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City readiness for connected and autonomous vehicles: A multi-stakeholder and multi-criteria analysis through analytic hierarchy process

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ABSTRACT

The past decade has seen a rapid acceleration in investment on and development of connected and autonomous vehicles (CAVs). Cities need to be ready for the mass adoption of CAVs, to harness their benefits and minimise negative impacts. However, currently there are no concrete frameworks and criteria to measure city readiness for CAVs, and existing literature lacks quantitative multi-stakeholder analysis for this multi-stakeholder issue. This study thus aims to contribute to the knowledge gaps by exploring different stakeholders' assessment criteria on cities' infrastructure readiness, policy and regulation readiness, and citizen readiness for CAVs, using analytic hierarchy process (AHP). Data were collected through an online survey (N = 381) with participants representing three professional and three general public stakeholder groups. The results show that infrastructure readiness was overall considered most important, and there were different opinions between stakeholder groups especially regarding policy and regulation readiness. These differences might be associated with stakeholder groups' expectations on the potential impacts of CAVs. Exchanges of views and concerns between different stakeholder groups are needed to gain a comprehensive understanding of how cities can be best prepared for CAVs.

1. Introduction

The past decade has seen a rapid acceleration in investment on and development of vehicle connectivity and automation technologies (Cohen et al., 2020). It is anticipated that connected and autonomous vehicles (CAVs) with high and full driving automation, i.e., Level 4 and Level 5 as defined by SAE International (2021), will be commercially available from 2030s, and achieve 50%–90% market penetration by 2060 depending on technological, marketing and policy scenarios (Litman, 2021; McKinsey & Co, 2016; Nieuwenhuijsen et al., 2018).

CAVs have the potential to reshape our cities and cause profound changes to urban lives. Not only can CAVs free up driving time for more productive and/or enjoyable time use during long travels (de Almeida Correia et al., 2019; Malokin et al., 2019), they can also make our roads safter by avoiding human-driver errors and deficiencies that have contributed to most traffic accidents (Luttrell et al., 2015; US Department of Transportation, 2018); improve energy efficiency of the transport system by mitigating road congestions (Stanek et al., 2017; Tran and Bae, 2021), implementing eco-driving (Ozkan and Ma, 2021; Zhao et al., 2019) and enabling vehicle platooning (Chen et al., 2021; Wadud et al., 2016); provide mobility services that are more affordable by reducing costs of human drivers (Bösch et al., 2018), and more accessible by serving users who are unwilling or unable to drive (Harper et al., 2016) and by solving the first/last-mile problem for which conventional public transport is inefficient to serve (Moorthy et al., 2017). Moreover, CAVs' more efficient use of road space provides opportunities to redesign our streets to be more walkable and to accommodate more diverse activities that transform the streets into lively urban spaces (NACTO, 2019; Riggs et al., 2020), and CAVs' reduced demand for parking can free up valuable land in city centres for more greenspaces and/or mixed land uses of higher density (Stead and Vaddadi, 2019; Yigitcanlar et al., 2019).

However, CAVs may also increase car dependence and encourage more car trips and longer commutes, leading to higher total vehicle miles travelled which consequently means more pollution and carbon emission (Auld et al., 2017; Kim et al., 2015), and cities sprawling into suburbs which is not sustainable development (Guan et al., 2021; Thakur et al., 2016). Higher car dependence may also encourage physical inactivity which impairs public health through links to an extensive list of diseases such as cardiovascular diseases, dementia, diabetes, and cancers (Rojas-Rueda et al., 2020; Sohrabi et al., 2020). Moreover, CAVs may also increase mobility disparity between the socially-advantaged

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and -disadvantaged, due to higher purchase costs of CAV cars (Bösch et al., 2018) and the possible choices to pay for privileged use of CAV cars (Sparrow and Howard, 2020), barriers in knowledge, skills and/or equipment to use CAV mobility services (Butler et al., 2021; Sourbati and Behrendt, 2021), reduced provision of public transport as a consequence of competition from CAV cars and investment and mode shifts to CAV cars (Kröger et al., 2019; Levin and Boyles, 2015; Morris 2014), and unequal geography of CAV infrastructure investments as a consequence of stronger political activism in wealthier communities and market process (Barnes et al., 2017). Apart from impacts on mobility and urban development, adoption of CAVs is also predicted to cause substantial loss of transport-related jobs, and the socially disadvantaged groups are more likely to be affected (Beede et al., 2017; Nikitas et al., 2021).

CAVs thus bring opportunities to transform our cities to be more efficient, safer, more sustainable, more equitable and more liveable, but also potential disruptions and new challenges that may lead to opposite consequences. Cities need to prepare their infrastructure, policies, regulations and citizens, and be ready for the mass adoption of CAVs, to harness the benefits of CAVs and minimise negative impacts.

Several studies have attempted to assess cities, regions or countries' readiness for CAVs. Khan et al. (2019) presented an index to measure city readiness for CAV deployment. The index covers hierarchical criteria under the themes of "Policy and Regulations", "Physical Infrastructure" and "Cyber infrastructure", with weightings developed as average importance scores assigned by 13 US city administration officials. Focusing on the demand side readiness, INRIX (2017) ranked cities in the US that are best suited to benefit from CAVs based on citizens' travel patterns and mobility needs, through analysing aggregated travel data. At country level, KPMG (2020) developed index to measure 30 countries' readiness for CAVs, based on hierarchical criteria under the themes of "Policy and Legislation", "Technology and Innovation", "Infrastructure" and "Consumer Acceptance". Criteria were rated based on publicly available information and equally weighted for calculating the final index score. Largely following the KPMG framework but with criteria weights developed using analytic hierarchy process (AHP), Mylonas et al. (2020) assessed the readiness of Greece for CAVs. However, their AHP analysis only involved the five authors. Qualitatively, Barnes et al. (2017) assessed the technological readiness and administrative readiness of Delaware, US, after previewing possible impacts that CAVs would have on issues such as infrastructure design and upgrade, cyber security, liability, car use and ownership, urban development, mobility equity and employment. Kimley-Horn (2016) proposed an activities roadmap to enhance the readiness of North Carolina, US for CAVs, through literature review and a stakeholder workshop, with a heavier focus on policy and regulation readiness. Johnson (2017) discussed how ready current road infrastructure is for CAVs and challenges arise from the gap. The answers remain uncertain, and more research on the infrastructure requirements of CAVs and clearer policy direction are needed.

While these studies provided some useful assessment tools and/or guidance for preparing cities for CAV deployment, a key limitation is the lack of quantitative multi-stakeholder analysis of the readiness criteria. Urban mobility is a multi-stakeholder multi-criteria issue, where different stakeholders will have different objectives reflected by their different assessment criteria and/or weights of criteria, and accounting for these divergences is critical to success (Barfod, 2018; Macharis et al., 2010). In the context of CAV deployment, stakeholders will include users of different transport modes, transport policy makers, transport service providers, vehicle manufacturers, infrastructure operators, transport researchers, and many more (Feys et al., 2020; Graf and Sonnberger, 2020; Kacperski et al., 2020). A thorough understanding of these different stakeholders' objectives, reflected by their different assessment criteria, is necessary for constructing a concrete framework for multi-stakeholder multi-criteria assessment of city readiness for CAVs.

This study aims to contribute to the knowledge gaps by exploring different stakeholders' assessment criteria regarding city readiness for CAVs. With a hierarchical set of readiness criteria covering the aspects of infrastructure, policies, regulations and citizens, the specific research questions are:

1. How important is each criterion regarding city readiness for CAVs?
2. How do opinions differ between different stakeholder groups?
3. How are the differences associated with stakeholders' knowledge of and attitudes toward CAVs?

