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Enhancing Sustainable Mobility: Multi-Criteria Analysis for Electric Vehicle Integration and Policy Implementation

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ABSTRACT

In contemporary times, regulations have been established to govern access and integration of electric vehicles, which hold immense potential in mitigating the adverse impacts of transportation arising from escalating mobility demands and rapid urbanization. Nevertheless, their implementation poses intricate challenges due to the multifaceted nature of sustainability and other complexities, as they are considered a prospective solution to address the pressing issue of climate change and achieve holistic sustainability. Moreover, this study elucidates the methodological approach employed for selecting a comprehensive set of criteria to be considered in energy planning initiatives involving the incorporation of electric vehicles, encompassing both renewable and conventional energy sources. The selection process was informed through a thorough review of existing literature and the insightful input from experts, utilizing the Likert scale and arithmetic mean as reference benchmarks. The outcomes of this research have yielded the identification of 27 sub-criteria, categorized into five distinct groups: technical, economic, social, environmental, and risk-related factors, thereby enabling a comprehensive evaluation of energy planning projects associated with the adoption of electric vehicles. The findings derived from employing the hierarchical analytical process with fuzzy logic FAHP highlight the considerable potential of most criteria and sub-criteria in devising effective measures. Notably, criteria related to policy-governance and environmental aspects emerged as the most influential, according to the collective expertise of the consulted group. This study significantly contributes to enhancing sustainable mobility and advancing progress towards attaining sustainable development goals. By delineating pertinent criteria and sub-criteria for the planning process, this research augments the literature dedicated to supporting informed decision-making in sustainable transportation, particularly through the potential application of a Multi-Criteria Decision Analysis (MCDA) method.

Keywords: MCDA, Car Dependency, Energy Planning, Rural Electrification, Energy Projects, Renewable Sources of Energy, Energy Policies
JEL Classifications: C44, C45, C46, C65

1. INTRODUCTION

It is not a secret that the urban population is presenting an upward trend day by day, each time it is the people who decide to make their lives and build their homes in urban areas, however, the rulers of these cities are making great efforts to accommodate this growing population, in such a way that they can have a good quality of life (Danese et al., 2022). Due to this situation and the trend as such, it has given rise to a new concept called sustainable development, however, this new concept requires the conscious and efficient use of each of the resources, thus managing to satisfy the needs of today without endangering those of the future generation (Borowska-Stefańska et al., 2021).

There is no doubt that the application of this concept of sustainable development to urban transport and mobility necessarily requires

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less consumption and dependence on automobiles (Bakker et al., 2019) and mobility in general driven by fossil fuels, in addition, said dependence on fossil fuels has been a source of negative controversies (Kowalska-Pyzalska, 2022), among which air pollution, noise, congestion, accidents, degradation stand out the most. Soil and greenhouse gas emissions (Ewert et al., 2020).

The high dependence even on fuels as a source for mobility increases and significantly impacts what is known as the risk of climate change, climate change is a threat, an existential reality for humans, flora and fauna alike (Kovačić et al., 2022). In response to this problem, concerted efforts have been made by different governments to mitigate these impacts at different geographical levels. These agreements and political commitments, in the long run, seek to comply with the objectives and goals defined for sustainable urban mobility (Wulf et al., 2023). One of these goals and commitments proposed as a common factor by the different governments is to greatly mitigate the use of private vehicles and stimulate more public transport and that this is not from a non-renewable source (Stark et al, 2018).

Most of the so-called first world countries have taken measures aimed at stimulating behavior change by mitigating dependence on private travel by car, for example, offering continuous improvement in the service and quality of public transport, so that their inhabitants have no excuses for not using it, in addition to providing active mobility facilities and introducing shared mobility. However, the consequences of these measures are often limited compared to measures that directly regulate vehicular access in urban areas. Although these measures differ in design and regulatory approach, commonly referred to as Urban Vehicle Access Regulations (UVARs) (Lin et al., 2017), these measures combine pricing, spatial interventions, and other restrictive schemes to limit vehicle access based on vehicle emissions, size, weight, type, and time of day characteristics (Nikitas et al., 2021).

Sustainable transport is defined as an option that facilitates access to goods (Wulf et al., 2023), resources and services while minimizing the need to travel in order to effectively and holistically address economic, environmental, and social requirements, among other impact criteria (Wulf et al., 2023). Most of the research related to sustainable transport has focused on the study of some particular criteria such as: economy, environment and social, other studies tend only to carry out research on sustainable transport in relation to environmental or economic criteria (Ramsebner et al., 2023). However, given this trend, in recent years more studies have emerged that add more evaluation criteria, these criteria vary according to the perspective of the authors or the scope of the study.

Example of this new research, (Diahovchenko et al., 2022) added a scientific and technological dimension to reflect its strong force in the growth of transport. (Kubik, 2022) emphasized the importance of an institutional dimension, postulating that it complements and allows interoperability between the three classical criteria. Some other criteria found in the literature include energy (Danese et al., 2022), operational with fiscal and governance dimensions (Kazemzadeh et al., 2023) and accessibility (Kubik, 2022). Regardless of these differences in the criteria implemented in the research, all studies point to sustainable transport planning, as they satisfy the conditions for a practical sustainability framework (Turoń, 2022b).

Since the criteria level is the basic decision unit of decision-making, it is essential to identify and select appropriate evaluation criteria to guide the process of planning and implementing measures for transport sustainability. Previous studies, including (Della Mura et al., 2022), have presented various sustainability assessment criteria and indicators within the transport sector, mainly for impact assessment and alternative assessment of projects. However, the uniqueness of UVAR measure planning with its various limitations such as equity concerns, social acceptability and effectiveness (Macioszek et al., 2023) makes it essential to identify suitable criteria for its evaluation.

The objective of this investigation is to achieve the identification of criteria to determine the viability of the acceptance and implementation of measures that contribute to sustainable transport. This research carried out a very practical methodology which allowed the validation of different objectives and recommended preconditions for urban transport professionals and planners with the criteria identified in the existing literature for the evaluation of transport sustainability. These sub-criteria were then classified into 5 sustainability criteria: economic, environmental, social, political -governance and mobility-technical. These criteria can be interpreted as follows:

1.1. Economic Criterion

The long-term economic growth of an urban area, including its residents and businesses, must be supported by urban transportation (Sousa and Costa, 2022). This criterion contains sub-criteria that indicate the cost-effectiveness factors of the use of UVAR maps and the potential costs incurred by users and companies in the study area.

1.2. Environmental Criteria

Transport must protect urban ecosystems and natural resources to ensure health and well-being now and in the future. The measurement includes criteria to assess the role of UVAR in the environmental impact of traffic activities (Turoń et al., 2022).

1.3. Social Criteria

Urban transport must contribute to social efficiency and improve the quality of life. The parameter defines the criteria to assess the potential impacts and vulnerability of society and the population related to the implementation of UVAR (Li and Liu, 2022).

