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Environmental Sciences Europe (2022) 34:103
https://doi.org/10.1186/s12302-022-00682-4

Environmental Sciences Europe

RESEARCH

Open Access

Identifying criteria for effective urban vehicle access regulations adoption

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Abstract

Background: Urban Vehicle Access Regulations (UVAR) hold great potential to reduce negative transport externalities driven by increased mobility demand and rapid urbanisation. However, as they are potential measures to the wicked problem of climate change mitigation and achieving overall sustainability, their implementation pathways are often complex due to the multidimensionality of sustainability and other challenges. Although decision support tools like the multi-criteria decision analysis might help simplify these complexities, selecting the appropriate criteria based on the peculiarity of UVAR remains pertinent. This study contributes to the sustainable transport decision support literature to address this challenge by identifying relevant criteria for the UVAR measure planning process using the Delphi survey approach.

Results: It begins with 23 criteria systematically selected from scientific literature and clustered into four dimensions in the first round. This was expanded into 30 criteria and five dimensions in the second survey round based on the participating experts' ratings and rankings. The consensus results showed that most of the identified criteria were considered to be of great potential in UVAR measure planning, with public acceptability, stakeholder engagement, political agenda, and the potential impacts on air pollution and accessibility considered the most important.

Conclusions: Apart from helping urban authorities select feasible and effective UVAR measures, the resulting assessment structure will also help identify the main barriers and drivers for UVAR adoption. The assessment structure will also aid the monitoring and evaluation phases of the measures upon implementation.

Keywords: Congestion charging, Low emission zone, Access restriction, MCDA, Delphi, Sustainability, Car dependency

Background

The urban population is increasing at an unprecedented rate. While cities endeavour to accommodate this increasing population, which is expected to rise to about 68% cumulative share of the global population by 2050 [1], a finite supply of fast depleting resources could lead to undesirable effects. The need to reverse this trend has led to the rise of the sustainable development concept. Sustainable development requires the conscious use of resources to meet the needs of today without jeopardising that of the future generation. Applying this concept to urban transport and mobility will require a reduced dependency on automobiles and fossil fuel-powered mobility, which have been the source of negative externalities, including air pollution, noise, congestion, accidents, land degradation and greenhouse gas emissions [1–4]. While these spatial and temporal effects might be local, the risk of climate change is an existential threat to humans, flora, and fauna alike. Concerted efforts to mitigate these impacts at different geographical levels have given rise to several policy agreements and commitments to meet defined goals and targets for sustainable urban mobility. A common point in these instruments is the

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need to reduce private car dependency in urban areas, particularly those powered by fossil fuels [5, 6].

Different measures are targeted at stimulating behavioural change away from dependency on private automobile travel, e.g. improvement of public transport service and quality, provision of active mobility facilities, and introduction of shared mobility. However, these measures' effects are often limited compared to measures that directly regulate vehicular access in urban areas [7, 8]. These measures include zero or low emission zones, road user charges, limited traffic zones, odd–even plate traffic schemes, superblocks, pollution emergency schemes, area pedestrianisation and traffic bans. Although these measures differ in design and regulatory approach, they are commonly referred to as Urban Vehicle Access Regulations (UVAR). UVAR combine pricing measures, spatial interventions and other restrictive schemes to limit the access of vehicles based on emission, size, weight, type, and time of day characteristics [9].

There are several instances of UVAR measures across the world, particularly in Europe, where over 700 schemes exist with varying impacts [10]. However, UVAR are posed as potential solutions to address the wicked problem of achieving sustainability, which overlaps a subset of other problems. These problems include climate change, environmental pollution, and inefficient allocation of public spaces. Consequently, UVAR adoption and implementation are often not devoid of complexities. These complexities arise due to the problem's unstructured, cross-cutting and relentless nature due to multiple stakeholders with diverse perspectives and conflicting interests yet with a high degree of interdependency [11]. Adopting and implementing solutions is challenging for policymakers and public management authorities, particularly in strategy making, organisation design, people management, and performance measurement. Addressing these multiple degrees of wickedness while using UVAR as a policy instrument will require a collaborative decision-making method. The method should mirror the multifaceted elements of transport sustainability, which primarily includes the urban area's different economic, social, and environmental objectives. Accordingly, designing and evaluating a feasible and optimal UVAR measure implies taking the different, perhaps conflicting, criteria of these sustainability dimensions into consideration using decision support tools such as Multi-Criteria Decision Analysis (MCDA).

The framework of MCDA involves evaluating different courses of action concerning different criteria, which encompasses the key dimensions of the decision-making problem [12]. Defining a framework for using this decision-making approach to assess the feasibility of UVAR measures will take a stepwise approach, from identifying the goal to defining the dimensions and characterising the criteria and sub-criteria.

An early definition of sustainable transport by the UK Round Table [13], as cited in [14], describes it as one which facilitates access to goods, resources and services while minimising travel need to effectively and holistically address economic, environmental and social requirements. Accordingly, many studies have provided a sustainability framework that includes the latter three requirements as the dimensions for analysis: economy, environment and social [15]. Ref.[16, 17] points out that most studies focus on these dimensions to varying degrees. While some attempt to balance these dimensions. Others tend to focus exclusively on the environmental or economic dimension. Nevertheless, more studies have emerged adding a fourth dimension which often varies depending on the authors' perspective or the scope of the study. For instance, [18] added a scientific and technological dimension to reflect its strong force on transport growth. [19] emphasised the importance of an institutional dimension, positing that it complements and allows interoperability between the three classical dimensions. Some other dimensions found in the literature include energy [20, 21], operational with fiscal and governance dimensions [22] and accessibility [23]. Regardless of these differences in identified dimensions, the studies all aim at sustainable transport planning as they satisfy the conditions for a practical sustainability framework. These conditions, as summed up by [24], include that they must consider economic, environmental and social well-being impacts; address the causes of unsustainability; include a stakeholder involvement component; and take the relative influence of agencies implementing sustainability-related policies and measures into account. These conditions are satisfied mainly by the studies mentioned earlier.

