Characterization of Methodologies for the Integrated Assessment of Urban Transportation Sustainability[a]

Caracterización de metodologías para la evaluación integral de la sostenibilidad del transporte urbano

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Abstract

Objective: To characterize methodologies for the integrated assessment of urban transportation sustainability and to identify research opportunities in developing countries. ***Materials and methods:*** A three-stage structured literature review is presented, and a taxonomy is proposed to characterize conceptual frameworks, analytical models, and indices and indicators. An analysis of indicators based on the eleven categories proposed is also presented. ***Results and discussion:*** The increase of scientific and institutional literature studying methodologies for sustainability assessment in the last two decades is evidenced. However, the methods still lack the integral inclusion of the economic, environmental, and social dimensions, particularly in the sustainability assessments of urban transportation. Most works are focused on introducting new indices and indicators and applying methodologies in European and North American countries. ***Conclusions:*** The characterization identifies the methodologies, institutions, and countries that have implemented methodologies for the integrated assessment of urban transportation sustainability. Likewise, the most frequent sustainability dimensions are identified, and research opportunities in developing countries are outlined.

Keywords: Sustainability, Urban transportation, Developing countries.

Resumen

Objetivo: Caracterizar las metodologías para la evaluación integral de la sostenibilidad del transporte urbano, e identificar las oportunidades de investigación en países en desarrollo. ***Materiales y métodos:*** Se hace una revisión estructurada de la literatura en tres etapas y se propone una taxonomía para la caracterización de marcos conceptuales, modelos analíticos, índices e indicadores. Se presenta también un análisis de los indicadores en once categorías propuestas. ***Resultados y discusión:*** Se evidencia un incremento en la literatura científica e institucional dedicada al estudio de metodologías para la evaluación de la sostenibilidad en las últimas dos décadas. Sin embargo, se observa también la carencia de métodos que permitan incluir las dimensiones económica, ambiental y social de manera integral, en particular para evaluar la sostenibilidad de los sistemas de transporte urbano. La mayor parte de los trabajos está centrada en el desarrollo de índices e indicadores, y en la aplicación en países europeos y norteamericanos. ***Conclusiones:*** La caracterización identifica cuáles son las metodologías, las instituciones y los países que han implementado evaluaciones integradas de la sostenibilidad del transporte urbano. Igualmente, se identifican las dimensiones de la sostenibilidad más estudiadas, y se reseñan las oportunidades de investigación en países en desarrollo.

Keywords: Palabras clave: Sostenibilidad, Transporte urbano, Países en desarrollo.

Introduction

Sustainable development has gained prominence as an area of research in the last two decades. Countries and institutions have addressed a work agenda in favor of fulfilling of the Sustainable Development Goals (SDG) 2015-2030 formulated by the United Nations (UN). However, the seminal work of Barbier [1] recognized that economic improvement has environmental and social impacts, and it is necessary to implement strategies to achieve sustainability in the three dimensions development is quantified: economic, environmental, and social, known as the *Triple Bottom Line* (TBL) [2]. Sustainability has been approached differently according to countries' degree of economic development: in developed countries, sustainability has revolved mainly around environmental aspects [3]. In developing countries, the situation is different because socioeconomic problems, such as high rates of poverty, failure to meet basic needs, and rapid urbanization have greater prominence [4], [5]. In Latin America and the Caribbean, a region with 27 developing countries [6], a degree of urbanization close to 79% [7] has generated growth in the transport supply. However, this growth does not meet the SDGs' conditions and has had a negative impact on public health, mainly due to the emissions generated by transport modes and how they affect air quality [8].

In this context, evaluating the impact of urban transport on sustainability is a scientific and institutional challenge. The evaluation of sustainability can be understood as a methodology that supports the decision-making process regarding what actions to follow to achieve more sustainable cities [9]. Despite its relevance, the study of the subject has been fragmented. On the one hand, there are studies focused on analyzing the effects of transport on air pollution without including the framework of sustainability [10]–[12]. On the other hand, studies focus on analyzing the effects of transport emissions on health do not consider other dimensions of sustainability [13], [14]. In an attempt to structure the literature on methodologies for evaluating sustainability from a general perspective, which includes different sectors such as energy, the production of goods, and supply chains, Ness et al. [15] present a classification in which it is established that one of the ways to evaluate sustainability is through integrated methodologies, that is, to take into account the three dimensions of the TBL simultaneously.