1.4. Technical-mobility Criteria

This aspect includes all the criteria to ensure the effective operation of UVAR without negatively affecting urban mobility and other aspects of sustainability (Fabri et al., 2022). Therefore, assess the situation with additional means of transportation and other institutional requirements.

1.5. Political and Governance Criterion

This criterion seeks to define the policies associated with sustainable transport and the use of renewable energy sources, defines the guidelines and commitments acquired and executed by the government in power (Mangipinto et al., 2022).

On the other hand, this research seeks to contribute and simplify decision-making processes, becoming a powerful tool for future research where it is desired to find the best solution or option against a group of alternatives regarding sustainable mobility, especially the implementation of electric vehicles. Inherently in this investigation, the following questions were addressed, which said answers were used to capture the objectives addressed, the concerns were:

What are the most appropriate criteria to assess the readiness or feasibility of implementing electric vehicles in cities?

Which sustainability criteria and which ones are relevant to the evaluation structure? What is the relative importance of the criteria and/or sub-criteria that are identified?

Which sub-criterion has more or less absolute and relative importance in each criterion?

These questions were answered through a statistical study approach that involved experts in the field of transport and urban planning to validate and consolidate the identified criteria for sustainable sustainability planning, coming from the existing literature. Finally, this research pays a double tribute to sustainable transport planning by addressing the research questions outlined above, firstly, it provides an evaluation framework to assess the feasibility of different UVAR measures, allowing cities to identify aspects where changes are required or to select an optimal measure in this case for the implementation of electric vehicles. Second, it presents equally important criteria and sub-criteria that are often not taken into account in the planning of transport policy measures (Christian Manuel Moreno Rocha et al., 2023).

2. MATERIALS AND METHODS

This section presents the fundamental concepts that guided this study. The intent is not to cover all topics, but to provide essential supporting information for understanding the research, context, and results.

2.1. Proposed Procedure

Regarding the identification and choice of the best criteria and sub-criteria, the first step consisted of a documentary analysis of the situation and current scenarios of the content of electric cars in Colombia and all the criteria that it manages to impact; with this, in addition, the generation and conducive to the collection of data and information relevant to the investigation with the intention of achieving the established objectives (Ramsebner et al., 2021). For this section, a qualitative research method was implemented to identify a series of specific criteria and sub-criteria to evaluate the viability of the measures for their implementation in cities and the massive introduction of electric cars (Ogunkunbi and Meszaros, 2022). The criteria and subcriteria were obtained from the study and analysis of a sustainable urban mobility planning framework and from the consultation of different research databases associated with this topic, keeping in mind that any measure taken on the issue of the implementation of electric vehicles is a political instrument that seeks to achieve strategies and vision to favor the mitigation of the impact of climate change and mobility in the long term (Kazemzadeh et al., 2023).

Another important step was to carry out the study of the current situation of the European Commission for Urban Vehicle Access Regulations, the objectives of the regime, in this commission there is a set of criteria, these were compared with the criteria and indicators of sustainable urban mobility already existing in the literature, especially from the reviews carried out by (Darshit, 2023). It was possible to review and analyze different relevant criteria, in such a way that they are specific, measurable, achievable, pertinent and with specific deadlines, in such a way that they can be used in some future research for decision-making by some metaheuristic method, which are generally adopted in the planning phase of sustainable urban mobility planning measures. For this particular investigation, forty-four items were identified (Goel et al., 2023). Of great importance for the analysis of feasibility and relevance, these were grouped into criteria using the foundations of sustainability, that is, economic, environmental and social, with a fourth and fifth criteria called technical and political and governance.

Being consistent with an Inductive type methodology, the genesis of this research is, starting from a general premise that electric cars are, to draw conclusions from a particular case or problem situation (Wang et al., 2022). Placing emphasis on theory, explanation, theoretical models, abstraction together with data collection, observation and experimentation. All data generated and/or analyzed during this study is included in this published article and its additional information file (Mouratidis, 2022).

Forty-four criteria/subcriteria were initially identified, criteria systematically selected from the scientific literature, of relative importance for the analysis of feasibility and relevance of the measures. The criteria and dimensions identified are presented in Table 1.

A questionnaire was prepared that was sent to 250 experts and answered by 214 experts distributed among university professors, businessmen and postgraduate students associated with the research topic, in order to identify the criteria to be taken into account in projects for the introduction of electric vehicles in the national market, sustainable mobility and sustainable transport. The questionnaire consisted of 46 questions and the following categories were defined according to the Likert scale with a scale from 1 to 5 as follows: (5) Totally agree, (4) Agree, (3) Neither agree nor disagree, (2) Disagree and (1) Totally disagree. The Likert scale allows establishing the level of agreement or disagreement of an expert with respect to a statement. The questionnaire was prepared using a Google form and was sent via email to each of the experts previously consulted and approved to participate in this research. For each criterion, the mean and standard deviation were calculated from the responses of the experts in relation to the criteria. Additionally, a scale was designed and 5 attributes related to the level of significance were established, as can be

Table 1: Proposal of criteria and subcriteria to be evaluated

Sub-criteria	Bibliographic reference
Technology maturity	(Gschwendtner et al., 2023)
initial investment	(Turoń, 2022a)
Armed conflict	(Christian M.Moreno Rocha et al., 2022)
equipment failure	
Impact on the ecosystem	(Moreno Rocha et al., 2022)
Energy efficiency	
Energy for schools and health centers	(Alemam and Al-Widyan, 2022)
equipment obsolescence	(Zhu et al., 2022)
Impact on the environment	(Martínez-Ruiz et al., 2022)
unforeseen costs	(de Mendonça and Haddad, 2022)
technology access	(Maity et al., 2022)
natural phenomena	(Zhang et al., 2022)
Energetic politics	(Moreno Rocha et al., 2022)
Availability of spare parts and maintenance	(Ancaya-Martínez et al., 2022)
Easy access	(Gielen et al., 2019)
Reliability	(He et al., 2022)
Operation and maintenance costs	(Diaz et al., 2022)
Generation of local jobs	(Baloch et al., 2022)
Gas emission	(Thomasi et al., 2022)
waste production	(Yang et al., 2022)
Physical infrastructure	(Wu et al., 2022)
Investment incentives	(Raza et al., 2022)
community acceptance	(Hafsi et al., 2022)
Useful life	(Pohl et al., 2022)
Local resources (water and soil)	(Yamaka et al., 2022)
resource potential	(Lennartz et al., 2022)
cost of capital	(Ahmed et al., 2022)
operating cost	(Cervera et al., 2016)
Impact on SMEs	(Şengül et al., 2015)
Fossil fuel consumption	
Atmospheric pollution	(Sousa and Costa, 2022)
Emissions of greenhouse gases	(Botero et al., 2021)
Impact on biodiversity	(Manuel et al., 2022)
congestion reduction	(Fabri et al., 2022)
Security	(Oner and Khalilpour, 2022)
Public transport quality	
Institutional capacity	(Borowska-Stefańska et al., 2021)
Robust cycling network	
Implementation of mobility as a service	(Yadegaridehkordi and Nilashi, 2022)
Criteria	
Economic	(Rocha et al., 2022)
Environment	(Manuel et al., 2022)
Social	(Hernández et al., 2021)
Mobility and Technical	(Turoń, 2022a)
Politics and governance	(Sileryte et al., 2022)

seen in Table 2. The attributes indicate the relevance of including or not including the criteria in the energy planning process. The scale for the evaluation of each one of the criteria was elaborated from equation (1):

$$R=(Ls-Li)/n \quad (1)$$

The standard deviation, or typical deviation, is a measure that provides information about the dispersion of the mean value of a variable. The standard deviation is always greater than or equal to zero (Wang et al., 2022).