Other approaches apart from MCDA have been successfully applied for evaluating transport measures. Life Cycle Assessment (LCA) combines criteria to assess the environmental impact of a product during its life course, e.g. for mutualised mobility [25] and environmental impacts of the transport system [26]. Cost–benefit analysis (CBA) involves computing the monetary value of a given project's benefits and costs to select an alternative that maximises benefit (e.g. [27, 28]). Assessment indicator models use a composite index, multi-level index, or multidimensional matrix model to evaluate the sustainability of transport models (e.g. [29, 30]). Other approaches include simulation models (e.g. [31]) and optimisation models (e.g. [32]). [33] enumerated the shortcomings of these approaches: difficulties in incorporating social aspects (LCA), estimating external and social costs (CBA), identifying appropriate number and

type of indicators (assessment indicator models), handling qualitative and correlated data (optimisation model) and capturing all data required for robust modelling (simulation). MCDA also have the demerit of being suboptimal in some applications, as solutions are generated through tradeoffs between multiple objectives. However, it is preferred for its ability to handle both qualitative and quantitative criteria across various dimensions. In addition, it provides deep insights into the problem structure and treatment of decision-makers' uncertainties [33–35].

Since there are many aspects to each sustainability dimension, a set of criteria is assigned to each dimension to evaluate progress towards sustainable transport. This necessarily does not have to be a top-down process as the set of criteria represents the objectives to be achieved. They can therefore be identified independently and categorised into the appropriate dimension in a bottom-up manner. With the criteria level being the basic decision unit of the decision-making, it is critical to identify and select suitable assessment criteria that will guide the measure planning and implementation process for transport sustainability. Previous studies, including [15, 16, 19–22, 36, 37], have presented several sustainability assessment criteria and indicators within the transport sector, primarily for impact assessment and project alternative evaluation. However, the uniqueness of UVAR measure planning with its distinct constraints like equity concerns, social acceptability, and effectiveness [9, 38, 39] makes it essential to identify suitable criteria for its assessment [17].

This research aims to fill this gap by identifying criteria to determine the feasibility of UVAR measure adoption and implementation. It begins by cross-validating different objectives and preconditions recommended for urban transport professionals and planners in the European Commission's Topic Guide for UVAR and SUMPs with the criteria identified in existing literature for transport sustainability assessment. It then categorises these criteria into four sustainability dimensions: economic, environmental, social, and technical. These dimensions are interpreted as follows:

- Economic dimension: the long-term economic growth of the urban area, including that of its inhabitants and enterprises, should be supported by urban transport. The dimension includes criteria which indicate elements of cost efficiency of implementing an UVAR scheme and potential costs to be borne by users and businesses in the covered area.
- Environmental dimension: transport should safeguard urban ecosystems and preserve natural resources to ensure good health and well-being, now and in the future. The dimension consists of criteria which assess the role of UVAR in the impact of transport-related activities on the environment.
- Social dimension: urban transport should promote social efficiency and improve quality of life. The dimension indicates criteria assessing potential impacts and vulnerabilities to society and its population due to UVAR implementation.
- Technical dimension: this dimension includes all criteria that ensure UVAR operates efficiently without affecting urban mobility negatively and other dimensions of sustainability. It, therefore, assesses the status of complementary transport modes and other institutional requirements.

This research aims to simplify the decision-making process involved consequently. It attempts to address the following questions:

- What are the most suitable criteria to evaluate the readiness or feasibility of implementing UVAR in cities?
- Which sustainability dimensions are relevant to the assessment structure? What is the relative importance of the identified dimensions?
- Which criterion is more/less important absolutely and relatively in each dimension?

These questions were answered through a Delphi study approach involving experts in the transportation and urban planning field to validate and consolidate the identified criteria for UVAR planning sourced from existing literature. The Delphi technique was adopted in this study because it allows evidence-based, experiential and practical knowledge to be brought together in an iterative and structured process [40]. Therefore, allowing experts to assess and discuss complex issues about which uncertain and incomplete knowledge exists while stimulating the generation of new ideas not earlier considered in the process [41].

The study makes a twofold contribution to sustainable transport planning by addressing the research questions. Firstly, it provides an assessment structure to evaluate the feasibility of different UVAR measures, allowing cities to either identify aspects where changes are required or to select an optimal UVAR measure. Secondly, it brings forth equally important criteria and dimensions often not factored into transport policy measure planning when considered within the purview of the classic triple dimensions of sustainable transport.

Table 1 Classification of the identified sustainable urban mobility criteria relevant to UVAR planning

Economic	Environment	Social	Technical
Capital cost	Air pollution	Accessibility	Availability of park and ride (P + R) facilities
Impact on SMEs	Fossil fuel consumption	Congestion reduction	Institutional capacity
Operating cost	Greenhouse gas emissions	Equity and social inclusion	Marketing and communication
Revenue	Impact on biodiversity	Impact on land use	Mobility as a service deployment
Travel cost	Noise annoyance	Modal shift	Public transport quality
		Public acceptability	Robust cycling network
		Safety	

Methods

In this section, a qualitative method was developed to identify criteria specific for evaluating the feasibility of UVAR measures for implementation in cities. The criteria were drawn from a sustainable urban mobility planning framework, recognising that UVAR measures are policy instruments that aid cities in achieving their long-term climate and mobility strategies and vision.

The first step was a document analysis of the European Commission's Topic Guide for UVAR and SUMPs [42]. Scheme objectives, preconditions for implementation, recommendations from good practice cities and case materials provided in the document were operationalised into criteria. This longlist of criteria was then compared with sustainable urban mobility criteria and indicators in existing literature, primarily from the reviews undertaken by [22, 33, 37]. Different relevant criteria were identified and assessed to confirm their feasibility in being transformed into SMART (specific, measurable, achievable, relevant and time-bound) indicators for multi-criteria decision-making analysis usually adopted in the measure planning phase of sustainable urban mobility planning [43].

Twenty-three criteria were identified to be of relative importance to the feasibility and relevance analysis of UVAR measures. They were clustered into dimensions using the three pillars of sustainability, i.e. economic, environment and social, with a fourth dimension termed technical. The latter dimension comprises other criteria contributing to the successful adoption and implementation of UVAR, but does not fit perfectly into the three established sustainability dimensions. The identified criteria and dimensions are presented in Table 1.

These dimensions and their criteria were then subjected to expert judgment through an online survey using a Delphi approach. This approach became necessary because, due to the large number of criteria identified, pairwise comparisons at an exploratory phase might be cumbersome to analyse and become less reliable. Moreover, assessing planned measures is subject to high uncertainty, and an expert-based subjective evaluation might be highly beneficial in reducing the degree of uncertainty.

Selection of study participants

Professionals with experience in transportation and mobility were identified from policy documents and scientific research outputs which discussed concepts related to UVAR and shortlisted for participation. Observing the list was made up predominantly of resource persons from academia. Further efforts were made to diversify the shortlist. Professionals affiliated with the consortium partners of the CIVITAS ReVeAL project (a project conducting action research on adding UVAR to the range of urban mobility transition approaches of cities) were added to the shortlist. Finally, through the network of the authors, a link was established with the EIT Urban Mobility, and representatives of the initiative's Academy and City Club were also shortlisted for the study. In all, 120 professionals were selected as potential participants for the study. The breakdown of their organisational affiliation is presented in Table 2.

