholder responses to this question are consistent with the findings of Wang et al. (2022), who conducted an online survey and follow-up interviews with AV industry members alone in California, USA. Similar to their findings, our study indicates that road markings and traffic signs are one of the most critical road infrastructure elements for AVs and are agreed upon among stakeholders. However, with the transition to digitalisation, it is important to start questioning the role and necessity of these elements. Therefore, we asked the participants for

Fig. 7. Word clouds for responses to the question on the most significant physical (left) and digital (right) road infrastructure attributes.

Table 2
Thematic representation of responses on key physical and digital infrastructure attributes for AVs to safe operation.

	Survey Respondent			
	Agency (72)	Academia (64)	Industry (32)	Total (168)
Physical and Environmental Factors				
Adverse Weather Conditions	3	2	0	5
Assessment and Maintenance of Road Infrastructure	5	2	5	12
Dedicated Lanes - Segregation of Roads for AVs	6	11	4	21
Drainage Systems	0	1	1	2
Events & Incidents (Accidents, Vehicle Breakdowns)	3	1	2	6
Facilities for Vulnerable Road Users (VRUs) Safety	4	4	2	10
Inductive Charging for Electric Vehicles	1	2	0	3
Junctions - Intersections & Roundabout	7	6	4	17
Lane Width	2	2	1	5
Lighting Condition & Infrastructure	1	2	0	3
Median & Crash Barriers	2	0	0	2
Parking Facilities (Pick-up and Drop-off Points, Service Points etc.)	1	5	0	6
Pavement (Road Surface Condition)	9	3	3	15
Road Alignments (Horizontal & Vertical Curves)	0	2	0	2
Road Edge Definition	1	0	2	3
Road Geometric Design (Visibility & Consistency)	10	1	3	14
Road Markings Quality and Conditions	40	22	16	78
Roadside Condition (Surrounding Road Environment)	6	0	4	10
Roadworks (Construction Zone)	2	0	4	6
Safe Harbour Areas	2	1	0	3
Shoulders (Widenings) for Minimum Risk Manoeuvre	3	1	1	5
Special Structures (Bridge, Tunnel, Underpass etc.)	0	2	0	2
Suitable Speed Limit Adaptation for AVs	3	5	4	12
Traffic Condition & Flow	2	1	1	4
Traffic Control Signals (Traffic Light)	5	5	2	12
Traffic Signs (Road Signage)	25	9	8	42
Total number of respondents (unique)	61	43	25	129
Digital and Operational Factors				
Connectivity - Comms. Infrastructure (Latency, Reliability, Speed etc.)	30	13	8	51
Connectivity - Long-range Communication (Cellular, C–V2X, etc.)	7	4	4	15
Connectivity - Short-range Communication (ITS-G5, V2X, etc.)	14	17	8	39
Cyber-security & Data Management & Sharing & Standardization	11	6	3	20
High-Definition Map & Digital Twin	22	16	10	48
Information Systems (Weather, Work zone, Incident etc.)	15	8	4	27
Positioning (Localisation)	7	5	5	17
Remote Fleet Management System	4	4	3	11
Sensors and Cameras	5	11	2	18
Traffic Lights Control and Status Communication	4	7	3	14
Traffic Management Centre and Control Systems	9	6	3	18
Total number of respondents (unique)	59	45	27	131

their opinions on whether road markings and traffic signs will continue to maintain their importance in the digital twin era, which refers to the digitalisation of the road environment. Around three-fourths of the respondents (72.5%) either strongly agreed (41.9%) or agreed (30.6%) with the statement that road markings and traffic signs will continue to maintain their importance in the digital twin era. On the other hand, about one in seven respondents (13.8%) believe that the requirements of road markings and traffic signs will no longer be important with the digitalisation of road environment. Fig. 8 displays the proportion of the responses based on the grouping variables. The results in the figure show that around 80% of industry respondents agreed with this statement. This demonstrates that physical road infrastructure plays an important role in the safe operation of ADS technologies, and the industry acknowledges this. The results were consistent across stakeholders, with no significant differences detected between grouping variables.[9]

Also, we asked a question about the role of HD maps for AV deployments and which road features that support AV operation can be eliminated or reduced in importance by the availability of HD maps. Respondents often stated that HD maps are one of the most critical elements for the safe operation of AV and important for AV deployment as they provide important localisation attributes that can supplement perception sensors such as cameras, LiDAR, radar and ultrasonic. Some of the other comments by participants are as follows: "*HD maps are going to be critical, especially for identifying risks and path planning where existing sensors cannot see around corners; HD maps are extremely important for navigation and the immediate level as well as speed management and warning and regulatory control; HD maps have a role in answering the "Where am I?" question for AVs, but they must be up-to-date and current, connectivity is key for updates and real time interaction*".