Table 2: Scale proposal to implement

Categories	Range of values	attributes
Totally agree	$4.2 \leq R \leq 5.0$	very high significance
OK	$3.4 \leq R < 4.2$	high significance
Neither agree nor disagree	$2.6 \leq R < 3.4$	moderate significance
In disagreement	$1.8 \leq R < 2.6$	little significance
strongly disagree	$1 \leq R < 1.8$	very little significance

$$\sigma = \frac{\sum_i^N |Xi - X|}{N} \quad (2)$$

$$\sigma = \frac{\sum_i^N (Xi - X)^2}{N} \quad (3)$$

The mean of a data set is determined by adding all the numbers in the data set and dividing by the number of values in the set. The median is the average value of a data set, ordered from smallest to largest (Goel et al., 2023).

$$X = \frac{x1 + x2 + x3 + x4 + \ldots + xn}{N} \quad (4)$$

2.1.1. Reliability

Reliability was determined using the Cronbach's Alpha instrument, which is one of the mathematical tools most widely used by researchers to estimate the reliability of questionnaires, in cases where a set of items are used that seek to measure the same attribute or field of content, as is the case in the present investigation. It stands out as the main advantage that only the application of a test and its ease of computation are required.

Cronbach's alpha is a coefficient used to understand the reliability of a scale or test (Remme et al., 2022). A widely used resource in psychometrics. Psychometrics is a discipline that measures and quantifies human psychological variables using a variety of techniques, methods, and theories.

$$\alpha = \frac{K}{K-1}\left(\frac{\sum_{i=1}^{K} \sigma^2 Yi)}{\sigma^2 X}\right. \quad (5)$$

2.2. Implementation of Fuzzy Hierarchical Analyte Process

The AHP is a decision-making method, proposed by Saaty in 1980, used to solve selection problems with multiple criteria. The main characteristic of this method is that a hierarchical structure is proposed, in which the problem to be solved is located at the top and the solution alternatives are at the bottom (Moreno Rocha et al., 2022). In the intermediate stages, the hierarchical criteria that are the basis for decision-making are established. To implement the AHP it is necessary to construct a set of pairwise comparison matrices in which each element at a higher level is used to compare the elements at the level immediately below.

These comparisons are made through preference relationships (for the alternatives) and importance relationships (for the criteria), which are evaluated through a numerical scale with integer values between 1 and 9. The advantages of the AHP method can be summarized as follows: It includes mathematical support It allows breaking down complex problems to analyze them by parts using paired comparisons It allows the use of quantitative and qualitative criteria It includes the participation of experts with different interests to reach a consensus.

However, the method also has some disadvantages reported by the researchers, among which the existence of a fixed measurement scale stands out, which can affect the judgment given by the respondent. In this context, the FAHP method arises, which is a variant of the AHP originally proposed by Saaty. In the FAHP method, the traditional numerical scale is replaced by a fuzzy triangular scale, which improves imprecision in the judgments made by experts in the decision-making process. With the application of fuzzy logic, the imprecision and subjectivity of human judgments is improved, since this technique can represent imprecise data, for this investigation a total of 10 experts were used, where they were consulted on the degree of importance of each of the criteria and sub-criteria. With the FAHP, a range of values is implemented that allows incorporating the uncertainty of the decision maker, using fuzzy triangular numbers according to the scale shown in Table 3 (Noorollahi et al., 2022).

The stages to implement the FAHP dog baby summarized ace follows (Imamverdiev, 2022):

2.2.1. Fuzzy assembly operations

- The complementary set of a fuzzy set A is one whose characteristic function is defined by (Díaz et al., 2022):

$$m_A = (x) - m_A(x) \tag{6}$$

- The union of two fuzzy sets A and B is a fuzzy set A ∪ B in U whose membership function is:

$$m_{A\,U\,B}(x) = máx\;\; m_A(x), m_B(x) \tag{7}$$

- The intersection of two fuzzy sets TO and B is a fuzzy set A ° B in U

With characteristic function:

$$m_{A \cap B}(x) = mín\;\; m_A(x), m_B(x) \tag{8}$$

The main operators that meet the conditions to be t-conorms are the maximum operator and the algebraic sum

$$m_{A\,U\,B}(x) = m_A(x) + m_B(x) - m_A(x)m_B(x) \tag{9}$$

and the main operators that meet the conditions to be t-standards are the minimum operator and the algebraic product

$$m_{A \cap B}(x) = m_A(x)m_B(x) \tag{9}$$

2.2.2. Fuzzy relationships

$$R\,(U,V) = ((x,y), m_R(x,y)) \| (x,y) \grave{o} U\,x\,V \tag{10}$$

assume

R (*x*,*y*) and *S*(*x*,*y*)

They are relations in the same product space $U\,x\,V$ The intersection or union between R and S, which are compositions between the two relations, are defined as (Yang et al., 2022):

$$m_{R \cap S}(x,y) = m_R(x,y) * m_S(x) \tag{11}$$

$$m_{R\,U\,S}(x) = m_R(x,y) * m_S(x,y) \tag{12}$$

If R ° S, R and S belong to discrete universes of discourse. It is defined as a fuzzy relation in U x W whose membership function is given by:

$$m_{R \circ S}\left(x,z\right) = \sup_{y \varepsilon V}[\mu_R(x,y) * \mu_s(y,z)] \tag{13}$$

where the SUP operator is the maximum and the * operator can be any T-norm. Depending on the t-norm chosen we can obtain different compositions; The two most used compositions are max-min composition and max-product composition:

- The max-min composition of the fuzzy relationships R (U,V) and S (V,W), is a fuzzy relation R ∘ S in UxW defined by the membership function

$$\mu_{R \circ S}\left(x,z\right) = máx_{y \varepsilon V}\; \min[\mu_R(x,y) * \mu_s(y,z)] \tag{14}$$

where $\left(x,z\right) \varepsilon\, UxW$

- The max-product composition of the fuzzy relations R(U,V) and S(V,W), is a fuzzy relation to R ∘ S

in UxW defined by characteristic function

$$\mu_{R \circ S}\left(x,z\right) = máx_{y \varepsilon V}[\mu_R(x,y) * \mu_s(y,z)] \tag{16}$$

where $\left(x,z\right) \varepsilon\, UxW$

2.2.3. Fuzzy implication

As we have already seen, in terms of fuzzy logic theory the proposition "If u is A, then v is B" where u ε you and v ε V, has an associated characteristic function that takes values in the interval. Examples of possible associated characteristic functions, extracted from applying the analogies between operators and the aforementioned tautology, are:

$m_{A \to B} = (x,y)$ (Maity et al., 2022):

$$m_{A \to B}(x,y) = 1 - \mu_{A \cap B}(x,y) = 1 - \min[\mu_A(x), 1 - \mu_B(y)] \tag{17}$$

$$m_{A \to B}(x,y) = max[1 - \mu_A(x), \mu_B(y)] \tag{18}$$

$$m_{A \to B}(x,y) = 1 - \mu_A(x)(1 - \mu_B(y)) \tag{19}$$

In fuzzy logic the Modus Ponens extends to what is called Generalized Modus Ponens and can be summarized as follows:

Premise 1: "u is A*"

Premise 2: "If u is A THEN v is B"

Consequence: "v is B*"

Where the fuzzy set A* need not necessarily be the same as the fuzzy set A of the rule antecedent and the fuzzy set B* need not necessarily be the same as the fuzzy set B that appears in the consequent of the rule.

Thus, the generalized Modus Ponens is a diffuse composition in which the first fuzzy relation is the fuzzy set A* and which can be expressed:

$$\mu_{B*}(y) = sup_{x\grave{o}A*1}[\mu_{A*}(x)*\ \mu_{A\to B}(x,y)\ ] \quad (20)$$

Taking into account that, in the applications of fuzzy logic to engineering, the characteristic function of the implication is built with the minimum and product operators, which in addition to being the simplest preserve the cause-effect relationship, we will have two options to choose from:

$$\mu_{A\to B}(x,y) = min[\mu_A(x), \mu_B(y)] \quad (21)$$

$$\mu_{A\to B}(x,y) = \mu_A(x).\mu_B(y) \quad (22)$$

2.2.4. Methods of syndication

- Maximum method: the output variable is chosen for which the characteristic function of the fuzzy output set is maximum. In general it is not an optimal method, since this maximum value can be reached by several outputs.
- Centroid method: Uses the center of gravity of the output characteristic function as the system output. Mathematically (Kabir et al., 2022):

$$y = (\int y\mu_A(y)dy)/(\int y\mu_B(y)dy) \quad (23)$$

It is the most widely used method in applications from fuzzy logic to engineering since a unique solution is obtained, although it is sometimes difficult to calculate.

- Height method: the center of gravity of the diffuse output set Bm is calculated for each ruler and then the system output is calculated as the weighted average:

$$y_h = (\int \bar{y}_m \mu_{B_m}(\bar{y}_m)dy)/(\int \mu_{B_m}(\bar{y}_m)dy) \quad (24)$$

2.2.5. Analysis with fuzzy logic

If it is a set of objects and a set of objectives, according to the extended analysis method of Chang (1996), the extended analysis is developed for each of the values of the objects; in this way they can be obtained for each objective X = $\{x_1, x_2, x_3, x_n\}$ $U = \{u_1, u_2, u_3, u_n\}$ (Manuel et al., 2022). Therefore, extended analysis values of m can be obtained with the following notation (He et al., 2022):

$$M_{gi}^1, M_{gi}^2, ..., M_{gi}^m = 1,2,3, ...n. \quad (25)$$

Where everything is triangular fuzzy numbers $M_{gi}^1(j = 1,2,3, ...m)$

Key steps of the model proposed by Chang (1996) (Moreno Rocha et al., 2022):

Step 1: The value of the object – th of the extended analysis is defined as: i

$$S_i = \sum_{j=1}^m M_{gi}^j \otimes \left[\sum_{i=1}^n \sum_{j=1}^m M_{gi}^j\right]^{-1} \quad (26)$$

To obtain, the operation of fuzzy addition of m values of the extended analysis is performed for a particular matrix, such that:

$$\sum_{j=1}^m M_g^j \quad (27)$$

$$\sum_{j=1}^m M_{gi}^j = \left(\sum_{j=1}^m l_j \sum_{j=1}^m m_j \sum_{j=1}^m u_j\right) \quad (28)$$

To get, perform the operation of blurred addition of values, so that:

$$\left[\sum_{i=1}^n \sum_{j=1}^m M_{gi}^j\right]^{-1} M_{gi}^1(j = 1,2,3, ...m) \quad (29)$$

$$\sum_{i=1}^n \sum_{j=1}^m M_{gi}^j = \left(\sum_{i=1}^n l_i \sum_{i=1}^m m_i \sum_{i=1}^m u_i\right) \quad (30)$$

Then the inverse vector of the equation is calculated, as follows:

$$\left[\sum_{i=1}^n \sum_{j=1}^m M_{gi}^j\right]^{-1} = \left(\frac{1}{\sum_{i=1}^n u_i}, \frac{1}{\sum_{i=1}^n m_i}, \frac{1}{\sum_{i=1}^n l_i}\right) \quad (31)$$

Step 2: The degree of chances of it is defined as: $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$

$$V\ (M_2 \geq M_1) = sup_{y\geq x}[min(\mu_{M1}(x), \mu_{M2}(y))] \quad (32)$$

And it can be expressed equivalently as follows:

$$V\ (M_2 \geq M_1) = hgt(M_1 \cap M_2) = \mu_{M2}(d) = f\ (d)$$

Forks $m_2 \geq m_1$

$$\text{Forks } l_1 \geq u_2 = \begin{cases} 1, \\ 0, \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} \end{cases} \quad (33)$$

Where d is the ordinate of the highest intersection point D between and μ_{M1} To compare and the values of y are required μ_{M2} M_1 M_2

$$V\ (M_2 \geq M_1)\ V\ (M_1 \geq M_2) \quad (34)$$

Step 3: The degree of possibility that a diffuse convex number is greater than k

Convex numbers are defined as:

$$\begin{aligned} &V\ (M \geq M_1, M_2, ..., M_k) = V[(M \geq M_1) \\ &y\ (M \geq M_2)\, y\ (M \geq M_k)] \\ &= min V(M \geq M_i), i = 1,23, ..., k \end{aligned} \quad (35)$$

So, assuming that:

$$d'(A_i) min V\ (S_i \geq S_k) \tag{36}$$

$$k = 1,2,3,\ ...,n; k \neq i W' = (d'(A_1), d'(A_2),\ ..., d'(A_n))^T$$

For. The weight of the vector is given by: $k = 1,2,3,\ ...,n; k \neq i W' = (d'(A_1), d'(A_2),\ ..., d'(A_n))^T$

$A_i\ (i = 1,2,3.,n)$

where are n elements $A_i\ (i = 1,2,3.,n)$

Step 4: The normalization of the vector presented as follows:

$$W = (d\ (A_1), d\ (A_2),\ ..., d\ (A_n))^T \tag{37}$$

Where W is not a fuzzy number but the set of weights for each matrix.