Table 2 Analysis of study participants by organisational affiliation

Affiliation	Invited participants	First round participants	Second round participants
Consultancy	20	6	5
Municipality or city government	12	6	6
Non-Governmental Organisation	8	2	2
Transport planning authority	15	5	3
University or research institution	49	37	19
Urban planning authority	16	5	5
Other	–	2	1

The potential participants were invited to participate in the study via email. The email conveyed a brief introduction to the study's scope and goal. The authors also asked the contacted persons to assist in identifying other potential subjects. However, no direct feedback was received to this effect. Halfway through the projected period for each survey iteration, reminder emails were also sent to boost participation.

First round of the survey

The first round of the Delphi study consisted of a combination of open-ended questions, sometimes directed by preceding closed-ended questions. These questions focused on ascertaining and consolidating the different criteria identified from existing literature to be factors that could influence the feasibility and the implementability of urban vehicle access regulation measures. The questions in the first section asked the participants to rank the relevance of the different dimensions (i.e. economic, environment, social and technical) the criteria were clustered to assess the readiness of cities for UVAR measures implementation on a 6-point Likert scale ranging from 1 (strongly irrelevant) to 6 (strongly relevant). This was followed by the open-ended question allowing participants to suggest alternative ways to cluster the criteria or additional suitable dimensions that had been excluded. The second section had a similar structure, except the questions were based on evaluating the importance of the criteria in each dimension as mentioned earlier and suggesting any relevant criterion omitted in the survey. The evaluation was done on a 5-point Likert scale ranging from 1 (not important) to 5 (extremely important). The third section of the questionnaire collected information about the demographic characteristics, area of expertise, familiarity with UVAR measures and willingness of participants to participate in a further round of the study.

Second round of the survey

The second round of the Delphi study used an online questionnaire similar to the first. However, this survey round consisted of only closed-ended questions asking participants to evaluate the relevance and importance of the dimensions and criteria based on the responses received in the first iteration. Additionally, the participants were asked to rank the criteria and dimensions in each category based on their relative importance, from the most important to the least important. This task was included to assess if there was concordance in the perceived importance of the criteria and dimensions, which could inform weights being attributed to the different elements in each category.

Controlled feedback highlighting the results of the first iteration and modifications was provided in the email inviting the participants to the second. This invitation was sent out only to participants who declared their availability to partake in subsequent iterations of the study. A link to a more detailed statistical summary of the responses received, including the median values and interquartile ranges (IQR), with the threshold values, was also provided on the introductory page of the survey.

Data analysis and consensus evaluation

Analysis of the responses of the participants in the first iteration was performed by the authors collaboratively with a panel of three highly experienced professionals. They are a senior mobility consultant at a private sustainable transportation research consultancy, a programme policy officer from a transport planning department and a planning support manager from an urban planning department. The panel members were excluded from participating in the survey rounds to reduce possible biases and ensure the quality of the analysis. The team scrutinised the identified and suggested criteria with other qualitative inputs from the participants to assess their relevance to the scope of UVAR adoption and implementation and defined threshold values to determine the degree of consensus amongst the participants in the subsequent round. The team did not remove any identified criteria from the first iteration because a threshold was not defined before the study's commencement. However, they unanimously agreed with several of the comments from the participants to delete a criterion that might be challenging to translate into a measurable indicator within an urban area's context.

The panel defined consensus as a median of ≥ 4, with $\geq 75\%$ answering 4 or 5 on a 5-point Likert scale. Similarly, a majority agreement was defined as a median of ≥ 4, with at least 60% of participants answering 4 or 5.

For the ranking exercise in the second survey round, Kendall's Test of Concordance was administered to evaluate the agreement between the participants by computing W, which is obtained by Eq. 1. W ranges between 0 and 1, with 1 specifying perfect agreement or concordance and 0 designating no agreement or independence of samples [44, 45]. The interpretation of the W values is provided in Table 3:

$$W = \frac{12S}{m^2(n^3 - n)}, \tag{1}$$

where W is Kendall's test of concordance value, S is the sum of squared deviations of the individual ranks from the mean value of the total ranks, m is the number of judges ranking the objects, and n is the total number

Table 3 Interpretation of Kendall's test of concordance value, *W*. Source: [46]

W	Interpretation
$W \leq 0.3$	Weak agreement
$0.3 < W \leq 0.5$	Moderate agreement
$0.5 < W \leq 0.7$	Good agreement
$W > 0.7$	Strong agreement

of objects being ranked. The test statistic takes a Chi-squared distribution obtained from Eq. 2:

$$X^2 = m(n-1). \quad (2)$$

Results

Participation

One hundred and twenty professionals in total were invited to participate in the study. 63 (52.5%) of these participated in the first round of the survey. The participating experts were geographically distributed across 23 countries, with 48/63 (76%) participants living in cities which have implemented effective transport demand management measures. Thirty-six of these participants specifically acknowledged the presence of UVAR measures in their cities. This verifies that most of the participants, besides having professional expertise, also have first-hand experience of UVAR in practice. The detailed summary of the participants' data is presented in Additional file 1: Figure S1 of the Supporting Information.

From this first round, 46/63 (73%) declared their willingness to participate in a subsequent round. Invitations were sent to these volunteers to standardise the results as a Delphi norm. Only 41 of these (representing 91%) responded and participated in the second round.

First survey round

The experts rated 27 items in this survey round and were prompted to provide qualitative inputs in four instances. Table 4 provides the descriptive summary of the rating for the four dimensions. The ratings for the criteria grouped according to respective dimensions are provided in Table 5 (the detailed result is presented in Additional file 1: Table S1-S2 of the Supporting Information). While no consensus criteria or threshold value was pre-defined before this round, some observations were made based on the central tendency and dispersion of the presented results. For a 5-point Likert scale, an interquartile range of less than equal to one indicates strong consensus amongst the participants, while greater values indicate polarised opinions. Most participants agreed that all dimensions are relevant to establishing the feasibility of implementing urban vehicle access regulation measures.

For the individual criteria, it can be inferred that 21 of the 23 criteria are considered very important (Median ≥ 4 and IQR ≤ 1). Of the remaining 2 with a wider opinion spread, the impact on land use was also deemed very important, while the impact on SMEs was considered moderately important.