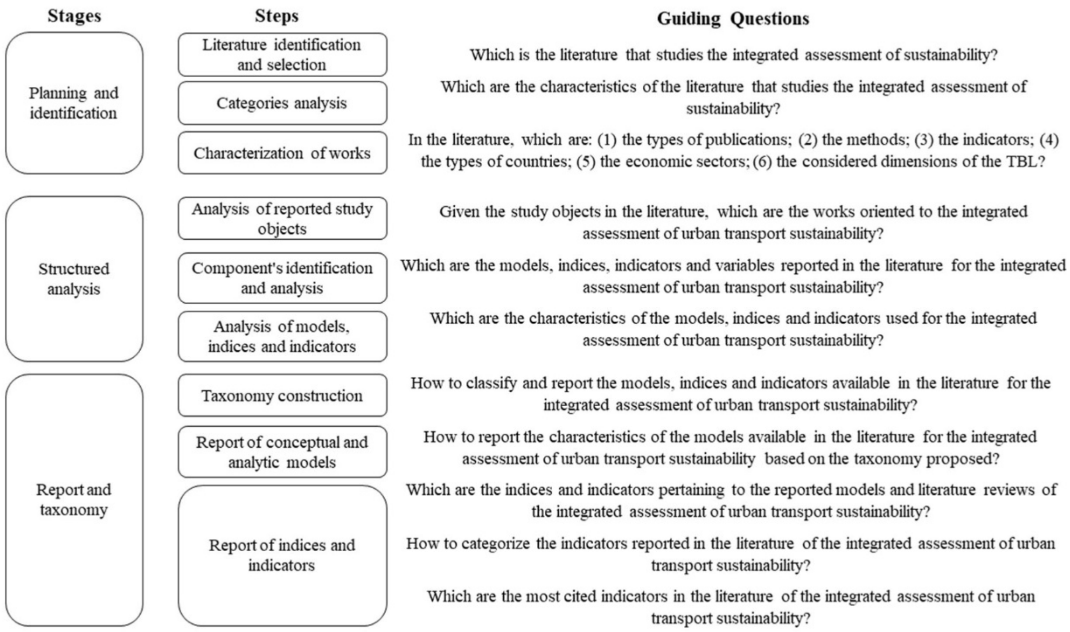
Given the increase in the literature dedicated to the study of sustainability and the differences between various sectors, it is necessary to focus on works that study sustainability in urban transport. Addressing this need, Karjalainen and Juhola [16] present a recent literature review of methodologies for evaluating sustainability focusing on urban transport, showing that research in the field is highly fragmented and focuses mainly on European cases. Reviews in the transportation sector report that the literature on the subject is still diverse in terms of approaches, terms, and techniques [17]. There are multiple methodologies based on indicators [18]–[20], and there is a strong tendency to introduce new systems of sustainability measurement indicators with little reference to previous works [16]. Additionally, the proposed methodologies do not yet explicitly consider the interactions between the dimensions of sustainability, evidencing the need to study models that provide a comprehensive and holistic view [21].

To address the limitations of the literature in the development of methodologies for the integrated evaluation of sustainability in the transport sector and considering the classification of integrated methodologies proposed in [15], this work aims to characterize the methodologies available in the literature that simultaneously consider the dimensions of the TBL for the integrated evaluation of the sustainability of urban transport (MIES-UT). In this way, this work analyzes the existing methodologies from this integrated perspective and proposes a categorization of indicators that facilitates the study of the transport systems, particularly in developing countries. For this, a structured review is performed using elements from three previous works [17], [22], [23], and a taxonomy is proposed that allows the identification of the conceptual frameworks, the analytical methods, and the indices and indicators of the MIES-UT. In the review, special emphasis is placed on the methodologies applicable to developing countries, given the particular conditions and the differential approach to sustainability. The analysis also identifies of research opportunities and the redirection that can be performed on the integrated evaluation of the sustainability of urban transport.

Materials and methods

A structured literature review was carried out, which uses several concepts of systematic methods [24], [25] and allows the establishment of the steps for the search, selection, and synthesis of the main findings, following the principles of clarity, replicability, and objectivity [25], [26]. Likewise, based on the ideas of Duque-Uribe et al. [27], the methodology was developed in three stages: planning and identification, structured analysis, and reporting and taxonomy (see Figure 1). In the first stage, a base sample of works was identified corresponding to the research objective, and the inclusion and exclusion criteria were defined. In the second stage, a structured analysis of the samples was performed, and key components of the MIES-UT were identified. In the third stage, based on the conceptual findings, a report of the MIES-UT components was made, and taxonomy was proposed for its analysis. Figure 1 describesthe three stages.

Figure 1. Methodology used for the review. Based on Duque-Uribe et al. [27]



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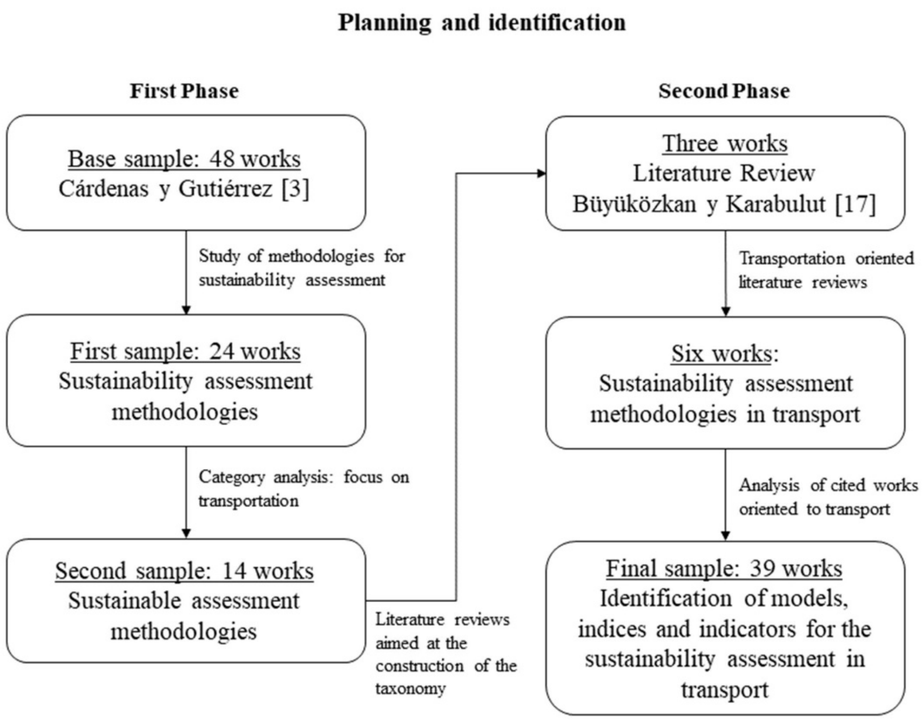
Literature reviews are important for better understanding a topic or area and learning how it has been studied and which issues require further review. Research on the evaluation of sustainability is quite extensive, and this is demonstrated by the presence of several literature reviews [28], [29] that collect research articles. Given the degree of progress that has been made regarding the evaluation of sustainability, the need for an integrative study of the available literature becomes essential. This requires a review of literature reviews (a tertiary literature review) [30], which is why this study takes literature review articles on sustainability assessment as a starting point and concentrates on research focused on transportation. It is recognized that this delimitation may exclude works published after the initial documents of the review.