For this case it should be borne in mind that W are now not fuzzy numbers, but vectors with the final weights. Table 4 represents the values used in the conversion of the linguistic syntax used by the experts and their respective valuation into fuzzy triangular and triangular numbers. Finally.

3. RESULTS

This section will show the results obtained in this investigation, it shows the results obtained in a proposal for the implementation of a model for the selection of a group of criteria and subcriteria, as well as the implementation of a MCDM model for the hierarchization of these.

3.1. Results of the Procedure in the Identification and Selection of the Criteria and Subcriteria

Regarding the procedure for the identification and selection of the most important criteria and sub-criteria when it comes to the implementation of electric vehicles, the results showed that most of the proposed criteria were significant for evaluating the feasibility of policy measures regarding the implementation of electric vehicles in the Colombian market and in accordance with the international commitment to improve sustainable mobility and the use of sustainable transport. While agreeing that all dimensions of sustainability considered were relevant, the study provides criteria to assess the feasibility of effective adoption of urban vehicle access regulations based on expert opinion drawn from the fields of transport and urban planning using a research approach and mathematical tools. In general, the evaluation structure presented in this study has the potential to be of immediate value and, therefore, a significant contribution to the policy discussion related to everything related to sustainable mobility and the use of sustainable transport, especially with regard to the planning and implementation of measures for the implementation of this type of electric mobility technology.

Table 2 shows the results obtained for the mean, standard deviation and level of significance that was obtained for each one of the subcriteria after each one of the results of the instrument applied to the group of experts had been analyzed. It can be seen that the highest average value was obtained for energy for schools and health centers with an average of 4.02 and the lowest value was for the armed conflict with an average of 2.63. In the same way, it is observed that the standard deviation that the criteria present with respect to the mean ranges between 1.03 and 1.17; which does not reflect the high level of dispersion of the evaluation carried out and issued by the experts.

After carrying out an analysis of each one of the results obtained, and being consistent with what is embodied in the methodology, we proceeded to establish and define 5 criteria for a better understanding of this research, which are: mobility and technical,

Table 3: AHP and FAHP scales (Bhattacharyya, 2012)

AHP scale	Importance scale	FAHP scale	FAHP reciprocal scale
1	equally important	(1,1,1)	(1,1,1)
2	Intermediate 1	(1,2,3)	(1/3,1/2,1)
3	Moderately more important	(2,3,4)	(1/4,1/3,1/2)
4	Intermediate 2	(3,4,5)	(1/5,1/4,1/3)
5	Strongly more important	(4,5,6)	(1/6,1/5,1/4)
6	Intermediate 3	(5,6,7)	(1/7,1/6,1/5)
7	Look and strongly more important	(6,7,8)	(1/8,1/7,1/6)
8	Intermediate 4	(7,8,9)	(1/9,1/8,1/7)
9	absolutely more important	(9,9,9)	(1/9,1/9,1/9)

Table 4: Results obtained for the subcriteria

Sub-criteria	Half	Standard deviation	Meaning according to the scale
Technology maturity	3.76	1.29	High
Initial investment	3.69	1.21	High
Armed conflict	2.63	1.17	Moderate
Impact on the ecosystem	3.80	0.96	High
Energy efficiency	3.91	0.92	High
Energy for schools and health centers	4.02	1.03	High
Natural phenomena	3.45	1.03	High
Energetic politics	3.83	0.88	High
Availability of spare parts and maintenance	3.63	1.03	High
Easy access	3.58	1.17	High
Reliability	3.90	0.94	High
Operation and maintenance costs	3.75	0.92	High
Generation of local jobs	3.86	0.83	High
Physical infrastructure	3.65	1.21	High
Investment incentives	3.63	1.35	High
Community acceptance	3.57	1.16	High
Local resources (water and soil)	3.65	0.97	High
Resource potential	3.95	0.91	High
Cost of capital	3.66	0.95	High
Operating cost	3.70	0.91	High
Fossil fuel consumption	3.33	1.16	Moderate
Atmospheric pollution	3.35	1.20	Moderate
Emissions of greenhouse gases	3.29	1.08	Moderate
Impact on biodiversity	3.43	1.00	High
Public transport quality	3.59	0.90	High
Institutional capacity	3.79	0.91	High
Robust cycling network	3.54	0.95	High

economic, social, environmental, political and *governance*. For the mobility and technical criteria, the following sub-criteria were grouped: quality of public transport (C1.1), robust cycling network (C1.2), technology maturity (C1.3), energy efficiency (C1.4), availability of spare parts and maintenance (C1.5), reliability (C1.6) and physical infrastructure (C1.7). However, it is important to understand that, in order to select the mobility and technical subcriteria, an analysis was carried out in accordance with what is presented in graph 1, where the subcriteria whose individual mean exceeded the group mean were selected. In addition, the selected subcriteria meet a High significance level. Therefore, 3 technical sub-criteria were selected: C1.3, C1.4 and C1.6. With this analysis, the mobility and technical criteria were established, with an average of 3.71, which is equivalent to a High level of significance, see Figure 1.

Economic, the same exercise was carried out as with the mobility and technical criteria, the following sub-criteria were grouped: Operation and maintenance costs (C2.1), resource potential (C2.2), initial investment (C2.3), investment incentives (C2.4), capital cost (C2.5) and operating cost (C2.6).

According to the information presented in graph 2, subcriteria C2.1 and C2.2 were selected, which exceeded the group mean and have a High level of significance. In this way, the economic sub-criteria were defined with an average of 3.73 and a high level of significance. For the social criteria, the following sub-criteria were grouped: acceptance by the community (C3.1), generation of local jobs (C3.2), energy for schools and health centers (C3.3) and security (C3.4). Considering graph 3, subcriteria C3.2 and C3.3 were selected, which had a High level of significance and exceeded the group mean. With this procedure, the social subcriteria were defined with a mean of 3.77 and a High level of significance, see Figures 2 and 3.

In the case of environmental criteria, these were grouped as follows: impact on the ecosystem (C4.1), consumption of fossil fuels (C4.2), air pollution (C4.3), greenhouse gas emissions (C4.4), natural phenomena (C4.5) and local resources (water and soil) (C4.6). From graph 4, subcriteria C4.1 and C4.6 were selected, which exceed the group mean and also have High significance levels. For this research, it was important to note that the environmental criteria had an average of 3.48 with a High level of significance, this reflects the importance that the environmental criteria has taken on compared to the other criteria when preparing and planning a project or research proposal, see Figure 4.

Finally, the policy and governance criteria were grouped into the following sub-criteria: institutional capacity (C5.1), armed conflict (C5.2), energy policy (C5.3) and easy access (C5.4). According to the results shown in graph 5, subcriteria C5.1, C5.3 and C5.4 were selected, which exceeded the group mean and have a high level of significance. With this analysis, the risk criteria had a moderate level of significance with a mean of 3.46, see Figure 5.

According to the analysis carried out from the results obtained with the evaluation of the experts, Table 5 summarizes the sub-criteria selected for energy planning projects at the time of the massive introduction of electric vehicles in Colombia using renewable and conventional energy sources. In total, 27 sub-criteria were selected, which were ordered from highest to lowest according to the mean they obtained within the category.