For the qualitative results, several recommendations were made on the criteria and dimensions to be included. For the dimensions, several mentions were made of the missing political and governance components of the assessment structure (e.g. actors and policymaking stakeholders, legal framework, and political agenda). Several participants stated that the technical dimension was not

Table 4 Descriptive statistics of the dimensions rating in the first survey round

Dimension	Range	Median	IQR
Economic	2–6	5	1
Environment	2–6	6	1
Social	2–6	5	1
Technical	2–6	5	1

Table 5 Descriptive statistics of the criteria rating in the first survey round

Dimension	Criteria	Range	Median	IQR
Economic	Revenue	1–5	3	1
	Capital cost	2–5	4	1
	Operating cost	2–5	4	0
	Travel cost	2–5	4	1
	Impact on SMEs	1–5	3	1.5
Environment	Fossil fuel consumption	2–5	4	0.5
	Air pollution	3	5	1
	Noise annoyance	2–5	4	1
	Greenhouse gas emissions	2–5	4	1
	Impact on biodiversity	1–5	3	1
Social	Public acceptability	2–5	4	1
	Equity and social inclusion	2–5	4	1
	Accessibility	3–5	5	1
	Congestion reduction	2–5	4	1
	Impact on land use	2–5	4	1.5
	Modal shift	3–5	4	1
	Safety	2–5	4	1
Technical	Public transport quality	2–5	4	1
	Institutional capacity	2–5	4	1
	Marketing and communication	2–5	4	1
	Availability of P + R facilities	1–5	3	1
	Robust cycling network	2–5	4	1
	Mobility as a service deployment	1–5	4	1

adequately defined and suggested it should be renamed or modified. Other suggestions include local acceptance, personal characteristics and considering some criteria as independent dimensions (e.g. considering congestion separately as it has economic, social and technical implications).

Upon the deliberations by the panel of experts, which included considering the descriptive statistics and qualitative inputs on a case-by-case basis, a policy and governance dimension was introduced (with four new criteria). The 'Technical' dimension was also renamed 'Mobility and Technical'. The definition of the renamed dimension was broadened to indicate efficiency in urban mobility, with new criteria added accordingly. Hitherto missing criteria were also added to the social dimension while some criteria were redefined and others moved to different dimensions to incorporate the suggestions of the study participants. However, the impact on biodiversity criterion was removed from the criteria as it was generally considered difficult to transform into a measurable SMART indicator within the urban context.

Second survey round

The result of the rating exercise in the second round of the survey for the dimensions under consideration is presented in Table 6, while that of the criteria is shown in Table 7. The detailed results are provided in Additional file 1: Tables S3-S4 of the Supporting Information.

Economic

A consensus was reached on the relevance of the economic criteria in assessing the implementability of UVAR in urban areas. This consensus was extended to travel costs for private users as the participants agreed that the potential effect of implementing UVAR on the private cost of road users is vital to its adoption. The majority also agreed that the availability of capital and operating costs also significantly impact UVAR adoption. However, many of the participants did not consider revenue and the potential impact of UVAR adoption on SMEs to be an essential criteria to be taken into account for the assessment structure.

Environment

The environment was considered the most relevant dimension in assessing the feasibility of UVAR adoption, with about 95% of the participants sharing this notion. Similarly, a consensus was reached on including air pollution, greenhouse gas emissions and noise pollution in the assessment criteria. A majority of the participants also agreed that the criterion to reduce fossil fuel consumption is also crucial for the planning and decision-making process.

Social

Assessing the potential impacts and vulnerabilities that may arise was deemed relevant to the measure planning process leading to a consensus on the social dimension. Consensus agreements were also reached for the criteria under this dimension except for impact on land use and the gender and social norm criteria. Only a majority agreement was reached for the former, while the latter did not meet the threshold value for inclusion as a criterion in the analysis structure.

Mobility and technical

75% of the participants rated the mobility and technical dimension relevant for assessing UVAR adoption. Likewise, public transport quality, the availability of walking facilities and a robust cycling network and facilities were unanimously agreed to be critical criteria when considering UVAR adoption. Most participants also agreed that the availability of marketing and communication platforms (public awareness and orientation), and the possibility of expanding or improving the UVAR scheme to meet future needs were also essential criteria for consideration. However, no agreement was reached on the importance of mobility as a service deployment (a complementary measure) for the UVAR scheme. In addition, the threshold for inclusion was not reached for the availability of P + R facilities.

Policy and governance

A consensus was reached on the relevance of the policy and governance dimension in assessing the

Table 6 Dimensions rating and consensus verdict in the second survey round

Dimension	Median	IQR	Number of participants answering 5 (%)	Number of participants answering 6 (%)	Relevance consensus
Economic	5	0	26 (63.41%)	10 (24.39%)	Consensus
Environment	6	1	15 (36.59%)	24 (58.54%)	Consensus
Social	5	1	21 (51.22%)	17 (41.46%)	Consensus
Mobility and Technical	5	0	23 (56.10%)	8 (19.51%)	Consensus
Policy and Governance	5	1	27 (65.85%)	11 (26.83%)	Consensus

Table 7 Criteria rating and consensus verdict in the second survey round

Dimension	Criteria	Median	IQR	Number of participants answering 4 (%)	Number of participants answering 5 (%)	Importance consensus
Economic	Revenue	3	1	14 (34.15%)	4 (9.76%)	NA
	Capital cost	4	1	27 (65.85%)	3 (7.32%)	Majority
	Operating cost	4	1	25 (60.98%)	5 (12.20%)	Majority
	Travel cost	4	1	19 (46.34%)	13 (31.71%)	Consensus
	Impact on SMEs	3	1	10 (24.39%)	7 (17.07%)	NA
Environment	Fossil fuel consumption	4	1	20 (48.78%)	9 (21.95%)	Majority
	Air pollution	5	1	14 (34.15%)	25 (60.98%)	Consensus
	Noise annoyance	4	1	21 (51.22%)	10 (24.39%)	Consensus
	Greenhouse gas emissions	5	1	14 (34.15%)	21 (51.22%)	Consensus
Social	Public acceptability	4	1	20 (48.78%)	20 (48.78%)	Consensus
	Equity and social inclusion	4	1	13 (31.71%)	20 (48.78%)	Consensus
	Accessibility	5	1	15 (36.59%)	24 (58.54%)	Consensus
	Congestion reduction	4	1	20 (48.78%)	14 (34.15%)	Consensus
	Impact on land use	4	1	17 (41.46%)	8 (19.51%)	Majority
	Modal shift	4	1	23 (56.10%)	14 (34.15%)	Consensus
	Safety	4	1	20 (48.78%)	17 (41.46%)	Consensus
	Liveability	5	1	14 (34.15%)	24 (58.54%)	Consensus
	Gender and social norms	3	1	17 (41.46%)	2 (4.88%)	NA
Mobility and technical	Public transport quality	4	1	21 (51.22%)	17 (41.46%)	Consensus
	Marketing and communication	4	1	26 (63.41%)	3 (7.32%)	Majority
	Availability of P + R facilities	3	1	10 (24.39%)	7 (17.07%)	NA
	Robust cycling network	4	1	20 (48.78%)	14 (34.15%)	Consensus
	Mobility as a service deployment	4	1	16 (39.02%)	5 (12.20%)	No agreement
	Ability for improvement/expansion	4	1	24 (58.54%)	6 (14.63%)	Majority
	Walking facilities	4	1	23 (56.10%)	15 (36.59%)	Consensus
Policy and governance	Political agenda	4	1	22 (53.66%)	17 (41.46%)	Consensus
	Legal and regulatory framework	4	1	21 (51.22%)	13 (31.71%)	Consensus
	Institutional Capacity	4	1	21 (51.22%)	8 (19.51%)	Majority
	Cross-agency cooperation framework	4	1	19 (46.34%)	3 (7.35%)	No agreement
	Stakeholder engagement	4	1	19 (46.34%)	20 (48.78%)	Consensus