Some experts noted that with up-to-date digital maps, some physical infrastructure requirements such as lane markings and signage can be gradually replaced by dynamic digital surrogates, thus reducing the physical maintenance of these features for AV operation would be possible. However, this requires all information to be digitally accessible in a reliable way and legally acceptable. Some commented that it is more around access to certified data/information that is more critical than the definition. This is because driving conditions change rapidly and so they need to be constantly updated and shared. They argue HD maps are not always up-to-date and currently lack sufficient updates and they hold no data on usage of roads or behaviours that would inform safer operation. Therefore, many believe that no physical road features can be eliminated for quite some time.

Given that there will always change in the city and be disruption to roads (e.g. due to blocking parked traffic, roadworks etc), respondents claim that AVs must be resilient enough to not completely depend on HD

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[9] According to the Kruskal Wallis H test, p value is greater than 0.05 for all grouping variables. ($\chi^2(2) = 2.563$, $p = 0.278$, with a mean rank score of 77.37 for Academia, 91.58 for Industry and 78.04 for Agency; $\chi^2(3) = 1.913$, $p = 0.591$, with a mean rank score of 75.63 for 0–9 years, 75.48 for 10–19 years, 81.56 for 20–29 years and 87.95 for >30 years; $\chi^2(3) = 4.654$, $p = 0.199$, with a mean rank score of 81.90 for United Kingdom, 75.88 for Europe, 88.05 for USA and 65.95 for Others).

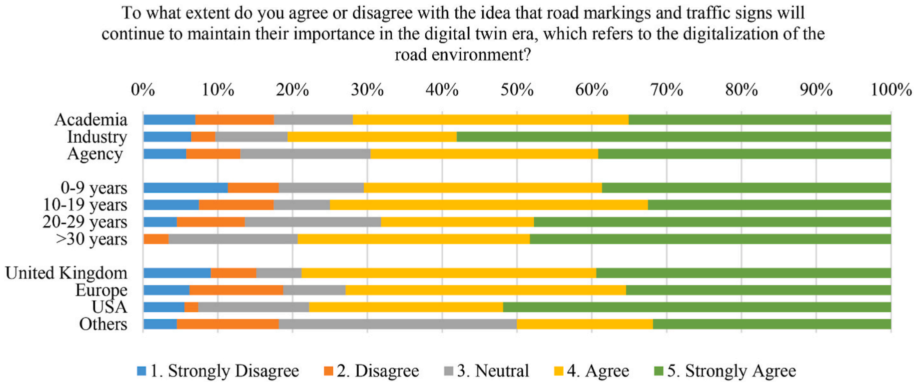

Fig. 8. Responses to the question regarding the road signs and markings importance in the digitalisation era, by type of organisation, work experience, and place of residence.

maps. Another common view is that physical road features will continue to maintain their importance as we will deal with mixed traffic for a very long time. Also, some underlined that both HD maps and existing road features (e.g. signs, markings) need to be "high quality" for redundancy. Therefore, the HD map itself will likely not be the solution without the support of physical road features.

Moreover, some of the points criticised by a few participants from the agency group are as follows: *"Do we have a commonly agreed standard on HD maps? Is there any communication from OEMs on the infrastructure needs to* support *their ODDs? Do we have a common picture on the digital twins?", "This is a question for the Industry, who is responsible for developing a vehicle that operates safely and efficiently. HD maps are clearly needed near term, but to what extent for what purpose is almost completely proprietary information held by private OEMs."*, and *"To date, most ADS developers have done their own mapping, so they do not "give away" what pieces of the map are needed for their vehicle to operate. They also clearly state they would not use a map created by the state agency because it would likely miss or not use the same formats/methods of data collection needed for their AV. Tricky spot to be in unless normalization occurs on data collection and needs."*.