3.2. FAHP Results

After identifying the most outstanding sub-criteria for the massive implementation of electric vehicles in a society, the Hierarchical

Figure 1: Selection of mobility and technical subcriteria

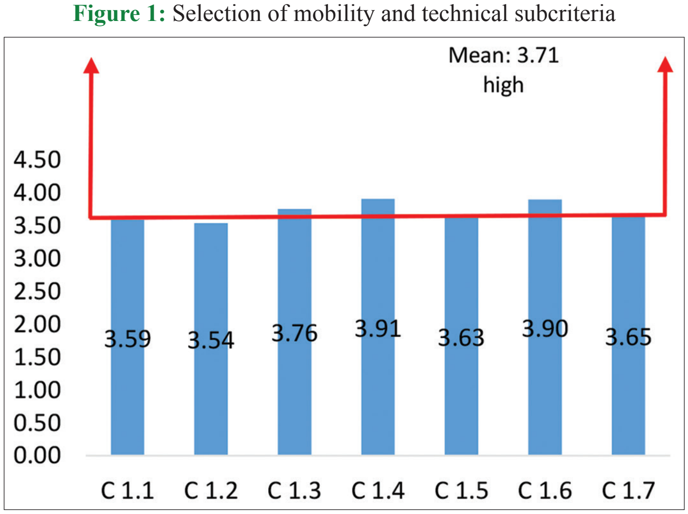


Figure 2: Selection of Economic Subcriteria

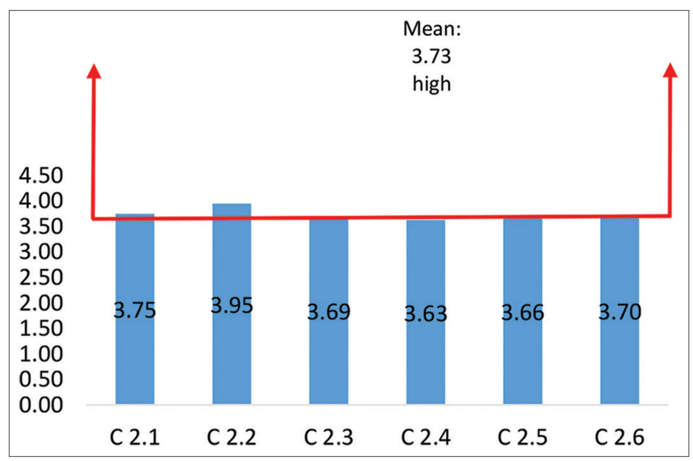


Figure 3: Selection of Environmental Subcriteria

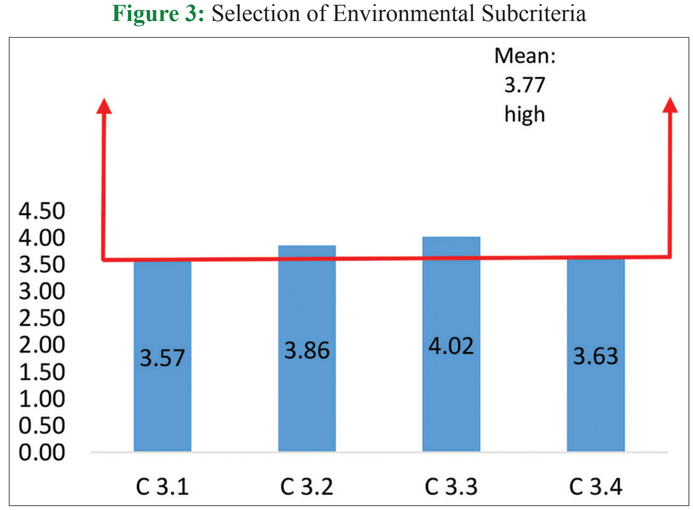


Table 5: Selected subcriteria

Selected criteria				
Mobility and Technicians	**economic**	**Social**	**environmental**	**Politics and governance**
1. Energy efficiency (3.91)	1. Resource Potential (3.95)	1. Energy for schools and health centers (4.02)	1. Impact on the ecosystem (3.80)	1. Energy policy (3.83)
2. Reliability (3.90)	2. Operation and maintenance costs (3.75)	2. Generation of local jobs (3.86)	2. Local resources (water and soil) (3.65)	2. Institutional capacity (3.79)
3. Technology maturity (3.76)	3. Operating cost (3.70)	3. Security (3.63)	3. Natural phenomena (3.45)	3. Armed conflict (3.63)
4. Physical infrastructure (3.65)	4. Initial investment (3.69)		4. Air pollution (3.35)	
5. Availability of spare parts and maintenance (3.63)	5. Capital cost (3.66)	4. Community Acceptance (3.57)	5. Fossil fuel consumption (3.33)	4. Easy access (3.58)
6. Quality of public transport (3.59)	6. Investment incentives (3.63)		6. Greenhouse gas emissions (3.29)	
7. Robust cycling network (3.54)				

Figure 4: Selection of Social Subcriteria

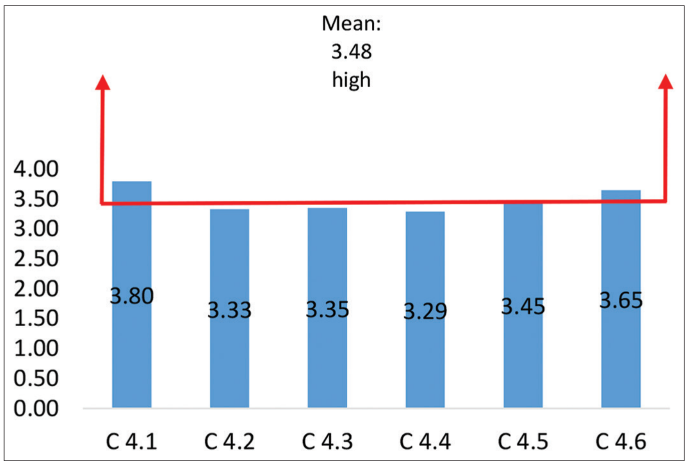
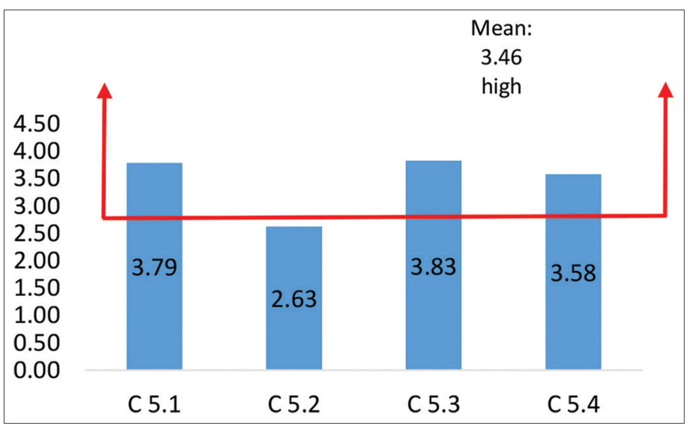