Planning and identification

The literature was identified in two phases. First, based on the literature reviewed in [3], the works that expressly study some methodology for evaluating sustainability were selected. Through this first inclusion criterion, the first sample of 24 works was found and was reviewed in its entirety, and six categories of analysis were applied, as illustrated in Figure 1. Additionally, a second inclusion criterion was applied to the first sample: it was identified whether each study had a focus on transportation. In this way, the sample was reduced to 14 works.

In the second phase, three activities were performed. First, the works that, according to the type, correspond to the literature reviews were selected. With the application of the second inclusion criterion, three works were found that reviewed MIES-UT: Büyüközkan and Karabulut [17], Purvis et al. [22], and Singh et al. [23]. The work of [17], to the best of our knowledge, presents a complete systematic review of the literature regarding the object of study. Therefore, as a second parallel activity, the works cited in [17] oriented to transport were selected. Thus, six more articles were obtained for the sample. Third, to the six works selected in [17], the same procedure was applied: the six documents were reviewed, and the works cited oriented to MIES-UT development were identified. An additional sample of 13 works was found in this analysis, which was included in the review, thus yielding a final sample of 39 works (see Figure 2).

Figure 1. Synthesis of the first stage: planning and identification



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Structured análisis

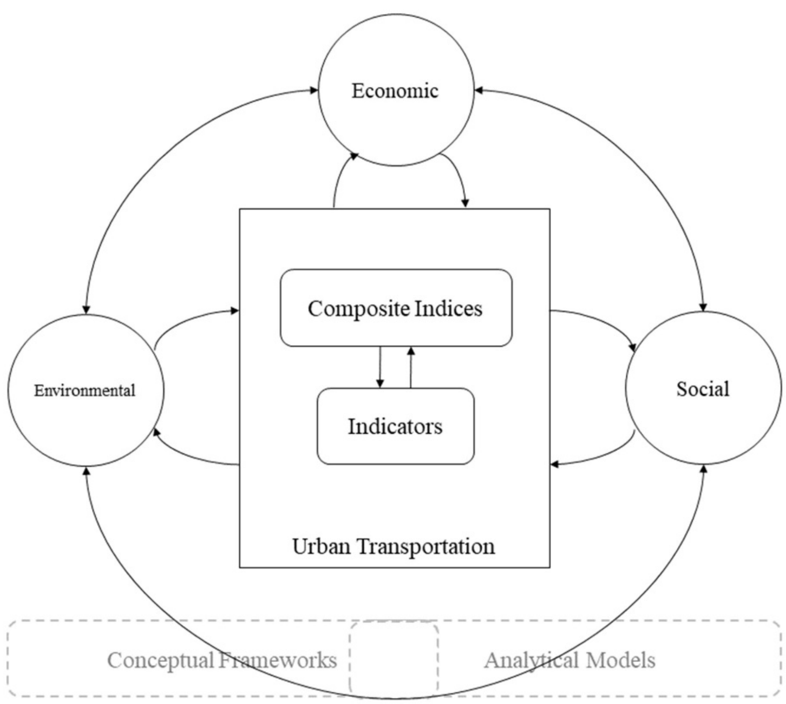
A structured analysis of the work sample obtained in the first stage was performed. An analysis of the objects of study and the components reported in the literature was performed. The main reported components of the MIES-UT were conceptual frameworks, analytical models, indices, and indicators [17], [23]. In this way, these components were analyzed, identifying their characteristics in terms of their approximations, the techniques used, and the proposed indicator schemes.

Report and taxonomy

Based on the review analysis, a taxonomy was built that facilitates responding to the research object and giving a structured report of the findings in the literature. The taxonomy is composed of three axes. In the first axis, the conceptual basis proposed in [22] is considered, where theoretical elements are presented to define the three dimensions of sustainability. The second axis is based on the findings of [17], who propose a classification scheme of two categories for the methodologies available in the literature: (1) conceptual frameworks and (2) analytical models. The third axis is based on the structure proposed in [23], where a differentiation between (1) composite indices and (2) sustainability indicators is made.

In this way, the taxonomy was implemented to report the findings in terms of (1) conceptual frameworks, (2) analytical models, and (3) indices and indicators, all in the context of the MIES-UT. Figure 3 illustrates the scheme of the proposed taxonomy. For clarity of the taxonomy and to have objective criteria of inclusion, exclusion, and classification of the methodologies, the definitions presented in [17] are used to differentiate conceptual frameworks from analytical models. As indicated by the authors, conceptual frameworks are associated with the need to have robust conceptual bases to identify the necessary data for the construction of sustainability indicators. On the other hand, analytical models are associated with evaluating of the data obtained and using analytical techniques for quantitative and qualitative processing that give meaning to the data.

Figure 2 . Proposed taxonomy



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Resultados y discusión

The reporting taxonomy constructed for this work was followed to characterize the MIES-UT available in the literature. In this way, an analysis of the conceptual frameworks, analytical models, indices, and indicators found was carried out in the context of the TBL dimensions. The sample of 39 works is described in Table 1, in which the type of publication, the type of country according to the classification of the United Nations *World Economic Situation and Prospects* (WESP) [6], and the contribution of each work to the four dimensions of the proposed taxonomy, and the dimension of the TBL studied in each one are identified.

The literature on the MIES-UT has been published not only in scientific journals (59% of the sample) but also by institutions and government commissions around the world (41%), such as the *Organization for Economic Co-operation and Development* (OECD), the *United Nations Environment Program* (UNEP), the European Union and its different commissions, the *European Environment Agency* (EEA), the *United States Environmental Protection Agency* (USEPA), the *United States Department of Transportation* (USDOT), and the *Transportation Association of Canada* (TAC). It can be observed that 64% of the studies are carried out in developed countries. In comparison, only 18% correspond to developing countries, and only two of them are based in Latin America, specifically in Brazil.