3.4. *What factors will need to be considered for the safe operation of L4 automated driving?*

3.4.1. *Rationale*

In 2018, KPMG introduced a framework to assess the AV readiness of countries at a national level, since then the scope of components and the number of countries has increased each year. Singapore and the Netherlands are the countries with the highest scores according to the latest version of the index, with their high-quality road infrastructure (KPMG International, 2020). However, the "*quality of roads*" indicator used in the index is subject to some criticism as to whether it is the optimum indicator (Visser, 2019). The common hypothesis is that AVs operate safely on high-quality roads, and countries with poor road infrastructure are predicted to be slow to adopt AVs. The indicator is taken from the road quality index in the World Economic Forum's global competitiveness report, and this particular index is based on the views of local business managers of road networks (World Economic Forum, 2019). Visser (2019) highlights that there are obvious constraints on how managers observe and shape their views on the quality of roads. Therefore, concrete evidence should be collected and preferred using an appropriate methodology rather than subjective opinions (FTIA, 2021). For city-level AV readiness, for example, Khan et al. (2019) have assessed the readiness level of cities in the USA by following a similar strategy with KPMG and focusing on aggregated level criteria. On the other hand, limited research has been conducted so far to investigate which roads are relatively suitable for AVs within the city network (Soteropoulos et al., 2020). This requires a disaggregated level analysis and raises questions about what factors will need to be considered in the assessment framework. This section presents possible factors and potential challenges on the infrastructure side of vehicle automation.

3.4.2. *Findings and interpretation of responses*

As noted earlier, respondents were asked to evaluate possible factors that will likely be important for road readiness assessment. For this, a scoring system of not at all important to extremely important (5-point Likert scale) was used to provide quantitative feedback on a total of thirty potential road safety assessment factors or infrastructure elements, which can affect the safe operation of L4 automated driving for the foreseeable future.[10] Table 3 presents the means, standard deviations (SD) of questionnaire items, and order of importance according to the mean of the items. The findings in the table indicate that all possible factors identified in the relevant literature are important according to the stakeholders, having greater than 3 (i.e. important). The mean values of 18 out of 30 items were calculated as greater than 4 (i.e. very important). Among these, positioning and roadworks are the most highly ranked criteria for automated driving operation according to experts. Facilities for vulnerable road users, intersection type and its quality, and HD maps are following these factors. On the other hand, road drainage system quality, availability of fibre optic communication along with the road network and presence of broadcast communication received relatively fewer votes from the respondents compared to the other parameters.

Interestingly, the findings reveal that stakeholders from academia, industry and agency groups have similar views on most of the criteria. When we look at the first 10 parameters of 3 groups, it is seen that 7 parameters are the same. Although the ordering of the factors differed slightly between the grouping variables, the Kruskal-Wallis H test results show that there is no statistically significant difference in attitudes towards potential factors between both the type of organisation and place of residence groups ($p > 0.05$ for all factors). Participants were also asked whether there were any other aspects of the road infrastructure challenges for automated driving tasks or automated driving systems functions that were not included in this survey. Some of the responses include: "*smart devices at road construction sites (e.g. worker vests, connected traffic cones, availability of construction information from government server); a national or global data system for facilitating AV operations beyond localised, spot deployments; guidance and standardization of policies*

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[10] It should be noted that different use-cases, different automation levels, and different mobility models might require different infrastructure requirements, including different functionalities and services. Therefore, it is not possible to foresee all configurations of road infrastructure that AVs will have in the future. For this reason, this question focused on generic driving task capabilities of highly automated vehicles (SAE Level 4) equipped with automated driving systems rather than focusing on specific use-case scenarios.

Table 3
Ranking of potential factors that affect the safe operation of L4 automated driving (N = 160).