implementability of UVAR in urban areas. For the importance of UVAR being on the political agenda, availability of legal and regulatory framework and stakeholder engagement criteria, a consensus was also reached amongst the participants. A majority agreement was reached on the importance of the availability of institutional capacity to implement, operate, and monitor UVAR schemes. However, the participants could not agree on the importance of having a cross-agency cooperation framework in assessing the implementability of UVAR measures.

Based on these findings, the resulting assessment structure is presented in Fig. 1.

Ranking exercise

Figure 2 shows the weighted importance rankings for the criteria and the overarching dimensions. The result of the Kendall test of concordance performed to test the agreement between the participants is presented in Table 8. The first row of the result shows the strength of agreement in the ranking of the dimensions considered in the study. The subsequent rows reveal the strength of agreement in the ranking of the set of criteria under each named dimension. For example, Economic shows the outcome of Kendall's concordance test on the priority orders assigned to revenue, capital cost, operating cost, travel cost, and impact on SMEs by the study

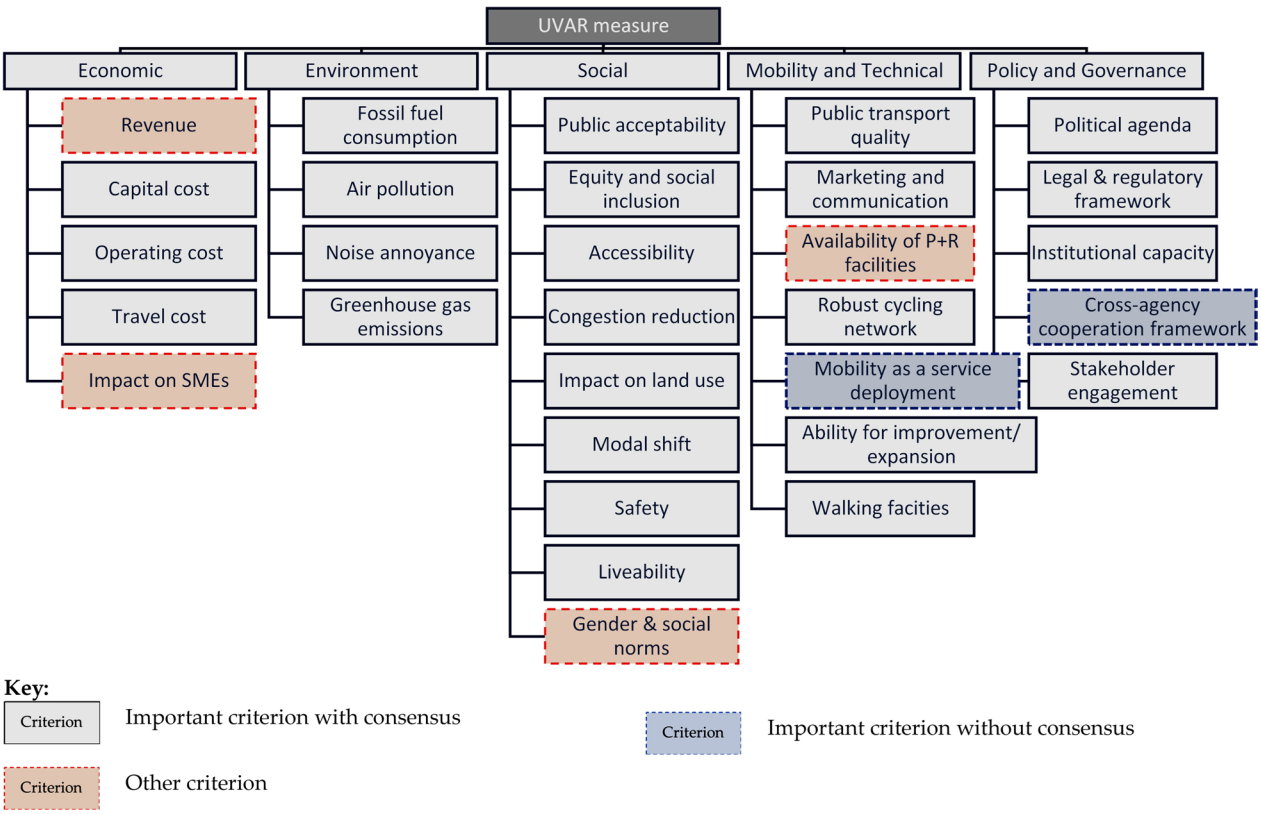

Fig. 1 Title: Assessment Structure for Urban Vehicle Access Regulations showing importance and consensus conditions from the study findings. *SMEs* small and medium-sized enterprises; *P* + *R* park and ride, *UVAR* Urban vehicle access regulations

participants. The detailed results of each ranking exercise are provided in Additional file 1: Tables S5-S10 of the Supporting Information.

Kendall's coefficient of concordance (W) shows that good agreement among the participants was reached ($W > 0.5$) for the criteria belonging to the environment, social, mobility and technical, and the policy and governance dimensions, with a level of significance greater than 95%. In contrast, a moderate agreement was reached for the environmental criteria rankings. For the set of economic criteria and the dimensions' ranking, the coefficient of concordance showed weak agreement, indicating diverse ranking perspectives for these items amongst the participating professionals.