Table 1. MIES-UT literature

No.	Ref	Publication Type[1]	Country Type [2]	Conceptual Framework	Analytical Model	Index	Indicador	TBL Dimension [3]		
								Eco	Env	Soc
1	[31]	SciJnl	DE			X	X	X	X	X
2	[32]	SciJnl	DE, ED		X		X			
3	[33]	Ins	DE	X			X		X	
4	[34]	Ins	DE	X	X		X	X	X	X
5	[35]	SciJnl	DE		X		X	X		
6	[36]	SciJnl	ED		X		X			
7	[37]	SciJnl	ED				X			
8	[38]	SciJnl	ED	X			X	X	X	X
9	[39]	Ins	DE	X			X			
10	[40]	Ins	DE	X			X	X	X	X
11	[41]	Ins	DE	X			X	X	X	X
12	[42]	Ins	DE				X	X	X	X
13	[8]	SciJnl	NA	X	X				X	
14	[43]	SciJnl	NA	X	X				X	
15	[44]	SciJnl	DE	X			X			
16	[45]	Ins	DE	X						
17	[46]	Ins	DE	X			X	X	X	X
18	[47]	SciJnl	DE	X			X	X	X	X
19	[13]	SciJnl	DE		X	X	X	X	X	X
20	[48]	SciJnl	DE				X	X	X	X
21	[14]	SciJnl	ED	X		X	X	X	X	X

No.	Ref	Publication Type[1]	Country Type [2]	Conceptual Framework	Analytical Model	Index	Indicador	TBL Dimension [3]		
								Eco	Env	Soc
22	[49]	SciJnl	NA				X	X	X	X
23	[50]	Ins	DE				X			
24	[51]	SciJnl	DE		X	X	X	X	X	X
25	[52]	Ins	DE	X			X	X	X	X
26	[53]	Ins	DE	X				X	X	
27	[54]	Ins	NA	X			X		X	
28	[55]	SciJnl	DE		X		X	X	X	X
29	[56]	SciJnl	DE		X		X	X	X	X
30	[57]	SciJnl	DE	X		X	X	X	X	X
31	[58]	Ins	DE	X				X	X	X
32	[59]	SciJnl	DE	X			X	X	X	X
33	[60]	SciJnl	ED				X	X	X	X
34	[61]	SciJnl	NA	X	X					
35	[62]	SciJnl	NA	X	X			X	X	
36	[63]	Ins	DE	X			X		X	
37	[64]	Ins	NA	X			X		X	
38	[65]	Ins	DE	X			X		X	
39	[66]	SciJnl	ED		X	X		X	X	X
Totals	SciJnl, DE Ins, ED	23 16	25 7	24	13	6	31	24	30	21
Totals	% of the sample	59% 41%	64% 18%	62%	33%	15%	79%	62%	77%	54%

1 SciJnl: Scientific Journal; Ins: Institutional.

2 DE: Developed Country; ED: Developing Country, according to [6]; NA: Not Available.

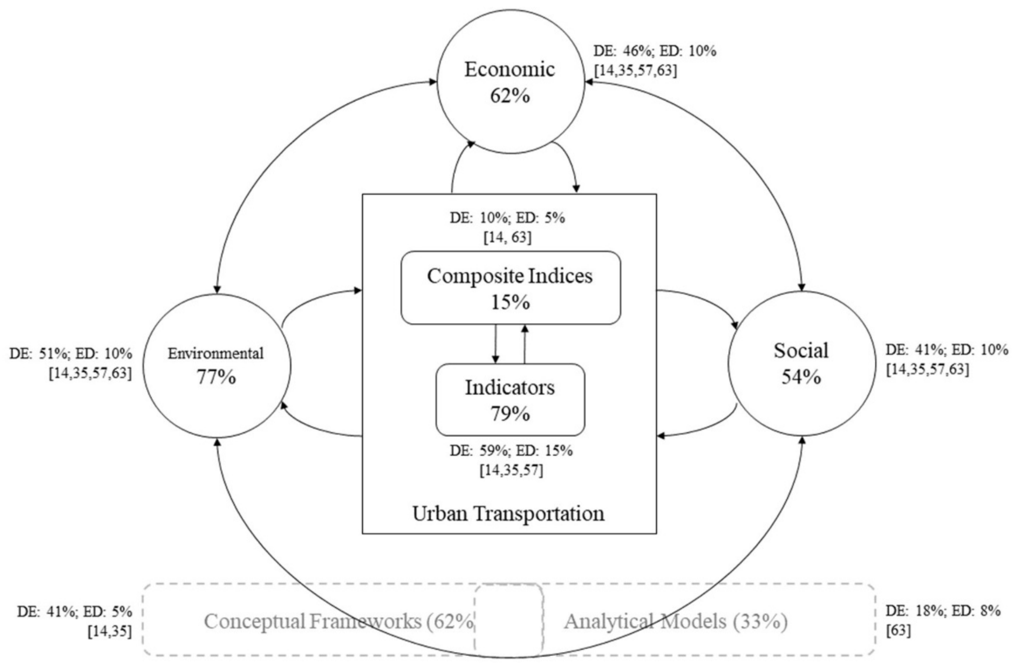
3 Eco: Economic; Env: Environmental; Soc: Social.

Source: Own source

A total of 62% of the works present conceptual frameworks. In contrast to the findings reported in [17], approximately one-third present analytical models, where a higher proportion of analytical models is found. Likewise, only five works present an analytical model based on developing a simultaneous conceptual framework and almost 80% of the works present indicators. Regarding the dimensions of sustainability, 54% of the works integrally study the dimensions of the TBL, and the trend outlined in the literature is preserved: most of the works are aimed at studying the environmental dimension (77%), then the economic (62%), and finally the social (54%).

