Transportation Research Part A 179 (2024) 103939

Contents lists available at ScienceDirect

Transportation Research Part A

journal homepage: www.elsevier.com/locate/tra

A composite index for the evaluation of sustainability in Latin American public transport systems

Alexandra Velasco [a,b,*], Regine Gerike [a]

[a] Institute of Transport Planning and Road Traffic, "Friedrich List" Faculty of Transport and Traffic Sciences, TUD Dresden University of Technology, Dresden, Germany

[b] Fraunhofer Institute for Transportation and Infrastructure Systems IVI, Dresden, Germany

ARTICLE INFO

Keywords:
Transit sustainability analysis
Composite index
Sustainable Latin American public transport
Normalization, sustainability assessment

ABSTRACT

Latin American public transport (PT) systems are the backbone of urban transport with high ridership levels but at the same time, they face substantial deficits in terms of their sustainability. No comprehensive framework for PT sustainability assessment exists so far that is tailored to the specific local situation in this region. Therefore, this study develops for the first time a theoretically sound and feasible index for assessing the sustainability of PT systems in Latin America, the Sustainable Public Transport Index for Latin America (SPTI-LATAM). The index is based on an Assessment Indicator Model (AIM) with overall 49 indicators in the five dimensions system effectiveness, social, environmental, economic, governance and integrated transport planning. The SPTI-LATAM is designed with three levels: 1) the basic index (BSPTI) containing 32 indicators; 2) the extended index (ESPTI) including 11 additional indicators; and 3) the global index (GSPTI) with 6 additional indicators. The BSPTI is computed for eleven case study cities to demonstrate its feasibility and to analyze the sustainability of PT systems in the region. The framework uses the Equal Weighting Aggregation (EWA) method for assigning weights to each indicator, the Weighted Sum Model (WSM) for aggregating the indicators to the overall index and international standards and benchmarks for normalization. The final scores of the BSPTI show that the case study cities have still challenges to reach sustainability since only two cities had scores slightly higher than the half of achievable points (55 and 51), while eight cities had scores between 40 and 50 points, and one city achieved 39 points. Deficits are identified mainly for PT service quality, for the environmental performance, for the governance dimension and less for PT system coverage. Overall, the analysis of the BSPTI-LATAM for the 11 case study cities shows that the index is suitable for benchmarking sustainability of local PT systems and ready to be used in research and practice.

1. Introduction

The goal of sustainable development is the widely accepted high-level normative framework for today's policy making in all sectors at all levels, beginning at the global level with the Sustainable Development Goals (SDGs) as adopted by the United Nations in 2015 (United Nations, 2016). There is no one single specific SDG for transport but many SDGs are relevant and the general idea of

* Corresponding author at: Alexandra Velasco, Institute of Transport Planning and Road Traffic, "Friedrich List" Faculty of Transport and Traffic Sciences, TUD Dresden University of Technology, Hettnerstr. 1, 01069 Dresden, Germany.

E-mail address: alexandra.velasco@tu-dresden.de (A. Velasco).

https://doi.org/10.1016/j.tra.2023.103939

Received 7 July 2023; Received in revised form 8 October 2023; Accepted 7 December 2023

Available online 24 December 2023

0965-8564/

sustainable development can be translated to the transport context, this is to meet "the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987). Transport systems need to provide accessibilities for all groups of all societies today and in the future, they need to enable persons (and goods) to reach their desired destinations as the basis for satisfying their needs. SDG 11 "Sustainable Cities and Communities" and particularly Target 11.2 describe these responsibilities of transport systems for enhancing sustainable development:

By 2030, provide access to safe, affordable, accessible, and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons (United Nations, 2016).

Various further SDGs and targets address the need to minimize negative effects of transport and to respect the earth's limited carrying capacities in order to ensure this access forever, for all today's and future generations.

Public transport (PT) is in the focus of Target 11.2. It is, in combination with the active modes walking and cycling and the emerging innovative mobility services such as sharing, pooling, or hailing, one core backbone of sustainable transport systems. PT systems have high capacities and can carry large amounts of people efficiently in terms of space, financial and environmental resources; they are inclusive and available for all parts of society, and they are suitable for short- and long-distance transport.

Various indicator systems for measuring progress of PT systems towards the goal of sustainable development have been developed in academia and by policy institutions (Guimarães et al., 2018; Di Yao et al., 2019). They are often organized along the three dimensions of social, economic, and environmental sustainability which are referred to as the triple bottom line (TCRP, 2019). Frameworks exist for comparing PT systems and for benchmarking their sustainability status (Currie & de Gruyter, 2018), for ex-ante assessments of planned policy interventions (Farooq et al., 2019), for ex-post evaluations of completed PT projects (Rao, 2021) and for optimizing PT services by minimizing the resources needed to achieve the sustainability ambition (Ammenberg & Dahlgren, 2021).