This study collected data from target stakeholder groups via an online survey and developed their criteria weights. This study does not intend to develop methods to measure how well a given city meets each criterion and thus to calculate a final readiness score of the city. Instead, this study focuses on weights development and comparison. Indeed, in many cases of multi-stakeholder multi-criteria analysis, criteria weights can be even more helpful than the final scores as they provided more detailed insight into stakeholders' objectives and viewpoints, and help identify specific areas in which focus and/or priorities should be given (Ghorbanzadeh et al., 2019; Lode et al., 2021; Macharis et al., 2010).

2. Methodology

This study used AHP to develop weighting systems for a set of criteria regarding city readiness for CAVs, from the perspectives of different stakeholder groups. The criteria set was constructed based on literature review. Pairwise comparisons of criteria by different stakeholders, which is the main task of AHP, were conducted through an online survey.

2.1. The analytic hierarchy process

Analytic hierarchy process (AHP) is one of the most popular multi-criteria assessment techniques that have been used to support complex decision-makings in transport planning, urban planning and many other areas (Ameen and Mourshed, 2019; Macharis and Bernardini, 2015; Saaty, 1990). It decomposes the assessment into a hierarchical set of assessment criteria and sub-criteria, and estimates relative importance of each criteria, i.e., numerical weight of each criteria, through pairwise comparisons made by decision-makers, experts and/or stakeholders (Ghorbanzadeh et al., 2019; Saaty, 1990).

The hierarchy of the criteria is structured from the top with the overarching decision goal, to a set of criteria relating to the comprehensive aspects of the decision goal, and in many cases, further down independently to sub-criteria for each or some of the criteria. A pairwise comparison matrix is constructed for each group of criteria and sub-criteria, with respect to their relative importance regarding the criteria or sub-criteria immediately above them in the hierarchy. Typically, a 9-point scale is used to indicate the relative importance, where 1 means the two compared criteria are equally important, and 9 means one is overwhelmingly more important than the other (Saaty, 1990; Dos Santos et al., 2019). For each pairwise comparison matrix, the vector of weights is calculated as the dominant eigenvector of the matrix. The consistency of the pairwise comparison answers is examined by Saaty's (1990) Consistency Ratio (CR):

$$CR = ((\lambda_{max} - n)/(n-1))/RI \tag{1}$$

Where λ_{max} is the dominant eigenvalue, n is the number of compared criteria in the matrix, and RI is a random consistency index. In this study, the standard threshold of 0.1 was applied where $CR < 0.1$ is accepted as being consistent.

Compared to other multi-criteria assessment techniques, the advantages of AHP is that it breaks down a complex issue into a clear hierarchical structure of more specific and more understandable elements, which is particularly useful when the assessment involves non-expert participants, and the consistency check is an additional assets in such applications (Ghorbanzadeh et al., 2019). It converts pairwise comparison results into numerical weights, allowing comparisons of a wide range of subjective and/or objective, qualitative and/or quantitative, and often incommensurable criteria, which is the case for city readiness for CAVs, in a rational and consistent way (Pedroso et al., 2018; Vidal et al., 2011). Therefore, AHP was used to develop the weighting systems in this study.

2.2. City readiness criteria

A hierarchical set of criteria of city readiness for CAVs was constructed based on studies reviewed in Section 1 and listed in Appendix A, as well as discussion with transport experts and urban planning experts at the authors' institutes. The strategy was to have a comprehensive but relatively high-level set of criteria, for reasons of: 1) it should cover as wide areas as possible that are relevant to the wide stakeholder groups involved; 2) there are still a lot of uncertainties in CAV development so it would be risky to assess any criteria containing very low-level details; 3) for the survey to be practical, the number of criteria needs to be limited since the number of pairwise comparisons will have squared growth ($1/2n(n-1)$). The resulted criteria and their structure are shown in Fig. 1. Explanation of each criterion is listed in Appendix A.

2.3. Online survey

An online survey was designed and conducted to collect data of pairwise comparisons of the constructed set of city readiness criteria from participants representing the targeted stakeholder groups, as well as their knowledge of and attitudes towards CAVs, and their basic demographic and mobility information.

The survey consisted of five parts: introduction; participant classification questions; pairwise comparisons; CAV knowledge and attitude questions; and demographic questions. In the introduction part, participants were informed of the purpose of this survey with a brief description of CAVs and their uncertain impacts. In the participant classification part, participants were asked to select a statement that described them best, which were used to classify them into six stakeholder groups (Table 1). In the pairwise comparison part, a brief explanation using simple words was provided for each criterion (Appendix A), together with an illustrative image to help participants to understand the criterion. A screenshot of the survey interface of one of the pairwise comparison questions is shown in Fig. 2.

The survey was disseminated via a third party survey agency as well as via the authors' professional and private networks, and was active online from August 2021 to October 2021.

3. Results and discussion

3.1. Overall analysis of the responses

In total, 434 survey responses were received, of which 381 were valid. Fig. 3 provides an overview of the distribution of participants across the six stakeholder groups and their demographic profiles. Over half of the participants are general public who use cars as their main mode of transport, which corresponds to the high percentage of car users (69% in 2019) in current mode share in England (Department for Transport, 2020). Only 10 participants represent transport service providers and hence their results need to be interpreted with caution. Overall, there is a balanced gender distribution although females are