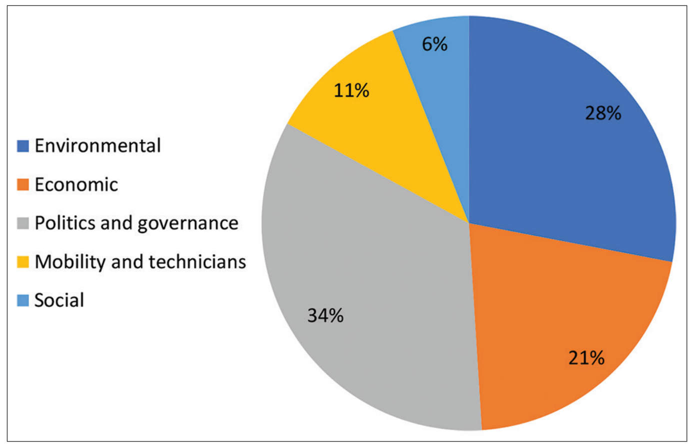
Figure 5: Selection of Politics and Governance Subcriteria



Analytical Process method with fuzzy logic was used, taking into account the responses of the 10 experts consulted. The objective was to weigh and rank each of the previously identified criteria and sub-criteria.

Table 6 and Figure 6 present the results of the ranking and weighting of the general criteria, especially highlighting the environmental and policy and governance criteria due to their greater weighting. This clearly reflects the concern of the expert group for the environmental aspect and all the sub-criteria associated with it, possibly with the purpose of meeting the sustainable development

Figure 6: Hierarchy of criteria according to FAHP



goals. In addition, it is evident that government policies and actions will be decisive for the success of the implementation of electric vehicles in society. On the other hand, Figure 7 shows the results of the hierarchization of the sub-criteria corresponding to the mobility and technical criteria. In this case, the experts highlight the maturity of the technology, the reliability and the availability of spare parts and maintenance as the most important sub-criteria. These results indicate that, when implementing electric vehicles, it is essential to evaluate the degree of development reached by the technology to be used, as well as its reliability both for users and for society in general. Furthermore, the availability and quality of spare parts and maintenance services play a crucial role in the adoption process of these vehicles. The results obtained through the Fuzzy Logic Hierarchical Analytical Process method provide a valuable guide for decision-making in the implementation of electric vehicles, highlighting the relevance of the environmental aspect and the crucial role of government policies, as well as the importance of technological maturity and the availability of support services in the successful adoption of this technology.

Figures 8 and 9 show the results obtained for the weighting and ranking of the economic and social sub-criteria respectively, the results obtained in the ranking of the economic sub-criteria may not be indifferent to those obtained in other investigations regarding the implementation of an energy project, the sub-criteria of operating costs and initial investment are the most important according to the group of experts consulted, this shows that it does

Table 6: Relative weights general criteria FAHP

Var1/var2	Fuzified matrix			Diffuse weights			Average	Normalized WI		
environmental	1 5/7	2	2 1/5	1/3	1/3	1/3	1/3	28%	Lambda	5.02
economic	1	1	1 1/6	1/5	1/5	1/5	1/5	twenty-one%	IC	0.006
Politics and governance	6/7	1	1 1/9	1/6	1/6	1/6	1/6	34%	CR	0.005
Mobility and technicians	1/2	3/5	23	1/9	1/9	1/9	1/9	eleven%		
Social	8/9	1	1 1/5	1/6	1/5	1/5	1/5	6%		
ADDITION	5	5 5/8	6 1/3				1	100.00%		
INVERSE SUM	1/5	1/6	1/6							

Figure 7: Classification of mobility and technical subcriteria

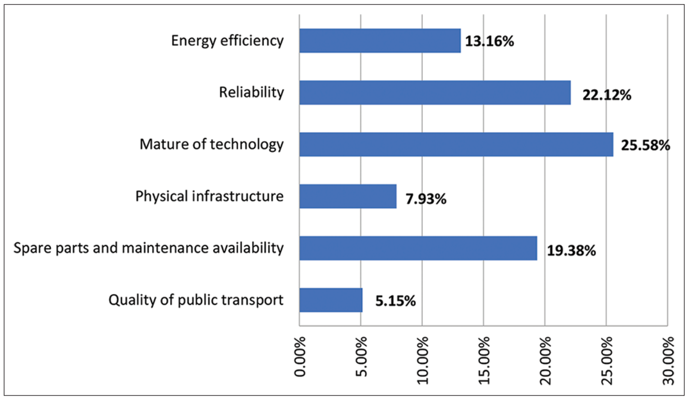


Figure 8: Classification of economic subcriteria

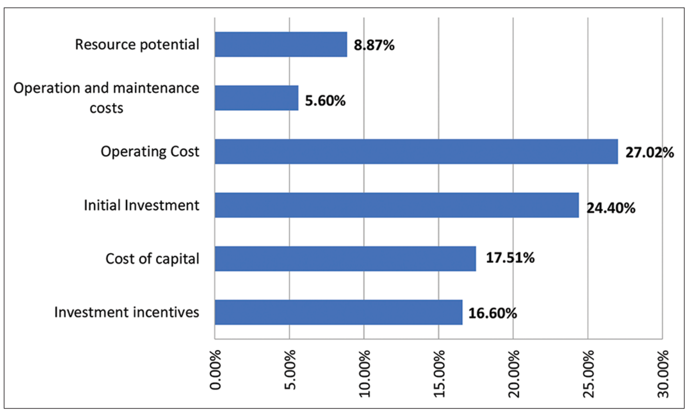


Figure 9: Classification of social subcriteria

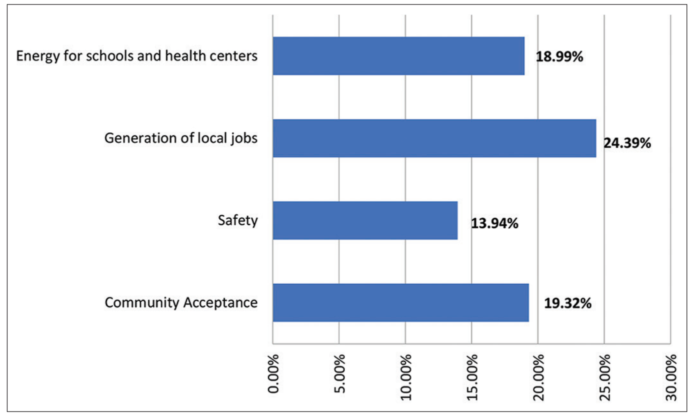
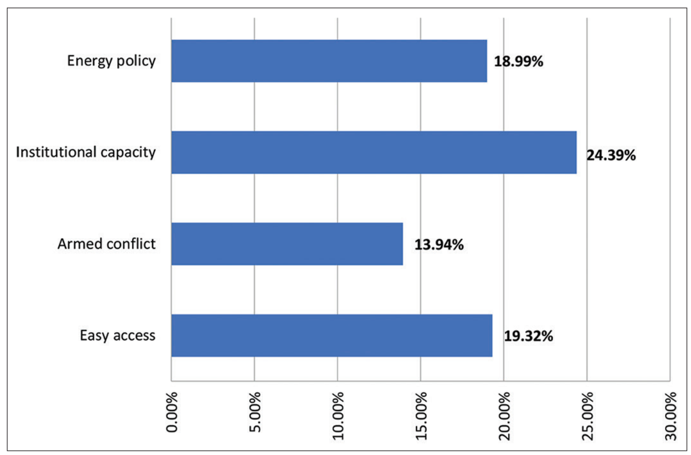