Rank	Factors	Rating[a]						Mean	SD
		1	2	3	4	5	DN		
1	Positioning/localisation (e.g. Galileo, Glonass and GPS signal accuracy, presence of reference station for localisation assistance, etc.)	0	2	15	31	100	12	4.547	0.733
2	Roadworks (e.g. presence of temporary road work zones/construction zone)	0	4	12	43	97	4	4.494	0.749
3	Facilities for vulnerable road users (e.g. pedestrian crossing type, availability of segregated bicycle lane, pavement configuration and width etc.)	1	1	22	36	97	3	4.446	0.804
4	Intersection type and its quality (e.g. junction type, presence of intersection channelisation, forced lane merges, property access density etc.)	1	5	16	35	97	6	4.442	0.857
5	High-Definition maps (e.g. availability of HD maps and its content)	1	4	13	50	83	9	4.391	0.809
6	Roadway users (e.g. different vehicle types (cars, trucks, buses etc.), pedestrians, cyclists, powered two-wheelers, etc.)	2	6	16	38	93	5	4.381	0.915
7	Road details and context (e.g. road types, number of lanes, road access etc.)	1	7	16	46	87	3	4.344	0.884
8	Special event (e.g. presence of incidents, accident, emergency vehicles, vehicle breakdowns etc.)	1	3	20	59	74	3	4.287	0.809
9	Road geometry challenges (e.g. low curve radius, hilly roads, narrow lane width etc.)	1	3	24	52	77	3	4.280	0.839
10	Road markings quality and its readability (e.g. lane marking condition, presence of ghost markings on the road surface etc.)	1	12	17	40	86	4	4.269	0.977
11	Special road section/road structure challenge (e.g. presence of tunnel or underpass, bridge or grade-separated structures, toll plazas etc.)	1	9	23	48	74	5	4.194	0.943
12	Road signs and signals visibility (e.g. readability and detectability of traffic signs by humans and sensors, traffic lights, variable message signs, etc.)	4	14	13	41	83	5	4.194	1.089
13	Information systems (e.g. real-time information on congestion, weather condition, incidents, roadworks, digital traffic rules and regulations etc.)	1	6	28	47	72	6	4.188	0.911
14	Weather condition (e.g. poor visibility due to bad weather like rain, snow, fog etc.)	1	7	27	53	67	5	4.148	0.910
15	Traffic management centre and control (e.g. provide real-time temporary lane closures, dynamic traffic signs, variable speed limits etc.)	0	9	29	50	67	5	4.129	0.920
16	Maximum speed limit (e.g. affecting response time of automated vehicle)	2	7	32	42	72	5	4.129	0.978
17	2G, 3G, 4G - mobile network coverage along with the road network	1	6	26	51	55	21	4.101	0.903
18	5G network coverage along with the road network	2	8	22	49	57	22	4.094	0.965
19	Road edges condition and median type (e.g. discontinuous or damaged road edges, median types/widths, presence of on-road parking facilities etc.)	0	10	36	55	52	7	3.974	0.917
20	Road surface condition (e.g. road surface type, presence of potholes, ruts, and uneven road surface etc.)	2	14	37	60	42	5	3.813	0.982
21	Lighting condition/illumination (e.g. glare due to sunshine or other cars, poor visibility due to darkness, availability of street lighting etc.)	2	13	45	49	46	5	3.800	1.003
22	Presence of roadside units (e.g. 5.9 GHz dedicated short-range communication)	5	7	33	46	35	34	3.786	1.044
23	Road furniture and roadside occlusions (e.g. dense vegetation surrounding road, bins, billboards, streetlamps, signage, traffic lights, etc.)	3	14	36	63	38	6	3.773	0.985
24	Traffic condition (e.g. volume of traffic, flow rate, congestion etc.)	4	15	45	47	45	4	3.731	1.062
25	Remote fleet management system (e.g. vehicle/fleet supervision with operator in control centre)	4	9	49	52	35	11	3.705	0.980
26	Infrastructure maintenance frequency and presence of asset management and maintenance strategy	7	14	45	42	45	7	3.680	1.128
27	Road accident severity (e.g. number and location of fatalities and serious injuries)	7	15	41	49	41	7	3.667	1.112
28	Road drainage system quality (e.g. surface water)	4	22	49	50	25	10	3.467	1.024
29	Availability of fibre optic along with the road network	11	17	38	26	32	36	3.411	1.261
30	Presence of broadcast communication (e.g. DAB, FM)	14	26	35	29	20	36	3.121	1.245