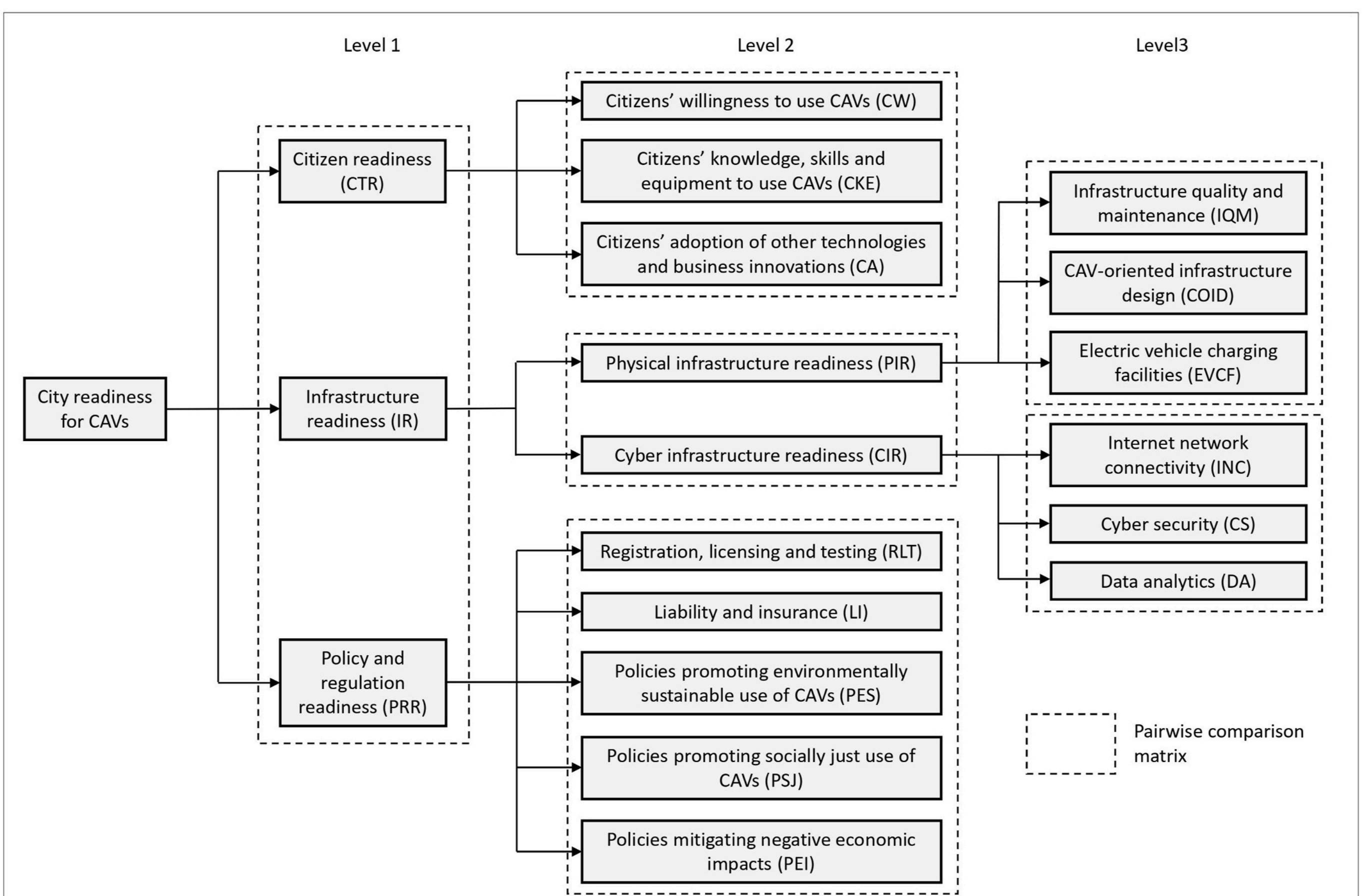


Fig. 1. The hierarchical set of criteria of city readiness for CAVs.

Table 1
Classification of the six stakeholder groups.

	Stakeholder groups	Statements	
Transport professionals	Transport experts	I am a transport or urban planning consultant at a consulting firm	
		I am a policy maker at a local, regional or national government or public body, and my work relates to transport and/or urban planning	
		I am a researcher at a research or higher education institute, and my work relates to transport and/or urban planning	
	Transport service providers	I work in a business that provides transport services (e.g., work at a bus company, a rail company, as a self-employed Uber driver, and so on)	
		I work in a business that operates transport-related infrastructure, including physical and cyber infrastructure (e.g., highway maintenance, IT and/or telecommunication services for transport, and so on)	
		I work at a vehicle manufacturer	
	Transport students	I am a university student doing a transport or urban planning related degree	
General public	General public - Car	None of above. Main mode of transport for commute and/or other daily activities:	Private car (as driver or passenger, including car sharing and ride sharing)
	General public – Public transport		Public transport
	General public – Cycle walk others		Cycling or walking Others

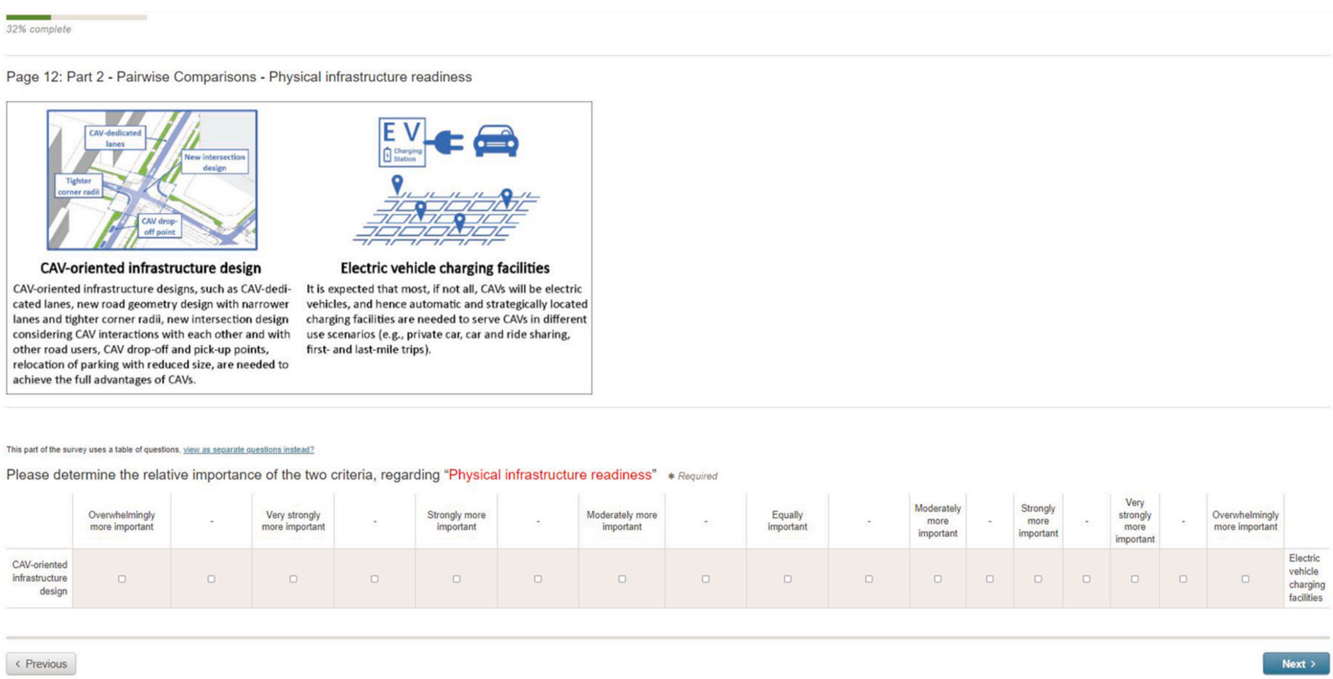


Fig. 2. The survey interface of one of the pairwise comparison questions.

slightly over-represented for general public car users while under-represented in other groups especially for transport service providers. There is also a largely balanced age distribution except for transport students who are mostly under 25. Most participants, even in the general public groups, have a bachelor's degree or above, which is higher than national average of 33% in England in 2019 (ONS, 2020) and which may reflect the higher interest in CAVs associated with higher education (Haboucha et al., 2017). Income distribution shows reasonable proportions with majority of the participants belonging to the low-medium bands. Almost all participants are UK residents except in the transport expert group where nearly half of the participants are based outside UK. There are more variations regarding home countries but the vast majority answered UK as their home countries. Overall, the sample is largely balanced and representative for UK population and the purpose of this study.

Fig. 4 shows the consistency of participants' pairwise comparisons, i.e., the Consistency Ratios (CR) of their comparison matrices. Across the six stakeholder groups and the five comparison matrix groups (excluding the infrastructure readiness matrix where CR is not applicable with only two criteria to compare), percentages of participants who performed consistent comparisons, i.e., with CR ≤ 0.1, range from 10% to 70% with most of them between 30% and 50%. There is no obviously patterned difference between stakeholder groups or comparison matrix groups, other than that CRs are overall higher for the *Cyber infrastructure readiness* matrix, which might be linked to participants' higher agreement in the importance of *Cyber security* as will be shown in Section 3.3.3.

The percentages of consistent comparisons may seem low. However, this is not uncommon in AHP, since human beings do not always make consistent judgements, especially when comparing complex items or concepts. For example, Goepel (2013) reported that only half of the participants achieved CR < 0.16 from sampled AHP projects. Nevertheless, to comply with the standard CR threshold of 0.1, only comparison matrices with CR ≤ 0.1 were kept for calculating criteria weights in this study.