The proposed taxonomy allows us to characterize which of the MIES-UT offers a comprehensive approach that simultaneously considers the dimensions of the TBL with emphasis on developing countries. Figure 4 identifies, for each dimension of the taxonomy, the proportion of the works of the sample that simultaneously consider the three dimensions of the TBL, illustrating the proportions of the works of developed countries (DE) and developing countries (ED), and reviews of works of the literature carried out on developing countries. As observed, in conceptual frameworks, analytical models, composite indices, and indicators, most of the works occur in developed countries (41%, 18%, 10%, and 59%, respectively) rather than developing countries (5%, 8%, 5%, 15%). Additionally, only four works present a MIES-UT in developing countries [14, 38, 60, 66], unlike the 16 works found in developed countries. This section analyzes the results obtained and characterizes the conceptual frameworks, analytical models, and indices and indicators.

Figure 3. Analysis of MIES-UT with emphasis on developing countries (DE)



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Conceptual frameworks

The conceptual frameworks of the MIES-UT have significantly developed in the last two decades, not only by the definition of new indices and indicators but also by adaptating to the conceptual bases of sustainability. As indicated in [17], conceptual frameworks define what sustainability performance reflects, what indicators to use, and what to expect from their measurement. These frameworks aim to identify what data to collect, for what purpose, and how it should be reported. Table 2 presents a synthesis of the 24 conceptual models of MIES-UT identified.

Table 2 . Conceptual frameworks

No.	Frame	Country	Ref	No.	Frame	Country	Ref
1	Belgium Indicators of sustainable development in transport sector	Belgium	[34] [39]	13	Performance assessment and evaluation method for passenger transportation	Brazil	[38]
2	Carbon Emissions Pinch Analysis (CEPA)	China Korea India Ireland New Zealand	[8] [43] [62] [61]	14	Social Sustainable Evaluation Framework	India	[14]
3	Composite transport sustainability index (ICST)	Australia	[57]	15	Sustainability indicators for urban land-use and transport (PROSPECTS)	NA	[34] [52]
4	Framework for the Evaluation of Transport Sustainability Performance	European Union	[40]	16	Sustainable freight transportation (SFT)	India	[14]
5	Germany: Agenda 21 indicators for sustainable mobility in municipalities	Germany	[34] [63]	17	Sustainable Transportation Indicators Project (STPI)	European Union	[34] [44]
6	Greenhouse Emission Pinch Analysis (GEPA)	Korea	[8]	18	Transportation Association of Canada (TAC)	Canada	[45] [47]
7	Joint Research Centre: Monitoring Progress towards Sustainable Urban Mobility	NA	[34] [58]	19	The European Transport policy Information System (ETIS)	Europe	[40]
8	Methodology for measuring the sustainability of car transport systems	United Kingdom	[59]	20	The transport and environment reporting mechanism (TERM)	European Union	[34] [41]
9	New Zealand: Proposal for indicators of the environmental effects of transport	New Zealand	[33] [34]	21	TRANSPLUS: Frame of reference to monitor and evaluate land-use and transport integration	European Union	[34] [46]
10	National Round Table on the Environment and the Economy (NRTEE)	Canada	[47] [53]	22	Transport Canada (TC)	Canada	[47]
11	OECD: Indicators for the integration of environmental concerns into transport policies	NA	[34] [54]	23	United States Department of Transportation (USDOT)	United States	[47]
12	Ontario Round Table on Environment and Economy (ORTEE)	Canada	[47]	24	United States Environmental Protection Agency (USEPA)	United States	[34] [64] [65]

Source: Own source

In line with the conceptual bases of the MIES-UT, the three-stage framework for identifying environmental indicators related to transport proposed by the USEPA [65] is one of the first, in conjunction with the frameworks of [33] and [64]. Bell's conceptual framework [33] presents a guide from the Ministry of the Environment of New Zealand that identifies environmental indicators for water and land and explains how these indicators fit into the *Environmental Performance Indicators* (EPI) lines of the Program. For its part, the work presented in the Commission for Sustainable Development [64] identifies the transport sector's role in environmental protection and, in turn, reviews its socioeconomic impact.

Other more recent frameworks that present conceptual bases oriented especially to the environmental dimension include variants of *Pinch Analysis*, which was developed for macroscale energy planning problems with carbon restrictions [8], [43], [61], [62].

In the evolution toward the generation of transport-oriented MEIS, Ricci [58] proposed a framework to evaluate progress toward sustainability in the planning and management of urban mobility, which is tested with case studies in five European cities: Barcelona, Bremen, Nottingham, Strasbourg, and Turin. De Villers et al. [39] developed and applied a framework of indicators for the sustainable development of transport in Belgium, while Bickel et al. [34] reviewed nine conceptual frameworks used in Germany, Belgium, and New Zealand. These authors present a report on the *SUstainable Mobility, policy Measures and Assessment* (SUMMA) project of the Directorate General of Energy and Transport of the European Commission, in which one of the key actions of the program for the growth of economic, environmental, and social conditions for the sustainable development of transport is addressed [46]. This report is built with the conceptual bases of the OECD indicators [54] of the project of sustainability indicators for transport proposed in [44] and sustainability indicators for urban land use and transport [52].