Discussion

The study aimed to identify the criteria to examine the feasibility of UVAR implementation. Two consecutive survey rounds mirroring the Delphi process provided information from transportation and urban planning experts. The participants' responses were analysed by an independent panel of experts and subjected to a scoring system based on predetermined threshold values. Kendall's algorithm was also used to determine the level of concordance among the participants. The results showed that most of the proposed criteria were significant for evaluating the feasibility of the policy measures. At the same time, the sustainability dimensions considered were all agreed to be relevant.

An interesting finding is from the ranking exercise for the dimensions where the political and governance dimension outranked the economic dimension. Sustainability is usually evaluated through the three classical dimensions of economy, environment and society, while other dimensions are often only considered as additional. The importance attributed to the policy and governance dimension could be due to the stakeholder engagement and political agenda criteria listed under the dimension, which some studies have established to be crucial to the success of UVAR adoption and implementation. While the importance of this finding can be undermined by the weak agreement amongst the participants, as indicated by Kendall's test of concordance statistic, the weak agreement raises another critical issue. The weakness of concordance in the sustainability dimensions reveals a fundamental flaw in broad transport sustainability

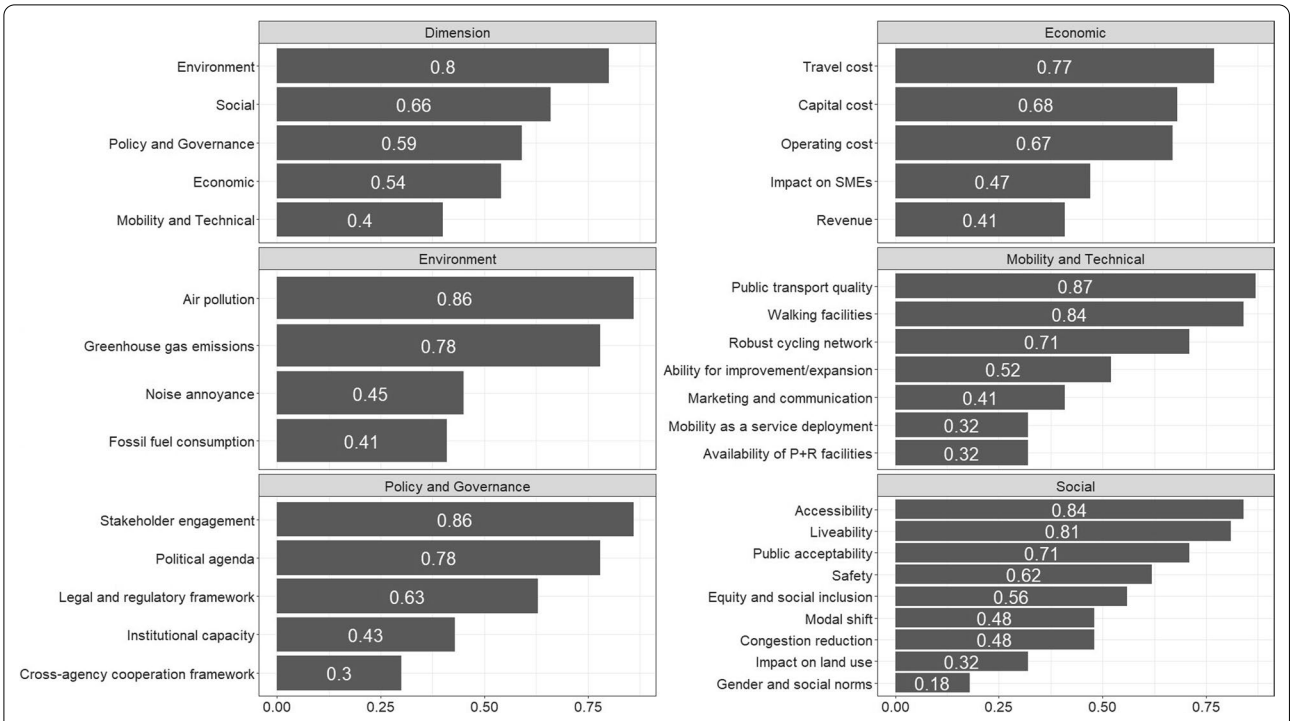

Fig. 2 Title: Weighted importance rankings of the dimensions and criteria assessment structure. *SMEs* small and medium-sized enterprises, *P* + *R* park and ride

Table 8 Results of Kendall's test of concordance

Ranked objects	Number of objects, n	Number of judges, m	Kendall's W	X^2	Interpretation
Dimensions	5	41	0.214	35.1	Weak agreement
Economic	5	41	0.230	37.8	Weak agreement
Environment	4	41	0.500	61.5	Moderate agreement
Social	9	41	0.512	168.0	Good agreement
Mobility and Technical	7	41	0.577	142.0	Good agreement
Policy and Governance	5	41	0.541	88.8	Good agreement

policies that emphasise and focus on a specific sustainability dimension over others. This direction should be trodden cautiously due to the overlaps between the different dimensions and interacting effects of targeted policy actions. Moreover, needs are constantly changing. For instance, fossil fuel consumption was not a big topic at the time of data collection of this study in 2021 but is now crucial in the wake of the energy crisis due to the Russia-Ukraine conflict.

Criteria rating

Based on the findings, the criteria can be categorised into three groups. The first group consists of all criteria meeting the threshold values (consensus and majority agreement). The second group consists of criteria with a median of at least four but without reaching the minimum agreement threshold value of 60%. The final group consists of criteria considered essential to have been included in the study but which most participants considered only to be of slight importance.

Important criteria with consensus

The first group consists of a majority of the criteria considered in this study (24 of 30). These criteria form the assessment structure's core and are deemed applicable to every urban context. They constitute the major drivers and barriers to implementing UVAR. Maximising or minimising these criteria is therefore critical to achieving the general objectives of adopting UVAR measures, i.e. decarbonising transport and stimulating sustainable

mobility behaviours in urban dwellers. Amongst these criteria include public acceptability, air pollution, accessibility, political agenda, and stakeholder engagement which have been hitherto acknowledged in previous studies and policy documents to be pivotal in determining the success of sustainable urban mobility policy instruments and measures [9, 43, 47–49].

Important criteria without consensus

The second group is the no agreement group. It includes mobility as a service deployment and cross-agency cooperation framework. The criteria were rated important by a bare majority of participants, which was not enough to be considered a consensus. For mobility as a service (MaaS), several pilots and deployments have signalled that it can drive a reduction in private car ownership and negative externalities [50, 51]. Nevertheless, this has not been fully established by large-scale deployments, and there is yet to be a guarantee that MaaS has the wholesome potential to contribute to sustainability on a commercial scale [50, 52]. This concern could suggest the reason behind participants' uncertainty in adjudging MaaS deployment as an essential criterion. Perchance it undoes the benefits derived from reducing private car ownership.