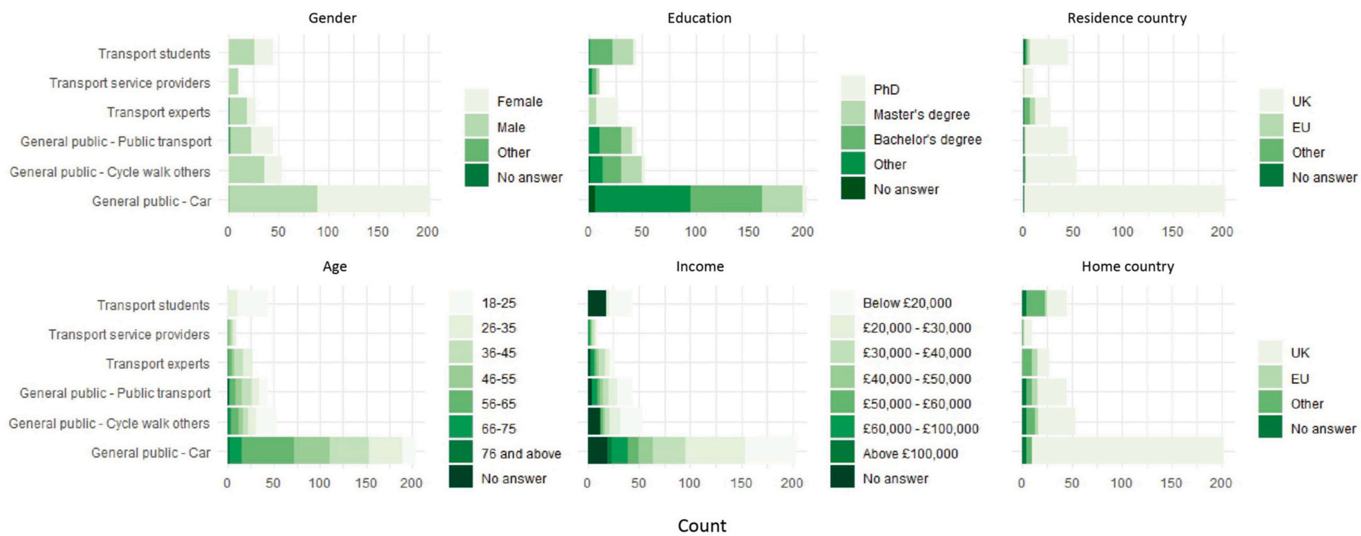


Fig. 3. Demographic profile of the participants.

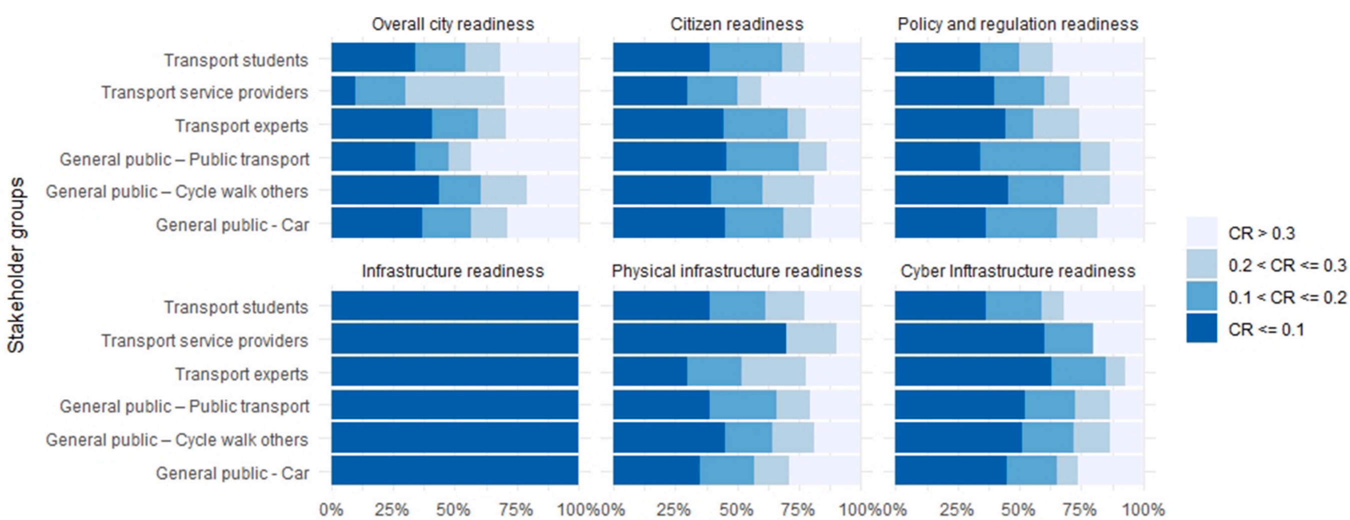


Fig. 4. Percentage of participants' comparison matrices in different Consistency Ratios (CR) bands.

3.2. *Weights by all stakeholder groups - how important is each criterion regarding city readiness for CAVs?*

Figs. 5–7 show the weights of Level 1, Level 2 and Level 3 criteria by all stakeholder groups, i.e., the whole sample. The weights are aggregated weights computed as geometric means of individual participants' weights which were computed using the Dominant Eigenvalue method (Saaty, 2003). Weights in Level 2 and 3 are further weighted by weights of criteria immediately above them in the hierarchy.

At level 1, the weights indicate that *Infrastructure readiness* was considered the most important (0.41), with *policy and Regulation readiness* (0.31) slightly more important than *Citizen readiness* (0.28). Indeed, infrastructure is fundamental to achieving many of the envisaged use cases of CAVs, and there are still major challenges in upgrading infrastructure to be CAV ready (Manivasakan et al., 2021).

At Level 2, regarding *Infrastructure readiness*, *Physical infrastructure* (0.23) was considered more important than *Cyber infrastructure* (0.18). This might be explained by that *Physical infrastructure* are the more basic requirements for any transport system to operate, although for intelligent transport systems including CAVs and their services, *Cyber infrastructure* is also vital and is where upgrades might be needed most

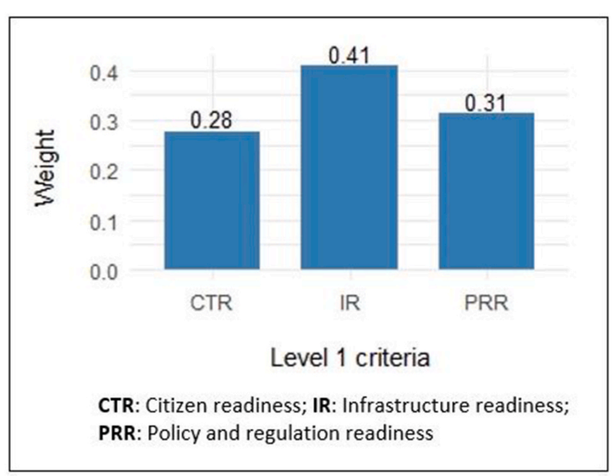


Fig. 5. Weights of Level 1 criteria by all stakeholder groups.