In more recent efforts to identify and characterize the MIES-UT, there is a greater emphasis on including the integrality of the TBL dimensions of the and greater specificity in the type and nature of the data required for the evaluation. Jeon and Amekudzi [47] review the main initiatives carried out in North America, Europe, and Oceania in the direction of sustainability in transportation systems. In addition to the identification of institutions and programs for transport sustainability, such as USDOT, USEPA, and TAC, the authors review the National Round Table on the Environment and the Economy (NRTEE) model [53] of Canada, then applied in Ontario (Ontario Round Table on the Environment and Economy (ORTEE)), which was derived from a set of studies on sustainability, focused on transport principles and related to the dimensions of the TBL. The same year, also in Canada, Hollingworth et al. [45] presented the analysis of a survey directed to different regions of the country with which critical indicators are defined, oriented to the use of the land, the cost and financing of transport, and the needs of the users. In Germany, the Federal Office of the Environment UBA [63] developed Agenda 21 with objectives and indicators for the sustainable mobility of municipalities, and Dobranskyte-Niskota et al. [40] propose the evaluation of transport sustainability performance based on the indicators of organizations such as the European Union.

In the last decade, four works published in scientific journals present the development and application of MIES-UT, comprehensively considering the dimensions of the TBL . One work is carried out in Europe, another in Australia, and two in developing countries, and of the latter, only one is carried out in Latin America, in Brazil. Smith et al. [59] establish a methodology to measure sustainability in transportation systems and define which indicators belong to each dimension of the TBL. Reisi et al. [57] developed a method to obtain a composite index of transport sustainability for the areas of Melbourne that includes nine indicators in the TBL dimensions relevant to urban transport. The case of Brazil is presented by de Almeida and Leal [38], who propose a structured method of performance evaluation of passenger transport systems in the context of sustainability in light of eco-efficiency metrics. Kumar and Anbanandam [14] consider the holistic participation of the TBL dimensions of sustainability and develop an index of social sustainability for freight transport systems.

Analytical models

Table 3 presents a synthesis of the ten analytical models identified. The identified analytical models show the diversity of integrated numerical techniques based on previous or their own conceptual frameworks. The sample studied provides a general description of the development of analytical techniques and the applications of the existing models of the last two decades.

The most commonly used approach in analytical models is the *multicriteria decision-making method* (MCDM). Awasthi et al. [29] presented a methodology based on the MCDM and fuzzy logic for evaluating and selecting of sustainable transport systems under uncertainty in France. In contrast, Bojković et al. [32] developed a model for a comparative evaluation of the transport systems of Central and Eastern European countries according to sustainability criteria using the *analytic hierarchy process* (AHP) technique. Jeon, Amekudzi, and Guensler [13] use the MCDM with composite sustainability indices and a variety of performance metrics to evaluate sustainability in transportation planning. To a lesser extent, some works apply linear programming, simulation, *computable general equilibrium (CGE), impact assessment methods, composite sustainability indices* (CSIs), and *cost-benefit analysis* (CBA), *cost-effectiveness analysis* (CEA), and diffuse *Delphi*.

Table 3. Analytical Models

No.	Model	Basic approach	Technique	Country	Ref
1	MCDM: Evaluation and selection of sustainable transportation systems under uncertainty	MCDM	Diffuse TOPSIS	France	[32]
2	Carbon Emissions Pinch Analysis (CEPA)	Linear programming	Supply-demand problems Location problems	China Korea India Ireland New Zealand	[8] [43] [62] [61]

No.	Model	Basic approach	Technique	Country	Ref
3	Framework for a cross-country comparative assessment of transport sustainability	MCDM	AHP	Central and Eastern European countries	[35]
4	Integrated and dynamic LCSA framework for sustainability assessment of new generation transportation systems	Simulation	System dynamics	United States	[56]
5	Integrated assessment framework	CGE	*Benchmark simulation* *Air concentration model*	China	[36]
6	Macro-level sustainability assessment framework for alternative passenger vehicles	*Impact assessment methods*	Input-output analysis	United States	[55]
7	Public Transport Sustainable Mobility Analysis Project (PTSMAT)	CSI	Normalization and weighting MCDM	Canada	[51]
8	Sustainability assessment framework	MCDM	Equal weights	United States	[13]
9	Sustainable Mobility, policy Measures and Assessment (SUMMA)	MCDA CBA CEA	LCA Scenario analysis Systems modeling	United States European Union	[34]
10	Transportation sustainability index for a livable city	Diffuse *delphi*	Big Data Analytical network Data mining	Taiwan	[66]

Source: Own source

One of the countries with more studies on analytical models is the United States: in [31], the SUMMA model for the United States is presented, and in conjunction with the European Union, in [13], the *Sustainability Assessment Framework* model is developed. In [52], a framework for evaluating sustainability at the macro-level for alternative passenger vehicles is presented, and in [53], a model is proposed for the integrated and dynamic analysis for the evaluation of the sustainability of new generation transportation systems in that country. The carbon emissions pinch analysis (CEPA) model, also studied as a conceptual framework, is the analytical model with the most significant number of applications and is used for the study of transport systems in China [8], Korea [40], India [59], Ireland, and New Zealand [58]. Chen and He [33] present the *integrated assessment framework* based on a CGE model for China, and in [48], the *Public Transport Sustainable Mobility Analysis Project*

(PTSMAT) was applied in Canada. Only two works use methods that provide a comprehensive view of sustainability: [53], with system dynamics, and [32], with the AHP. Some works use data mining techniques to predict dynamic changes in transport indices [63], but, in general, there is fragmented literature on the development of analytical models for MIES-UT.

Indices and indicators

The literature shows the need to measure the systems' performance that makes up society in terms of the dimensions of the TBL. As indicated in [23], composite indices and sustainability indicators have become a helpful methodology when addressing this need since they allow us to simplify, quantify, analyze, and communicate the system's information that is the object of study. This section identifies and analyzes the most commonly used composite indices and indicators to measure the sustainability of urban transport. Table 4 shows the six composite indices identified.