[a] (5-point Likert scale where 1 = ‘Not At All Important’, 2 = ‘Low Importance’, 3 = ‘Importance’, 4 = ‘Very Important’ and 5 = ‘Extremely Important’ and DN = Don’t Know).

regarding deployment for ensuring the interoperability of all AVs and the supporting *digital infrastructure”,*

Notwithstanding, some experts criticised the concept of the survey regarding the infrastructure requirements for automated driving. They claim that AV technology is still immature, and it is not yet clear what the infrastructure requirements are for a safe L4 AV. For example, one respondent stated that “*We are still in the development and testing phase, so it is not possible to predict now which technologies will prove successful and therefore which infrastructure needs”*. Another respondent points out the importance of societal benefits of emerging technologies and noted that “*We do not need to be facilitating AV deployment until it proves it is beneficial to overall community goals. If it is not, then why should governments be doing anything to facilitate deployment?”*. Lastly, an academy respondent criticised the road evaluation approach, commenting, *“The questionnaire assumes most of the provision of information should be supplied by the road or road operators. AVs should handle transient hazards and make the best use of all available information but not be dependent on it. Even if an AV does not get a 5G warning signal for road works the public will expect it to use its own detection and recognition systems and respond appropriately”*.

4. Conclusions and recommendations

This study focused on the road infrastructure side of automated driving and aimed to clarify potential infrastructure challenges requiring considerations in the early stages of L4 AV deployment through an online survey of 168 experts and stakeholders from 29 countries. The research focused on four topics: (1) deployment paths of L4 AVs, (2) the concept of road certification for automated driving, (3) basic road infrastructure elements for the safe operation of automated driving, and (4) factors affecting safe operation of L4 automated driving. In the light of these topics, the convergence and divergence of opinions among different types of stakeholders were presented.

There are several factors that have a crucial role in understanding the deployment paths of L4 AVs: types and purpose of AVs, operating zones, compliance and enforcement strategies, technological advancements, and infrastructure investment are the most important among these. There was guarded optimism that L4 AVs with carefully defined ODDs will likely be available for public use within the next decade, but only on small sections of road networks. This is mainly because neither current technology nor the road infrastructure is ready for the network wide operation of AVs. This raises the important question of which roads or areas would be conducive to AV use. There is a difference in opinions regarding the types of roads to be considered safe for the initial phase of L4 automated driving. In general, motorways are expected to be early cases for the implementation of AVs because of their controllable and well-maintained driving environment. However, there were also some supports for the earliest implementation for low-speed urban areas with supporting infrastructure. In a way, these results suggest that there will likely be different types of L4 AV deployments that operate in different areas of the network (Shladover, 2022). This uncertainty in deployment paths will present challenges for road agencies and city authorities in identifying the infrastructure requirements of different technologies and their integration into future urban networks. The wider impacts of AVs could also be quite different depending on the deployment paths.

There was consensus among all stakeholders about the importance of road infrastructure and the surrounding environment for automated driving. In parallel with this, there was clear support for the assessment of roads for automated driving operation, especially during the early stages of deployment. There is a broad consensus among stakeholders that infrastructure owners and operators should be responsible for this assessment, although there were some suggestions in favour of independent organisations and accredited auditors, too. There are also some difficulties in evaluating roads and implementing operation restrictions. In particular, recognition and classification of subsets and ODDs could be difficult. Segmented and different levels of automated driving in mixed usage areas could bring new uncertainties and develop new risk scenarios. Therefore, cooperation and fair sharing of responsibilities among all relevant stakeholders are important to reduce possible risks (García et al., 2021). On the other hand, there were a few strong opposition to road assessment, on two separate grounds: that vehicle automation has not been proven to be beneficial yet, or that the manufacturers should be responsible for safety assurances of these vehicles on roads where they choose to operate. Besides, certification of roads will entail more responsibility and extra costs for the existing road authorities.