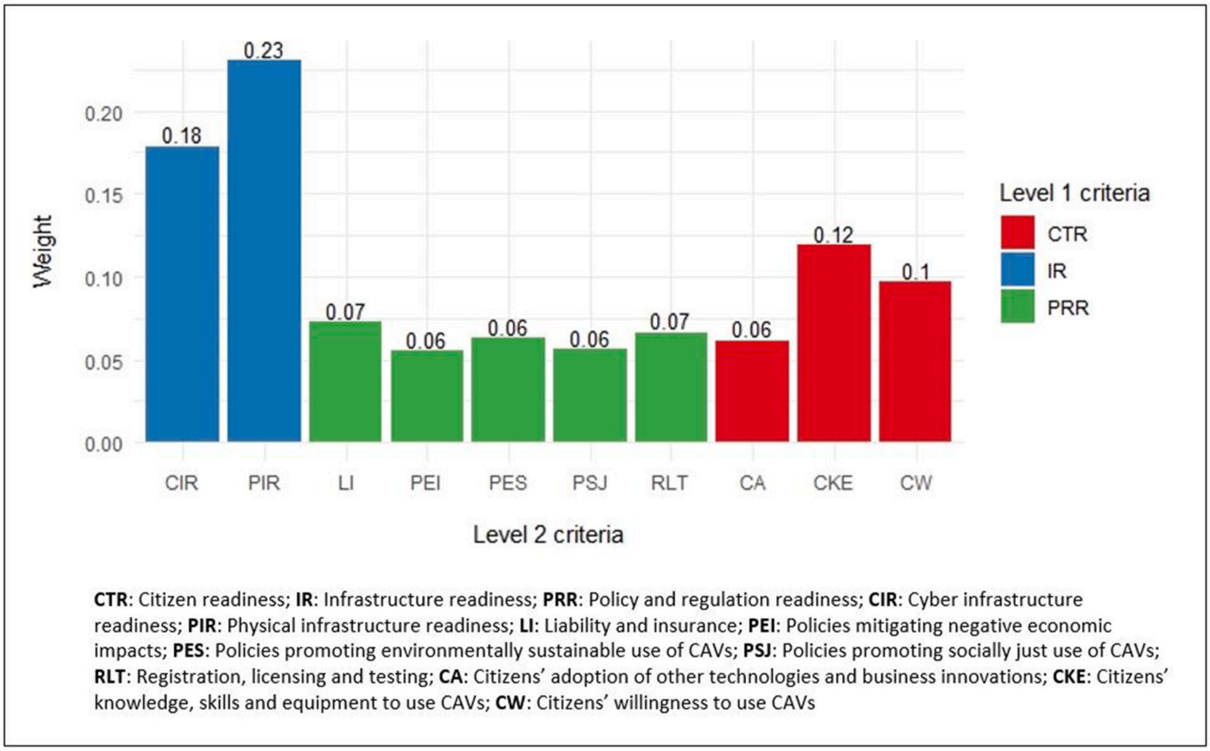


Fig. 6. Weights of Level 2 criteria by all stakeholder groups.

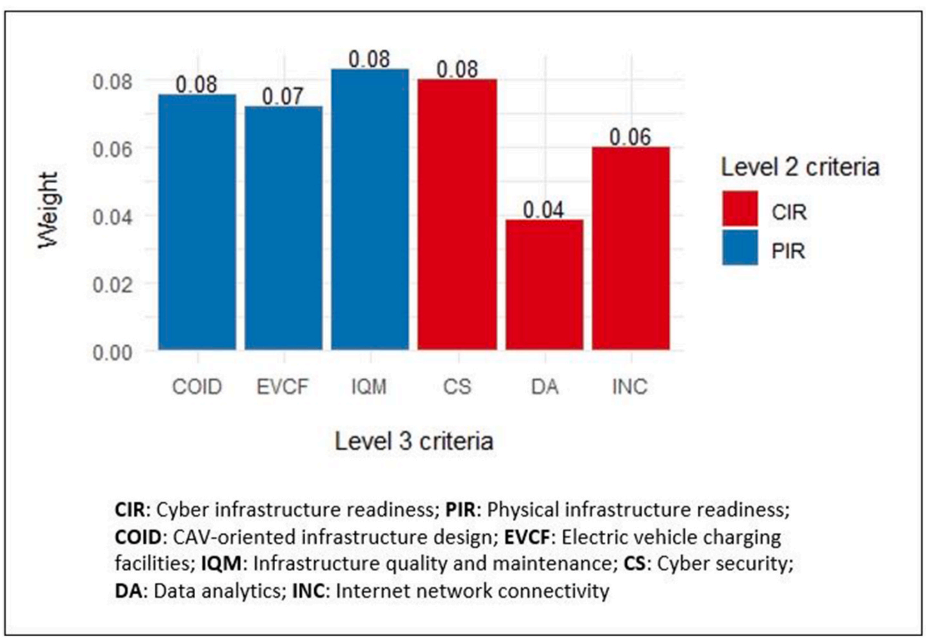


Fig. 7. Weights of Level 3 criteria by all stakeholder groups.

(Johnson, 2017). Regarding *Citizen readiness*, *Knowledge and equipment* was considered most importance (0.12), closely followed by *Willingness to use CAVs* (0.10), with *Adoption of other innovations* considered least important (0.06). This suggests that training and supporting programmes could play an effective role in promoting CAV deployment, in addition to marketing campaigns which we are likely to see a lot in the near future. Regarding *Policy and regulation readiness*, more even weight allocation was found, with *Registration, licensing and testing* (0.07) and *Liability and insurance* (0.07) considered slightly more important than *Policies promoting environmentally sustainable use of CAVs* (0.06), *Socially just use of CAVs* (0.06), and *Policies mitigating negative economic impacts* (0.06).

At Level 3, largely balanced weights were given to *Infrastructure quality and maintenance* (0.08), *CAV-oriented design* (0.08) and *Charging facilities* (0.07) regarding *Physical infrastructure readiness*. Indeed, these are all essential in many use cases for successful operation of CAVs and services. Regarding *Cyber infrastructure readiness*, *Cyber security* was considered most important (0.08) and *Data analytics* least important

(0.04), with *Internet network connectivity* in between (0.06). This result could be expected, since the consequences of cyber security failures could be disastrous (Sheehan et al., 2019), while poor data analytics in many cases might just be a performance issue (e.g., Cui et al., 2018; Lin et al., 2018), although the cumulative costs of the performance impairment could still be high at system level.

3.3. Weights by individual stakeholder groups - how do weights differ between different stakeholder groups?

Using the same weight calculation method as for weights by all stakeholder groups, Figs. 8–10 show the weights of Level 1, Level 2 and Level 3 criteria by each of the six stakeholder groups, to compare differences between groups.

3.3.1. Weights by individual stakeholder groups – level 1 criteria

At Level 1, the three general public groups and transport students gave similar weight allocations, with *Infrastructure readiness* being the most important (0.37–0.43), and *Citizen readiness* and *Policy and regulation readiness* having approximately the same importance (0.27–0.3 and 0.27–0.34). Larger differences are found with transport experts and transport service providers, with the former gave low weight to *Citizen readiness* (0.19) and high weight to *Policy and regulation readiness* (0.44), and the latter gave the opposite (0.41 and 0.11). It indicates that decisions made or supported by transport experts alone without effective public consultation may overlook the importance of citizen readiness in CAV deployment, while transport service providers may need more considerations on the wider social and environmental impacts and the necessity of proper regulations when designing and delivering CAV services.

It can also be seen that weights by general public who use cars as main mode are almost the same as weights by all stakeholder groups. This is also the case for weights of criteria at Level 2 and 3. This is because this group has by far the largest share in our survey responses, 53% for full sample and 49%–55% for samples with CR ≤ 0.1 for the six pairwise comparison matrix. Nevertheless, car users were not over-represented in this study considering the mode share of 69% by car in England in 2019 (Department for Transport, 2020).

3.3.2. Weights by individual stakeholder groups – level 2 criteria

At level 2, all stakeholder groups considered *Physical infrastructure* (0.2–0.24) to be more important than *Cyber infrastructure* (0.16–0.26)), except transport service providers. Largely similar weight allocations across the stakeholder groups were also found in criteria regarding *Citizen readiness*, where *Citizen knowledge and equipment* was considered most important (0.08–0.19) and *Adoption of other innovations* least important (0.04–0.08).

More differences were found in criteria regarding *Policy and regulation readiness*. In particular, transport experts considered *Policies promoting environmentally sustainable and socially just uses of CAVs* to be most important (0.12 and 0.13), while they were not so dominant in other stakeholders' weights, especially *Policies for socially just uses of CAVs* (0.01–0.05). This might be because that, a lot of the scientific research on potential disruptive consequences of misuses of CAVs has only attracted attention within the academia and expert communities. While on the other hand, marketing for vehicle automation has always tended to highlight benefits (e.g., Waymo, 2021), potentially leading to public impression that these benefits are guaranteed even without proper policy interventions. Dialogues between different stakeholder groups to exchange their views and concerns behind their weights would be necessary to gain a comprehensive understanding of how cities can be best prepared for CAV deployment for different groups, as well as for the city and the society as a whole.