Composite indices are useful for grouping indicators. According to [57], making decisions based on too many indicators is inappropriate and complex. However, there are opposing opinions regarding indices: for some authors, composite indices are not reliable because their construction is subjective, while for others, they are valuable tools that transmit information and allow quick comparisons. In the sample of indices identified, different techniques for their construction are used. By referring exclusively to weighting techniques, [57] uses a weighting method of component analysis and factor analysis in the construction of the *index of composite transport sustainability* (ICST). This method is based on the variation in the data and not on expert opinions, solving the problem of subjectivity; this method was applied in Australia.

Table 4. Indices

No.	Index	Number of categories and indicators	Scale/ normalization	Weighting	Aggregation	Country	Reference model		Ref
							Conceptual	Analytical	
1	Composite Index of Global Sustainability	3 subscripts 9 indicators	Standardized values and Z scores	Expert opinions	Sum of subscripts	Spain France Holland United Kingdom Switzerland			[31]
2	Composite Sustainability Index (CSI)	4 categories 15 indicators	Utility function of a single attribute in normalized linear scales	Equal weights	Weighted sum	United States		8	[13]

No.	Index	Number of categories and indicators	Scale/ normalization	Weighting	Aggregation	Country	Reference model		Ref
							Conceptual	Analytical	
3	Composite Transport Sustainability Index (ICST)	3 subscripts 9 indicators	Division of the value of each indicator over time by its average value	*Principal component analysis/factor analysis* (PCA/FA)	Sum of subindices	Australia	3		[57]
4	Freight Transportation Social Sustainability Index (FTSSI)	4 facilitators 16 dimensions 74 attributes	NA	Fuzzy logic	Fuzzy triangular numbers, Linguistic variables	India	16		[14]
5	ND	4 categories 26 indicators 12 factors	Z score function Approach based on reference distance	Monte Carlo simulation	Weighted sum	Canada	7		[51]
6	Transportation Sustainability Index for a Livable City	3 categories 18 indicators	Rate of each indicator by quarter from 2009 to 2016	*Fuzzy Method Delphi* (FMD)	Time series ARIMA model	Taiwan	10		[66]

Source: Own source

For the United States and Canada, in [13], equal weights are assigned to each indicator, giving each dimension the same relative importance in the calculation of the CSI. In [51], a stochastic analysis model allows an assignment of weights following an MCDM, and a CSI is constructed based on the PTSMAT framework. In contrast, in [31], [14], and [66], which were developed in Europe, India, and Taiwan, respectively, expert opinions are used to weight the indices. The difference is that the work from India [14] focuses on the social dimension and formulates the *freight Transportation Social Sustainability Index* (FTSSI) from the aggregation of different social indicators. The work from Taiwan [66] defines composite indices that attempt to fully explain the sustainability of transport according to the dimensions of the TBL.

Attempts to categorize and classify the sustainability indicators of urban transport are reported in the literature. This initiative is evidenced mainly in the conceptual frameworks proposed by international organizations, especially in the context of the European Union, and with a predominance of strict classification in the dimensions of the TBL. For example, the European Commission and the EEA proposed the transport and environment reporting mechanism (TERM) conceptual framework, classifying the indicators as descriptive, performance, efficiency, and total well-being indicators. On the other hand, in the framework of [39], the indicators are grouped by topic, where the trends of the modal transport of passengers, the structure of the vehicle fleet, the energy consumption per year, the efficiency of transport utilization, and the price index stand out. Minken et al. [52] propose categories such as economic efficiency, accidents, equity, and social inclusion in the framework of PROSPECTS. However, despite these attempts at classification, the diversity and extent of transport sustainability indicators make their categorization and analysis difficult.

For these reasons, to identify and comprehensively characterize the transport sustainability indicators found in the literature, eleven categories are proposed, defined as follows:

1. Accessibility: possibility of accessing a means of transport according to user needs [50].
2. Quality: capacity of the means of transport to meet the users' needs. Satisfaction is achieved by offering an optimal service that meets the minimum requirements demanded by users [60].
3. Characterization of transport and vehicle fleet: the vehicle fleet comprises a set of vehicles used to transport users; the characterization determines the mobility dynamics and general characteristics of the vehicle fleet [34].
4. Socioeconomic characterization: determines the socioeconomic attributes of users associated with transportation systems. These attributes are related to the household's disposable income. The output is the disposable income destined for the consumption of essential products and the maintenance of one's own means of transport or use of public transport [36].
5. Emissions: release of atmospheric pollutants from fixed sources such as industry and electricity generation or mobile sources such as transport and cargo vehicles [8].
6. Diseases, accidents, and deaths: main adverse health effects caused by transport and emissions. Long-term exposure to air pollutants can cause cardiovascular diseases, respiratory diseases, lower life expectancy, and a higher incidence of lung cancer [40].
7. Impact on the environment: an overview of the adverse environmental effects (air, climate, and natural habitats) caused by modes of transport in atmospheric emissions and noise pollution [47].
8. Regulation, government, and public policy: intervention policies that control the use and growth of means of transport: regulation that applies to both vehicles and their emission levels, trying to keep these levels below an average [59].
9. Land use and transportation infrastructure: amount of land used to developof public infrastructure and space necessary for mobility. Its purpose is to reduce distances, travel times, transport costs and improve transport efficiency [66].
10. Energy use and consumption: energy resources necessary for the operation of transport. It is the amount of energy used associated with the fuel consumption of vehicles and other means of transport [34].

11. Financial values: financial components associated with users and means of transport [51].

A total of 314 indicators were found in the selected literature, which were refined to include only those used in at least one conceptual framework or an analytical model and cited in the literature by at least two authors, resulting in 244 indicators. With this sample, a Pareto analysis was performed using the number of works cited and used each indicator as a criterion. For this, an ABC classification was constructed following the guidelines of [67]. Table 5 presents the analysis results, classifying the sample of indicators into the eleven proposed categories. Of the sample obtained (244), 91 indicators correspond to 65% of the citations in the literature, 86 indicators correspond to 25% of the citations, and the remaining 67 correspond to 10%, these being categories A, B, and C of the Pareto classification, respectively. In category A, air pollutant transport emissions indicators are the most frequent in the literature, used in ten conceptual frameworks, seven analytical models, and cited by 23 authors.