Similarly, cross-agency cooperation has been identified to have an important role to play in achieving sustainable urban development owing to the involvement of different agencies and organisations. A system of collaboration between these multiple agencies and organisations to harmonise their different objectives for the desired goal is of utmost importance. Despite this, challenges such as funds, resources and expertise allocation have persisted and have limited the practicality of such coordinating frameworks across different levels of governance [53]. Such limitations could have made the participants not consider the cross-agency cooperation framework a vital assessment factor. In addition, the success of arrangements like establishing interdepartmental working groups in SUMP development projects could have proved as worthy walkarounds having such frameworks. Notwithstanding, the two criteria in this group can be considered on a case basis by urban areas intending to utilise the assessment structure.

Other criteria

The final group of criteria includes revenue, impact on SMEs, gender and social norms and availability of P + R facilities. Although they have been identified to be of only slight importance, the criteria were included in the study as they can drive or limit the implementation of UVAR. In line with the results, they are issues that usually emerge and are used as pros and cons in the UVAR adoption discussion, except for the availability of P + R facilities. Revenue earmarking for transport development has been one of the strategies to overcome public aversion to UVAR, particularly pricing measures. However, being considered a criterion of slight importance indicates that using UVAR as a tool for revenue generation does not align with the principal UVAR objective of reducing private vehicle usage.

On the impact on SMEs, previous research findings have highlighted a neutral or positive effect of UVAR implementation on SMEs [54–56], and this awareness has probably provided grounds to convince the participants that UVAR implementation does not put SMEs at risk as often projected. For the third criteria, gender and social norms, it has been established that there is no simple link between body types and gender norms in decision-making on transport issues. However, transport has proven to be gender-sensitive, with differences in male and female mobility patterns [57]. Female trips are often undertaken using sustainable modes, provided they feel emotionally safe and secure [58]. In addition, due to their complex trip chaining, they are usually more cost-sensitive [59]. The participants might have considered this to imply that UVAR may not affect the gender sensitivity of urban mobility. However, the research findings have possible implications for UVAR implementation, which could be ascertained only with gender and social norms impact assessment. For example, while more public spaces and alternative mobility services improvement might be co-benefits of UVAR implementation, keeping them safe, secure and affordable is vital. In addition, maternity and healthcare needs might be essential considerations while planning exemptions for residents.

Lastly, the availability of P + R facilities, although recognised as vital in transport planning to decrease the inflow of private cars to urban downtown [60], is a tricky medium-term solution for sustainable urban development. This is because a non-strategic deployment of these facilities (location, usage cost, size) may further stimulate suburban sprawl. Hence, it could be antithetical to reducing private car dependency and transport decarbonisation.

Criteria ranking

Regarding ranking, the criteria/dimensions at the top and bottom of the rankings are quite similar to the criteria that are rated the most and least important/relevant in the rating exercise. This highlights the consistency of the participants in both exercises. Nevertheless, Kendall's concordance test only established an acceptable agreement for the environmental, social, mobility and technical, and policy and governance criteria. The weak agreement observed in the study for the rankings of the

dimensions and the economic criteria suggests difficulty in prioritising the elements in that category and further proves the complexity of decision-making processes. However, a further survey round was not conducted as this will be laborious for the participants, especially since consensus and moderate agreement has been reached on 80% and 67% of the criteria ratings and rankings, respectively.

Dimensions

Environmental and social needs were considered the most relevant sustainability dimensions in UVAR measure planning and decision-making. Although economic with mobility and technical dimensions were ranked least, these dimensions contain criteria which are quite important. They are essential due to competing needs for financial resources in urban areas and the need to provide suitable complementary mobility alternatives to effectively substitute private car usage in cities. This almost equal relevance of all the dimensions could have been responsible for the weak agreement, as indicated by Kendall's W value. It is, therefore, imperative for cities, while planning UVAR measures, even when the vision is tied to one of these dimensions, to undertake an integrated and balanced approach to deter the possibility of policy and measure failure owing to the strong interdependencies of the sustainability dimensions.

Economic criteria

Assessing the changes in travel costs to individual users and the availability of financial resources to cater for the capital and operating costs were the top criteria for the participants. Internalising external costs due to private usage through the polluter's pay principle is one of the principal theoretical backgrounds of UVAR [61]. However, decision-makers have a fine line to tread while attempting to undertake this, as enormous operating and capital costs might lead to budgetary constraints, which might stiffen the efficient discharge of the public authority's responsibilities elsewhere. At the same time, these costs cannot be directly transferred to private users because any measure leading to a sharp increase in the private cost of travel will most likely lead to public resistance. Therefore, it raises the need for careful optimisation of investment costs on planned UVAR measures within budget limits while ensuring an increase in the individual cost of private travel is met with a justified improved level of service of alternative modes to justify the rise in costs.

Environmental criteria

The top three criteria in this dimension, including air pollution, GHG emissions, and noise pollution, further reflect the need to reduce the negative transport externalities by achieving an ambient urban environment characterised by good air quality, reduced emissions, and low noise levels. An ideal UVAR measure will therefore be one that will minimise these criteria both locally and globally. An essential aspect for decision-makers is to exercise caution while introducing exemptions to vehicle access control. This is because such considerations and compromises (e.g. allowing access fees to be paid by polluting vehicles, subsidising private ownership of alternative fuelled vehicles), even while bearing good motives, may limit the effectiveness of the UVAR measures.

Social criteria

Most common UVAR measures are designed to improve the liveability of urban spaces without undermining their accessibility. The promise of these two largely influences the third top criterion in this dimension, acceptability. These three, ranked as the top criteria, re-emphasise the objective function and constraining limit that must be operationalised during UVAR measure design and planning.

Mobility and technical criteria

The criteria of utmost importance in this dimension are public transport quality, availability of walking facilities and robust cycling network and infrastructure. These three are the principal mobility modes required in the paradigm shift from car-centric urban areas to cities for people [62]. As presented in the results, without prejudice to other criteria in this dimension, ensuring these three criteria are maximised is vital to achieving sustainable urban transport without limiting people's mobility, as recommended by the European White Paper on Transport [63].