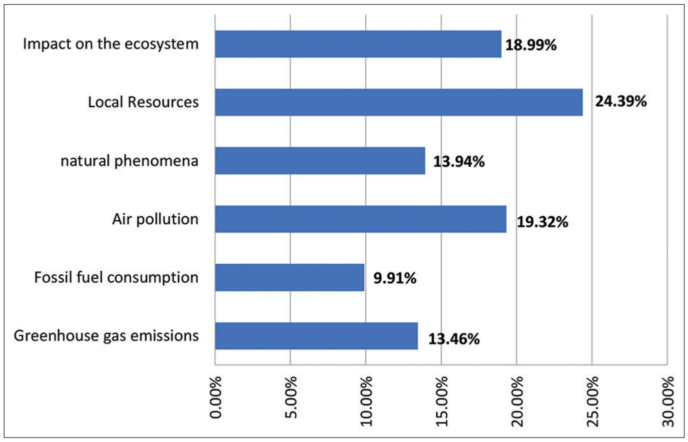
Figure 10: Classification of policies and governance subcriteria



not matter whatever the project to be developed, from an economic point of view the most important thing is the initial value of the investment, the value of the cost in the operation of said project and more, it is a new technology to be implemented, such as electric vehicles. For the results found in the social subcriteria, it stands out that the generation of work and safety are the most important according to the experts consulted. For this particular criterion, the percentage difference between the subcriteria was not so great, showing that all of them must actually be taken into account when implementing electric vehicles in society, it is not only enough to generate work and how safe this technology is, but also, for example, to guarantee that with this technology the efficient energization of schools and health centers can be achieved. if this occurs, it very surely brings the acceptance of a community.

Corresponding to the Classification of Policies-Governance and Environmental subcriteria, corresponding to Figures 10 and 11 respectively, the results found are of great interest, this is because it is the institutional capacity that is most responsible when implementing electric vehicles, it is because it is public policies, the guidelines presented by a government in turn for a country, which will define the success or not in the implementation of electric vehicle technology, it is that perhaps a government can generate incentive s economic, tax, etc. in such a way that it motivates the greater implementation of electric vehicles and in such a way achieves the gradual replacement of traditional vehicles operating by traditional sources. Regarding the results of the environmental subcriteria, the importance that the experts have given to the local resource stands out, because it is the element from which the energy transformation would be obtained to achieve energization and/or transformation in everything related to the construction and implementation of electric vehicles, in order to reduce the economic costs of this technology, if local resources were not available, they would have to be transported from another location, which would imply an increase in prices for the end user, likewise the amount of air pollution that is generated

Figure 11: Classification of environmental subcriteria



is of great importance. Can generate throughout the process and/or chain of construction and implementation of electric vehicles.

4. CONCLUSIONS

This document offers a complete vision of the development over time in research and implementation regarding the introduction of electric vehicles in order to improve or obtain sustainable transport, through a scientometric study, which allows academics to understand the current state and future development patterns of research regarding this topic. As an indication for prospective research, we can emphasize the need to understand the emergence and regionalization of specific techniques and their variations, broaden the research within the identified countries to gain a deeper understanding of their scientific output on the subject under investigation, apply thematic models to find latent themes in the investigated database, and systematize method variants and their interfaces with other research areas, such as machine learning.

On the other hand, as a result of this research, a significant spectrum of very precise conclusions can be addressed, which contribute significantly to the sustainable development objectives and sustainable transport planning, the latter currently lacking clearly defined criteria and sub-criteria that help investors and planners to make a better decision, this due to the complexity within a large number of criteria and/or sub-criteria that can be evaluated. As a consequence of this problem, it is evident that urban transport planners and other actors require and/or need decision-making support tools to help the adoption and implementation phases of strategies that efficiently and continuously help to solve the problem related to sustainable transport and mobility. This Research succeeded in providing criteria, as well as sub-criteria, to assess the feasibility of effective adoption of urban vehicle access regulations based on expert opinion drawn from the fields of transportation and urban planning using a statistical methodology.

Another important result of this research is that the evaluation structure presented has the potential to be implemented immediately and, therefore, becomes a significant contribution to the discussions and commitments acquired by the different governments in national and international policies, especially with regard to the planning and implementation of UVAR measures. In addition, this tool is an adequate complement to the set of tools that may already exist in the reassessment of some policies or strategies that you define today in everything related to the implementation of electric vehicles in the large cities of the world, therefore, the evaluation structure will help these cities to evaluate these recommended measures in alignment with their sustainability objectives.

Regarding the response of the group of experts consulted, 5 criteria and 27 sub-criteria with high importance for the purpose of the study were identified. However, criteria such as economic, environmental and political and governance, resulted with an important added value, this refers to the commitments made by governments to meet the objectives of sustainable development. On the other hand, sub-criteria such as Energy Efficiency, Resource Potential, Energy for Schools and Health Centers, Ecosystem Impact, and Energy Policy were considered only slightly important and were left to the discretion of urban policy makers to include or exclude in the decision-making process.

To conclude, although the proposed research structure can satisfactorily evaluate the viability of different UVAR measures, it is important to highlight some improvements for future research as a continuation of this. In the first place, the results may have a subjective value due to the predominance of academic specialists and the non-specific scope of the precise area of study. Future research may have a little more delimitation of the area to be implemented, while ensuring a balanced representation of stakeholders such as citizens and business operators. This will allow differences in agreement on specific criteria and sub-criteria to be fully investigated to determine if they are random or reflect stakeholder group preferences, thereby mitigating that degree of subjectivity. Secondly, the research implemented the consultation of a group of experts and a statistical method for the criteria and sub-criteria, however, the possibility that the participants rank their concerns instead of the importance of the object is a demerit of this approach. Furthermore, this approach implies that weights can only be determined within a category, while global weights can only be inferred. Thirdly, thanks to the implementation of FAHP, the weighting and ranking of each of the criteria and sub-criteria identified with the initial statistical methodology was achieved.

MCDA weighting approaches can be used, some metaheuristic methods such as AHP or TOPSIS can be implemented, which can produce hierarchical structures consistent with the sustainability framework. All these proposed improvements and modifications will be investigated and implemented in our future investigations to provide decision makers and other interested parties with more information on the evaluation of UVAR measures.

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