Table 5. Classification and analysis of indicators

	Indicators			Citations		A		B		C	
Category of Indicators	Counts	Complies	%	Counts	%	91	37%	86	35%	67	27%
Accessibility	9	8	89%	27	4%	6	7%	1	1%	1	1%
Quality	17	13	76%	36	5%	7	8%	4	5%	2	3%
Characterization of transport and vehicle fleet	86	70	81%	178	26%	24	26%	35	41%	11	16%
Socioeconomic characterization	40	32	80%	64	9%	7	8%	10	12%	15	22%
Emissions	16	10	63%	63	9%	5	5%	1	1%	4	6%
Illnesses, accidents, and deaths	10	10	100%	39	6%	4	4%	3	3%	3	4%
Impacts on the environment	26	15	58%	46	7%	7	8%	1	1%	7	10%
Regulation, government, and public policy	21	13	62%	35	5%	5	5%	5	6%	3	4%
Land use and transport infrastructure	29	24	83%	57	8%	7	8%	11	13%	6	9%
Energy use and consumption	15	11	73%	46	7%	5	5%	6	7%	0	0%
Financial values	45	38	84%	91	13%	14	15%	9	10%	15	22%
Totals	314	244	78%	682							

Source: Own source

The integrated evaluation of transport sustainability based on indices and indicators presents an important obstacle: as indicated in the literature [17], the high level of subjectivity, both in the selection of indicators for the construction of indices and in their evaluation, generates complexity due to the qualitative nature of several criteria, in particular concerning social and institutional aspects, making the evaluation a subjective practice. Additionally, the complex causal links and the difficulty of integrally distinguishing the impacts of sustainability result in using a diverse terminology of indicators, generating similar definitions with different names. For example, in the sample of indicators identified, there are cases such as the use of energy in transport and fossil fuel energy for transport, two indicators that have the same connotation; however, each author proposes a different name for them. This means that many indicators overlap thematically or are almost identical, generating a dispersed volume of concepts and uncertainty related to the data used. The characterization of the literature shows the need to unify criteria both in the naming and definition of indicators and in their selection, guaranteeing an objective evaluation based on indices and comprehensive indicators of sustainability.

It was necessary to create categories, which allowed us to demonstrate the lack of common terminology and address, through grouping, the conceptual bias to overcome the obstacle of variability in terminologies in the use of indicators. The validation process consisted of reviewing the definition given by each author and comparing it with that given by other authors for indicators with similar names to perform the grouping processes. An example of this was the indicator of air pollutant transport emissions, a result of the grouping of indicators proposed by 23 different authors, who proposed different names for this indicator. Categorization is a necessary task not only to create common terminologies but also to facilitate the analysis of sets of indicators in a given context.

Conclusions

A characterization of the methodologies for the integrated evaluation of the sustainability of urban transport (MIES-UT) has been presented, developed through a structured review of the literature, and the analysis with a proposed taxonomy that, based on three previous works, includes the study of conceptual frameworks, analytical models, indices, and indicators. The characterization increased the scientific and institutional literature dedicated to MIES-UT in the last two decades. However, it was also evident that despite the increase, there is still a latent need to develop more integrated methodologies that simultaneously include the dimensions of the TBL and the relationships between its components. Similarly, it was found that most of the works are carried out in developed countries, while only 18% correspond to developing countries, and only two of them are from Latin America.

The identified frameworks show a wide diversity in the conceptual bases used to evaluate sustainability, which also makes it complex to define a single strategy for the MIES-UT [68]. As in previous findings in the literature, the social dimension of sustainability is the least studied (42%). There is a need to include causal relationships between the three dimensions of TBL explicitly. It is also evident how the conceptual bases are defined in a greater proportion by institutional works (58%), and only 17% of the selected sample presents the application of MIES-UT. The adaptation of conceptual frameworks to the dynamics of developing countries constitutes a future opportunity. Only two sample works are carried out in these countries, showing the research gap in this subject.

The characterization of analytical models also showed a diversity of integrated numerical techniques, in which methods such as MCDM, AHP, and fuzzy logic predominate. Only two works use methods that provide a comprehensive view of sustainability with system dynamics and AHP. It was also found that most of the works in the literature focus on cases from the United States and China. Like the findings in [16], the available works focus primarily on European cases. No MIES-UT based on analytical models was found that was oriented to study in developing countries or Latin America, again confirming a research opportunity.

The analysis of indices and indicators showed opposing opinions regarding the use of composite indices due to the subjectivity involved in the use of weighting methods dependent on the opinions of experts [57]. On the other hand, no indices applications were found to measure the sustainability of transport in developing countries in the selected sample. In addition, despite the attempts made by some international institutions, especially the European Union, to group and categorize sustainability indicators, there is no homogeneity in the categorization or terminology that guarantees a comprehensive evaluation of sustainability in transport, making it difficult to analyze existing indicators. In this way, this work proposes categorizing indicators in the MIES-UT in developing countries. It is recognized as a research opportunity to apply these categories to cases in developing countries that allow their delimitation.

The MIES-UT applicable to developing countries includes the *Transportation Sustainability Index for a Livable City,* the respective analytical model applied in Taiwan [63], the conceptual framework *Performance Assessment and Evaluation Method for Passenger Transportation* applied in Brazil [35], and the *Social Sustainable Evaluation Framework* in India [14]. In addition, there is the use of some indicators in Brazil [57], where the MIES-UT mainly focuses on the social dimension. Developing countries constitute an opportunity for work and research on the MIES-UT, mainly due to the socio-economic problems that have a more significant role, as well as the high indices of poverty, failure to meet basic needs, and rapid urbanization.

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