Policy and governance criteria

Stakeholder engagement, political agenda, and the presence of an enabling legal framework (legislation) for UVAR measure deployment were adjudged the most important policy and governance criteria. The importance of these three to successful UVAR adoption has been established by several studies [48, 64, 65]. Participatory planning through stakeholder engagement has the propensity to improve the legitimacy and social acceptability of UVAR measure designs. Exploring stakeholder engagement avenues will help change stakeholders' perception of UVAR to schemes for making the cities people focused rather than a war on private car usage. Therefore, the legitimacy benefited from this approach can reassure the political class that putting UVAR on the agenda and providing a legal framework will not necessarily become a political suicide as often foreseen by policymakers [38].

Study limitations

The Delphi process is subjective and depends on the researchers and participants to form the research path. On the one hand, the initial survey is developed based on a literature review, and the selection of the criteria included depends on the heuristic technique adopted by the researchers. On the other hand, only experts and professionals with strong opinions on the subject matter are often willing to participate in such a lengthy iterative process, mainly resulting in skewed data [66]. To limit these biases, the study allowed qualitative inputs from the participants in the first survey round with an assurance of anonymity to open the survey to diverse views. As a further quality control step, the qualitative inputs by participants were reviewed by an independent panel of experts. While a member check could have been used to achieve this, the approach usually implies running another survey round at the risk of participants' dropout. Notwithstanding, the possibility remains that not every criterion and opinion was captured in the study as true of every Delphi study.

Furthermore, regarding the study's geographical scope, it should be noted that it was not designed for decision support for a specific urban area even though most of the participants are resident in Europe, and their location may have conditioned their inputs. This initially informed the study's decision not to work directly with indicators as urban areas often adopt different indicators with different methodologies and methods for calculation. In addition, understanding the difference in urban mobility realities based on geographical contexts informed the decision not to exclude the non-consensus criteria from the assessment structure presented in the study. Hence, they are made available to support the UVAR measure planning decision-making process in areas where they may be considered necessary.

Conclusions

Urban vehicle access regulations are vital in promoting and achieving the transition to the sustainable urban mobility paradigm. Nevertheless, it is often missing in many cities' urban mobility transition approaches due to its complexities. Consequently, decision support tools are needed by urban transport planners and other actors to aid the adoption and implementation phases of UVAR. The study provides criteria for assessing the feasibility of effective urban vehicle access regulations adoption based on the opinion of experts drawn from the fields of transportation and urban planning using a Delphi approach.

Building on previous studies and the contributions of these experts, 30 criteria were identified and consolidated into an assessment structure within the study. These criteria were clustered into five categories: economic, environment, social, mobility and technical, and policy and governance—an indication that other dimensions are relevant in the drive towards sustainable urban mobility beyond the traditional three pillars of sustainability.

Overall, the assessment structure presented in this study has the potential to be of immediate value and hence a significant contribution to policy discussion, especially as it concerns UVAR measure planning and implementation. It provides a suitable complement to the planned ReVeAL UVAR toolkit, which will suggest multiple UVAR building blocks based on the urban area's peculiarities and objectives as provided by the user input. The assessment structure will therefore aid these cities in assessing these recommended measures in alignment with their sustainability goals.

Based on the expert consensus and agreement, 24 criteria were identified as important for the study's purpose. However, criteria like MaaS deployment, and cross-agency cooperation framework, which were considered important, did not reach a consensus. Other criteria like revenue generation, impact on SMEs, gender and social norms, and the availability of park and ride facilities were considered only slightly important and left to urban policymakers' discretion to include or exclude in the decision-making process. As the study identified the suitability of the criteria based on expert judgement without evaluating specific urban contexts, the assessment structure must be customised to local needs, if necessary, and operationalised with relevant SMART indicators. Furthermore, while the assessment structure was developed with the scope of providing decision support during the ideation and planning phase for UVAR measures, it will also be of value to urban transport stakeholders for the ex post monitoring and evaluation of the measures.

Although the proposed assessment structure can satisfactorily evaluate the feasibility of different UVAR measures, future research extensions are worth noting. Firstly, the results may be biased due to the dominance of resource persons from academia and the study's non-city-specific scope. Future research can be extended by undertaking the survey within the context of a particular urban area while ensuring a balanced representation of stakeholders, including citizens and business operators. This will allow for the differences in agreement on specific criteria to be thoroughly investigated to determine whether they are random or reflect the stakeholder group preferences. Secondly, the study used expert opinion and a linear aggregation method to arrive at weights for the criteria and dimensions. The possibility of participants ranking their concerns rather than the object's importance is a demerit of this approach. Also, this approach implies that weights

can only be determined within a category while global weights can only be inferred. Future research can use other MCDA weighting approaches, like the AHP or fuzzy set approaches, which can produce hierarchical structures consistent with the sustainability framework. These improvements and modifications will be researched in our future work to provide decision-makers and other stakeholders further insights on UVAR measure assessment.

Abbreviations

IQR: Interquartile range; *m*: The number of judges (participants) ranking the objects (dimensions/criteria),; MaaS: Mobility as a service; MCDA: Multi-criteria decision analysis; *n*: Total number of objects (dimensions/criteria) being ranked; NA: Not applicable; P + R: Park and ride; *S*: Sum of squared deviations of the individual ranks from the mean value of the total ranks; SMART: Specific, measurable, achievable, relevant and time-bound; SMEs: Small and medium-sized enterprises; UVAR: Urban vehicle access regulations; *W*: Kendall's test of concordance value; X^2: Chi-square value.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12302-022-00682-4.

Additional file 1: **Figure S1.** Summary of Participants' Data. **Table S1.** Ratings Result: Dimensions (Frequency). **Table S2.** Ratings Result: Criteria (Frequency). **Table S3.** Ratings Result: Dimensions (Frequency). **Table S4.** Ratings Result: Criteria (Frequency). **Table S5.** Ranking results: Dimensions. **Table S6.** Ranking results: Economic Criteria (Frequency). **Table S7.** Ranking results: Environment Criteria. **Table S8.** Ranking results: Social Criteria. **Table S9.** Ranking results: Mobility and Technical Criteria. **Table S10.** Ranking results: Policy and Governance Criteria.

Acknowledgements

The authors are grateful to the members of the CIVITAS ReVeAL project consortium, the EIT Urban Mobility community and all study participants for their valuable inputs to this study.

Author contributions

GAO analysed, interpreted and visualised the data for the study, and was responsible for the preparation of the original draft of the manuscript. FM coordinated and supervised the entire study and reviewed the original draft of the manuscript. All authors read and approved the final manuscript.

Funding

Open access funding provided by Budapest University of Technology and Economics.

Availability of data and materials

All data generated or analysed during this study are included in this published article and its Additional information file.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Received: 7 July 2022 Accepted: 2 October 2022
Published online: 15 October 2022

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