3.3.3. Weights by individual stakeholder groups – level 3 criteria

At Level 3, there is less difference between the six stakeholder groups. All of the groups gave more balanced weights to criteria regarding *Physical infrastructure readiness*, varying within a small arrange from 0.06 to 0.09. Noticeably, general public who use walking or cycling as main mode gave a relatively high weight to *Charging facility*, which might be associated with their preference for and/or advocacy of cleaner mobility. Larger gaps are found in weights of criteria regarding *Cyber infrastructure readiness*. All stakeholder groups considered *Cyber security* the most important (0.07–0.11) and *Data*

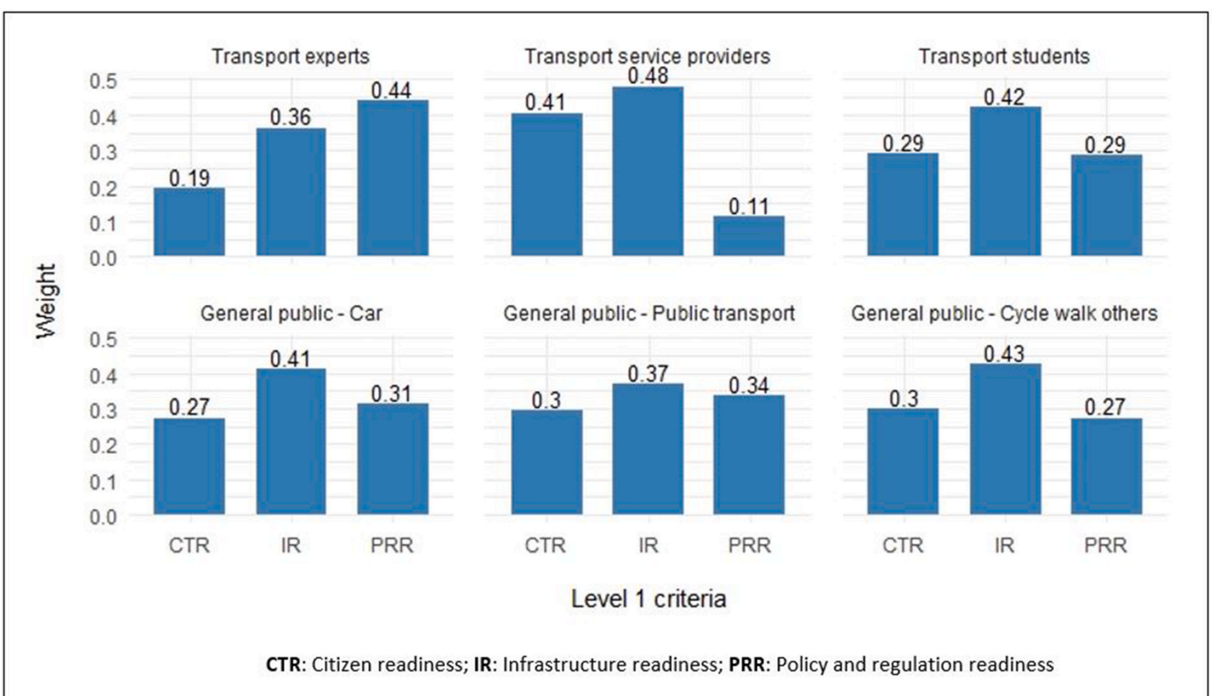
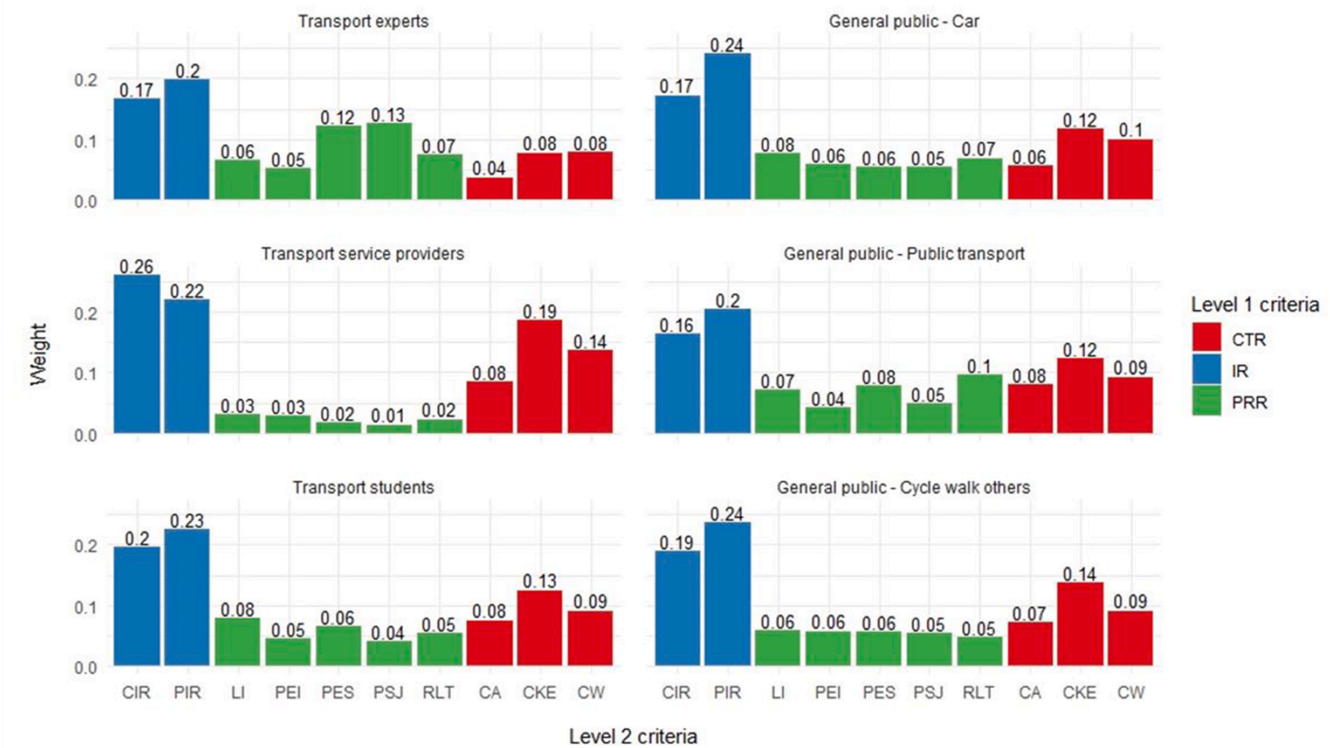
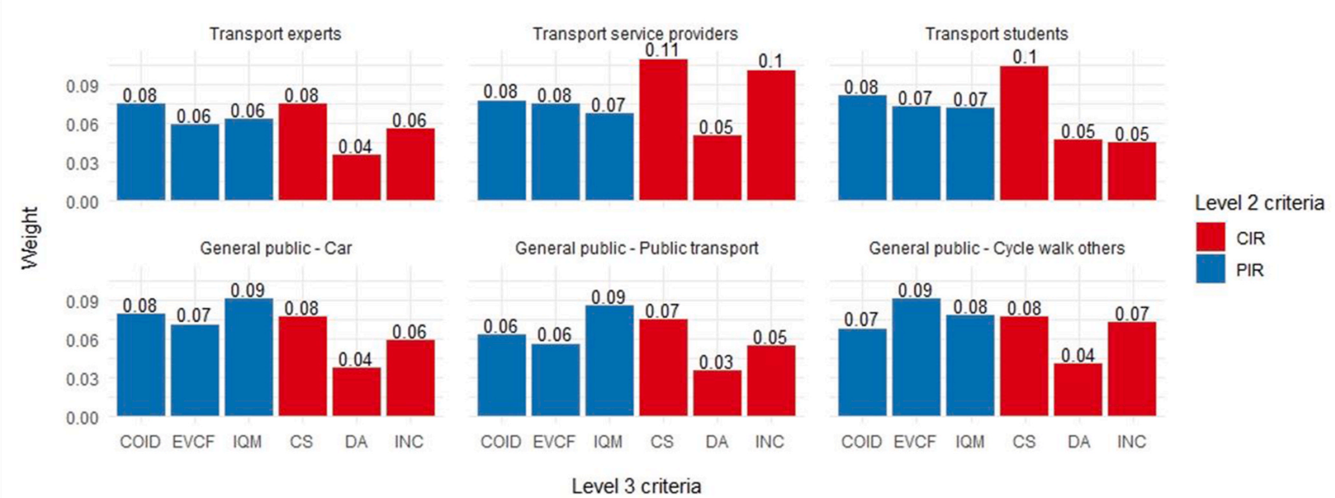


Fig. 8. Weights of Level 1 criteria by individual stakeholder groups.