Given the “mismatches” noted above, policymakers and transport authorities should start to consider their strategic positions for this new category of road users. They need to consider early actions to mitigate possible negative outcomes from vehicle automation while deciding to support the infrastructure-related requirements of AVs models. However, this may present new challenges for authorities in determining what specific types of action are necessary and appropriate to ensure that automated driving supports sustainable transport planning in cities (Fraedrich et al., 2019; Wadud et al., 2016). This might be particularly important because motorways are seen as the safest roads by many experts for initial deployments. If the AV industry focuses solely on “highway automation” due to limited investment in urban roads, the expected potential benefits of AVs in urban areas (e.g. increasing the mobility of the disabled, reducing the demand for parking, providing affordable and accessible mobility for the community, etc.) might not be realised soon (Fagnant and Kockelman, 2015; Litman, 2020). This may also affect future vehicle ownership patterns, as shared AV models are expected to be more effective in urban areas due to the potential patronage of users (Wadud and Mattioli, 2021). Thus, initiatives should begin by investigating potential applications and their effects on cost structures, transportation, and the environment.

Regarding the basic infrastructure attributes, this study provides expert insights on physical and digital road infrastructure features that may be critical to the safe operation of automated driving. It is clear that most of the measures regarding the physical road infrastructure for conventional vehicles (e.g. clear and visible road markings and traffic signs) will also continue to be important for automated driving. This highlights the importance of maintenance strategies for road infrastructure for both existing road users and emerging technologies. However, new challenges are expected to emerge, particularly on the digital side of road infrastructure, which must be overcome before AVs starts operating on the roads. Reliable and cyber-secure communication and information systems, localisation support infrastructure and special equipment for roadworks areas are only some examples. Therefore, collaborations between stakeholders and standardisations of the basic requirements are necessary not only to build trust but also to verify that AVs and operation environments are safe. Although the lack of cooperation among stakeholders – especially between the technology industry and the road authorities – is crucial, progress has been slow so far.

In this context, the study presented experts’ views on potential factors (e.g. proper delineation of road marking, quality of road surface, lighting, cellular network coverage etc.) that can be critical for the safe operation of automated driving. Responses revealed that stakeholders have similar opinions on most of the identified factors. However, addressing infrastructure-related requirements for all these factors may not be possible and feasible in the short term. Given the current state of the road and city authorities, it is unclear how they will find sufficient funds for AV-related investments, including resources to provide any new infrastructure, if needed (Saeed, 2019). In addition, some dynamic driving scenario-based factors such as interaction with vulnerable road users, accident response or emergency vehicle operations are difficult to overcome with infrastructure improvements. Therefore, AVs must demonstrate their ability to operate safely in some conditions without infrastructure support. For this reason, a combination of smarter vehicles, infrastructure modification and improved operations and maintenance practices will be required for the roads to be ready for automated driving. A structured and incremental approach is needed for achieving readiness for automated driving (Somers, 2019).

On the other hand, most of the road network will probably not be able to support AV operations unless the necessary investment are made (Manivasakan et al., 2021; Soteropoulos et al., 2020). In other words, AVs will likely not be available on all road networks due to the need for a certain level of technical maturity and infrastructure support. This will likely lead to equity issues in access to “AV compatible roads”. Therefore, equity in accessibility to AV services should need to be carefully evaluated by the authorities. This seems to be particularly important because the survey shows that the equity concerns have not been well addressed so far. If we consider road assessment in general, the challenge is not only to determine what roads should AVs be allowed to operate, but also on what roads will they be able to operate. The findings of this study can be used to develop a classification scheme that categorises and harmonises the capabilities of a road infrastructure to support and guide AVs.

Some issues are still unresolved and require further investigation. For example, the importance of almost all items asked in the survey appears to depend on the specific application of AV technologies. As such, future research should address each possible model of automated driving use cases. For instance, automated freight vehicles are getting increasing attention in the market and may have different infrastructure-based requirements for safe operation. It is also worth noting that the current level of development of AV technologies and road infrastructure varies between countries (KPMG International, 2020), so priorities regarding requirements and investments may vary. The different political structures of each country and the limits of what is politically possible, may affect the priorities and actions, too. Given the majority of the responses were from the Western industrialized economies, such regional differences in priorities and opinions may have been under-represented here and requires attention in future.

Author statement

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

Data availability

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

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