CTR: Citizen readiness; **IR**: Infrastructure readiness; **PRR**: Policy and regulation readiness; **CIR**: Cyber infrastructure readiness; **PIR**: Physical infrastructure readiness; **LI**: Liability and insurance; **PEI**: Policies mitigating negative economic impacts; **PES**: Policies promoting environmentally sustainable use of CAVs; **PSJ**: Policies promoting socially just use of CAVs; **RLT**: Registration, licensing and testing; **CA**: Citizens' adoption of other technologies and business innovations; **CKE**: Citizens' knowledge, skills and equipment to use CAVs; **CW**: Citizens' willingness to use CAVs

Fig. 9. Weights of Level 2 criteria by individual stakeholder groups.



CIR: Cyber infrastructure readiness; **PIR**: Physical infrastructure readiness; **COID**: CAV-oriented infrastructure design; **EVCF**: Electric vehicle charging facilities; **IQM**: Infrastructure quality and maintenance; **CS**: Cyber security; **DA**: Data analytics; **INC**: Internet network connectivity

Fig. 10. Weights of Level 3 criteria by individual stakeholder groups.

analytics the least important (0.03–0.05), except transport students who considered *Internet network connection* no more important than *Data analytics*. Overall, the patterns of weight distribution of the six individual groups are largely consistent with that of all groups.

3.4. CAV knowledge and attitudes by individual stakeholder groups - how are weight differences associated with CAV knowledge and attitudes?

Fig. 11 shows participants' agreements on statements regarding their CAV knowledge and attitudes. As can be expected, the three transport professional groups have better CAV knowledge than the three general public groups do, with the majority of them are aware of recent CAV development and/or CAV debate. They also have slightly higher intention to use CAVs, which is congruent with findings in other studies that show positive relationships between CAV knowledge and acceptance (Charness et al., 2018; Ward et al., 2017). Expectations on CAVs' wide-reaching impacts are mostly positive and/or neutral, especially regrading impacts on environmental sustainability, which is similar to findings in Kacperski et al. (2021). Overall, transport students are the most optimistic.

Relating to weight differences between stakeholder groups, the slightly more disagreements on CAVs' contributions to environmental sustainability and social equity from transport experts may to some extent explain the higher weights they gave to the two corresponding policy criteria at Level 2 and the *Policy and regulation readiness* at Level 1. Meanwhile, the largely neutral opinions of transport service providers on CAVs' impacts may explain their lower weights for these policy readiness criteria. The differences in CAV knowledge and intention to use between the transport professional groups and the general public groups do not seem to influence the weights they gave, at least not with any clear patterns.

4. Conclusions

This study fills the knowledge gap in quantitative multi-stakeholder analysis of city readiness for CAVs, and provides policy implications on how cities can be best prepared for CAVs. Using online survey and AHP, this study explored assessment criteria regarding city readiness for CAVs, covering the aspects of infrastructure, policies, regulations and citizens, and rated by six stakeholder groups including transport experts, transport service providers, transport students, general public who use cars as main mode, general public who use public transport as main mode, and general public who cycle, walk or use other modes as main mode.

The results show that overall, *Infrastructure readiness* was considered most important, with *Physical infrastructure* being more important than *Cyber infrastructure*. While *Citizen readiness* was considered slightly less important than *Policy and regulation readiness*, relatively high weight was given to *Citizens' knowledge and equipment* as a sub-criterion, Some differences were found between stakeholder groups. Transport experts gave relatively high weight to *Policy and regulation readiness* and low weight to *Citizen readiness*, while transport service providers did the opposite. Under the *Policy and regulation readiness*, transport experts also gave more dominant weights to *Policies promoting environmentally sustainable and socially just uses of CAVs*, while other groups did not prioritise these two criteria. These differences might be associated with stakeholder groups' attitudes towards CAVs, especially their expectations on CAVs potential impacts on environmental sustainability and social equity.

Based on the findings, policy implications from this study are:

- Infrastructure upgrade should be prioritised to get cities ready for CAVs.
- CAV training and supporting programmes could play an important role in promoting CAV deployment.
- Transport experts may overlook the importance of citizen readiness. Effective public consultation would be helpful in decision-making.
- Disagreements are more likely to occur regarding CAV policies. Dialogues between different stakeholder groups would be necessary to gain a comprehensive understanding of how cities can be best prepared for CAV deployment.

These findings and implications, however, need to be taken with the limitations of this study in mind. The broadness as well as details that can be covered in this study is limited, since the number of criteria that can be assessed is limited for AHP to be practical, and there are still large uncertainties in CAV development. The number of participants representing transport service providers are very low in this study, although this is not an issue for the AHP method, results from this group cannot be confidently generalised, and require extra caution when comparing to other groups.

CRediT authorship contribution statement

Like Jiang: Conceptualization, Methodology, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Haibo Chen:** Funding acquisition, Project administration, Conceptualization, Methodology, Formal analysis, Writing – review &

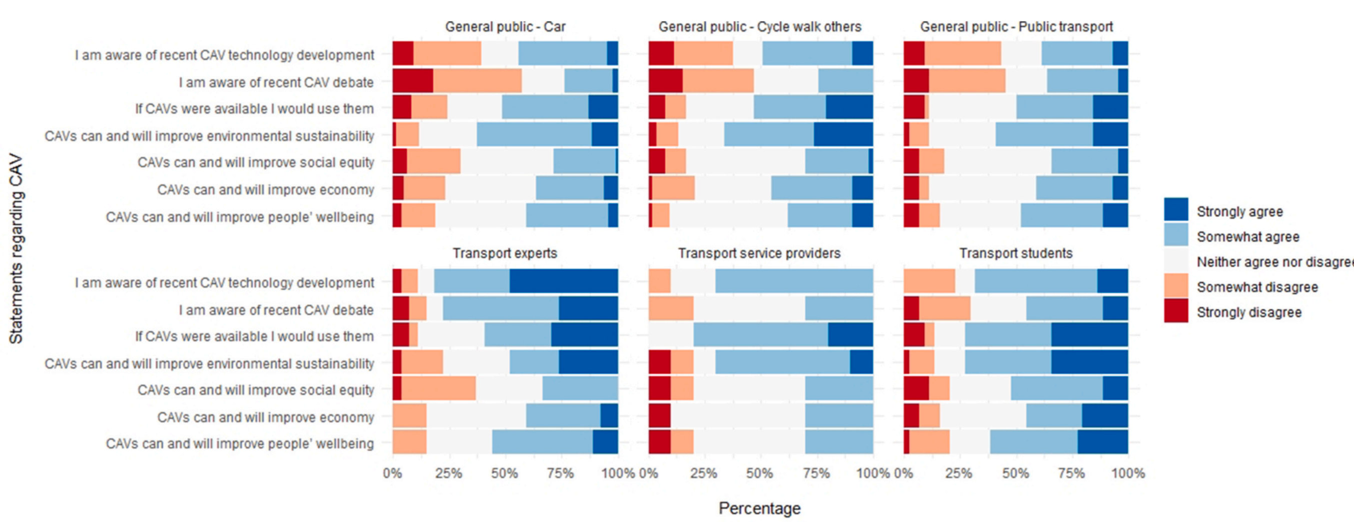


Fig. 11. Participants' knowledge of and attitudes towards CAVs.

editing. **Zhiyang Chen:** Conceptualization, Methodology, Visualization, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Criteria of city readiness for connected and autonomous vehicles

Criteria	Descriptions	References
Level 1 criteria regarding city readiness		
Infrastructure readiness	Infrastructure includes both physical infrastructure (e.g., roads, park facilities) and cyber infrastructure (e.g., mobile network). Current transport infrastructure needs to be improved and/or adapted to meet some specific needs of CAVs and/or to take full advantages of CAVs.	Duvall et al. (2019); Khan et al., 2019; KPMG, 2020; Oliver et al. (2018)
Policy and regulation readiness	Policies and regulations need to be redesigned, not only to regulate the uses of vehicles and roads (e.g., license, liability, road-use rules for car users, cyclists and pedestrians), but also on issues such as social, environmental and economic impacts.	Barnes et al. (2017); , Duvall et al. (2019); Khan et al., 2019; Kimley-Horn (2016); KPMG, 2020
Citizen readiness	Citizens, the users of CAVs, need to be willing to use CAVs and the new mobility systems, and be equipped with necessary knowledge and/or equipment.	Golbabaei et al. (2020); INRIX, 2017; KPMG, 2020
Level 2 criteria regarding infrastructure readiness		
Physical infrastructure readiness	Physical infrastructure includes provision and maintenance of roads, bridges, tunnels, signages, parking facilities, etc that are already in use for conventional road transport, but also new infrastructures like electric vehicle charging facility, CAV-dedicated lanes and stops that are emerging or will emerge for new vehicles and mobility systems.	Johnson (2017); Khan et al., 2019; NACTO, 2019; Saeed (2019)
Cyber infrastructure readiness	CAVs use data received by their own sensors, from other vehicles, road infrastructure and the internet to make driving decisions and automate driving. So fast and secure internet network of high coverage is needed, along with fast and advanced data analytics for optimised driving decision making.	Khan et al., 2019; KPMG, 2020; Sheehan et al. (2019)
Level 2 criteria regarding policy and regulation readiness		
Registration, licensing and testing	Cities or states need to update regulations and technical procedures for vehicle registration, licensing and testing, to ensure that all CAVs comply with hardware, software and data requirements, and are roadworthy over their lifespans.	Fagnant and Kockelman (2015); Koopman, and Wagner, 2016
Liability and insurance	Who should be liable in a traffic accident involving CAVs? the user, the manufacturer, or a 3rd party managing the intelligent road infrastructure? The answer will depend on many factors, and clear liability rules need to be defined and correspondingly insurance policies for CAVs developed.	Alawadhi et al. (2020); de Miguel et al. (2020); Fagnant and Kockelman (2015)
Policies promoting environmentally sustainable use of CAVs	CAVs may lead to increase in total carbon emission, air pollution and noise due to increased car dependency and total car travels, despite their advantages in fuel efficiency and road network efficiency. Policies need to be made to help promote environmentally sustainable use of CAVs, for example, by encouraging CAV ride sharing, CAV public transport and active travel modes (e.g., walking and cycling).	Soteropoulos et al. (2019); Taiebat et al. (2018); Wadud et al. (2016)
Policies promoting socially just use of CAVs	CAVs can enhance the mobility of vulnerable groups such as the disabled, elderly and children, but they may also increase mobility disparity between the socially-advantaged and -disadvantaged, due to higher costs of CAVs, the competition of CAV cars with public transport, and unequal geography of CAV infrastructure investment. Policies need to be made to help promote socially just use of CAVs, ensuring equitable access to jobs, housing, education, and transportation for all citizens.	Barnes et al. (2017); Cohn et al. (2019); Harper et al. (2016); Sparrow and Howard, 2020
Policies mitigating negative economic impacts	CAVs may have some negative economic impacts, such as unemployment of taxi, bus and lorry drivers, loss of state and local government revenues from fuel tax, parking charges and traffic violation fines. Cities or states need to have policies ready to mitigate such negative economic impacts, for example, by providing training opportunities to transform the labour market, finding alternative revenue sources or adjusting budget allocation.	Beede et al. (2017); Mares et al. (2018); Terry and Bachmann (2019)
Level 2 criteria regarding citizen readiness		
Citizens' willingness to use CAVs	High uptake of CAVs may not be possible if citizens are not willing to use them. Research has shown that people with certain demographic characteristics are more likely to accept CAVs. Cities with a more pro-CAV demographic profile will certainly have an advantage in CAV uptake, but CAV education and campaigning programmes can also help changes citizens' attitudes towards CAVs and promote acceptance.	Golbabaei et al. (2020); Kacperski et al. (2021); Mathis et al. (2020)
Citizens' knowledge, skills and equipment to use CAVs	Citizens may need to have certain knowledge and skills (e.g., internet and digital literacy) and equipment (e.g., smart phones and methods of electronic payment) to be able to use CAVs. CAV training and supporting programmes can help citizens to be better prepared for CAVs.	Barnes et al. (2017); KPMG, 2020
Citizens' adoption and use of other technologies and business innovations	Adoption and use of other technologies and business innovations such as online ride-hailing, e-bike sharing, online food delivery and Airbnb will help citizens to	Golbabaei et al. (2020); KPMG, 2020

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(*continued*)

Criteria	Descriptions	References
	experience a more smooth transition to the new mobility services brought about by CAVs, e.g., CAV car sharing and ride sharing.	
Level 3 criteria regarding physical infrastructure readiness		
Infrastructure quality and maintenance	Roads, bridges, tunnels and other structures need to be of high quality and well-maintained with clear and standardised markings and signages, for CAVs to easily detect and read relevant information and to perform effectively. In addition, roadside sensors will be installed on lanes, curbs, sidewalks, etc. and they will also require good maintenance.	Johnson (2017); Khan et al., 2019; Saeed (2019)
CAV-oriented infrastructure design	CAV-oriented infrastructure designs, such as CAV-dedicated lanes or routes, new road geometry design with narrower lanes and tighter corner radii, new intersection design considering CAV interactions with other road users or considering platooning, CAV drop-off and pick-up points, relocation of parking with reduced size, are needed to achieve the full advantages of CAVs.	Duvall et al. (2019); Johnson (2017); Saeed (2019)
Electric vehicle charging facilities	It is expected that most, if not all, CAVs will be electric vehicles, and hence automatic and strategically located charging facilities are needed to serve CAVs in different use scenarios (e.g., private car, car and ride sharing, first- and last-mile trips)	Khan et al., 2019; KPMG, 2020
Level 3 criteria regarding cyber infrastructure readiness		
Internet network connectivity	CAVs need to be connected and communicate with other vehicles, road infrastructure and traffic control centres to make often instant driving decisions and perform driving tasks. Fast and reliable internet connections need to be available wherever CAVs go.	Khan et al., 2019; KPMG, 2020
Cyber security	The data and internet connection for CAV operations need to be secure and resilient against physical and cyber attacks and damages (e.g., hacking of roadside communication devices, disruption to internet access during and after natural disasters).	Khan et al., 2019; KPMG, 2020; Sheehan et al. (2019)
Data analytics	Both real-time traffic data (e.g., vehicle location and speed data from vehicle and/or roadside sensors, pedestrian movement data from roadside cameras) and static map data (e.g., maps of road networks and trip destinations) can be used and analysed, by individual CAVs and/or traffic control centres, to optimise driving decisions, e.g., route choice, parking choice, service allocation. Large amount of data will need to be processed in little or no delay to perform such services.	Cui et al., 2018; Khan et al., 2019; Lin et al., 2018

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