Most of these indicator systems focus on Europe, North America, and parts of Asia; hardly any indicator system for operationalizing sustainable PT exists for Latin America (Velasco Arevalo et al., 2023). This is a major gap seeing the high importance of PT in this region in combination with the substantial need to improve its services. Around 56 % of urban trips are made on PT systems in Latin America (CAF, 2016), half of the users are women who are more exposed to aggressions (ONU-Habitat, 2012), low incomerś mobility mainly relies on PT, especially for those living in the outskirts of cities (CAF, 2011). These high PT shares can be applauded from the sustainability point of view, they should be maintained and increased in the future but with growing societal welfare and income this needs substantial improvements in PT service quality. So far, the share of public transport is decreasing over time in the region whereas private motorized is increasing. Some cities have witnessed a considerable reduction in their PT shares, i.e., Santiago de Chile had 60 % PT share in 1991 and 45 % in 2012, and Bogotá passed from 60 % in 2005 to 50 % in 2015. At the same time, the motorization rate in Latin America has increased with an average annual growth of 4,7% (Rivas, M.E., et al., 2019). In 2012, 85 % of the Latin American PT fleet were diesel buses and microbuses (ONU-Habitat, 2012) leading to around 1,300 tons of local pollutants (CO, NOx, HX, and MP10) and 90,000 tons of CO2 every day (CAF, 2016).

In addition to this high relevance, Latin American PT systems have further specific characteristics that differ from PT systems in the Western World and require specific indicator systems tailored to this region. Aggression in PT vehicles and stations is a major issue in Latin America, particularly for women. In 2016 in Asunción (Paraguay) and Lima (Perú), 38 % and 49 %, respectively, of PT female users reported any type of harassment while in Colombia, the percentage reached 60 % of female users suffering any type of sexual aggression in PT (Galiani & Jaitman, 2016).

Paratransit as informal PT, which is characterized by unscheduled operations, atomized ownership, and the use of smaller vehicles is another typical characteristic of PT systems in Latin America. Paratransit offers transport options to many people, especially low incomers living in the outskirts of the cities (Venter et al., 2018), but it also comes with challenges such as the low coordination of services, old and inefficient vehicles as well as the bad working conditions for the staff (Cervero & Golub, 2007).

The existing PT indicators systems do not cover these specific realities for Latin America (Dobranskyte-Niskota et al., 2009; European Commission, 2020; Victoria Transport Policy Institute, 2021); some require traffic models, spatial analysis and field surveys that are difficult and expensive to apply on a regular basis (WBCSD, 2016; Jasti & Ram, 2019a; Awasthi et al., 2018); some list indicators are not suitable due to the gap in the technical maturity of PT systems (Ammenberg & Dahlgren, 2021; Chen & Wu, 2013; Lin et al., 2021); some indicators of high relevance for sustainable PT operation in Latin America such as paratransit, female users harassment, security or gender exclusion in PT operation are missing in the existing indicator systems.

To fill this gap, this study develops the Sustainable Public Transport Index for LATin AMerica (SPTI-LATAM) with the ambition to incorporate all relevant sustainability dimensions, to consider the specific characteristics of PT systems in this region and to allow for applications from all stakeholders' perspectives including users, municipalities, operators, and the whole society. The SPTI-LATAM is set up for comparison and benchmarking of PT systems, it should reliably measure progress towards sustainability ambitions and at the same time it should provide flexibility to be adapted to local conditions and to consider specific needs and transport systems. The new index is directly applied to eleven case study cities in Latin America to demonstrate its feasibility and to investigate the sustainability of each of the PT systems. Besides comparisons of PT systems between cities and regions, the SPTI-LATAM should also support monitoring over time for individual cities or regions as the basis for identifying and reporting progress in order to purposefully design policy measures to reach sustainability ambitions.

The article is organized as follows: the next section two provides an overview of relevant literature followed by the third section which introduces the methodology for developing the SPTI-LATAM and its characteristics. The fourth section presents the results of the application of the SPTI-LATAM for the eleven case study cities. Discussions about the outcomes of the index and important lessons for the implementation of a sustainable PT system are underpinned in section five and finally, the sixth section comes with limitations and conclusions about the SPTI-LATAM.

2. Related literature

Velasco Arevalo et al., (2023) provide a comprehensive overview of academic and non-academic frameworks and indicators for measuring PT systems' status and progress towards the sustainability ambition. Most of the identified references focus on local case studies probably mainly for reasons of limited comparable and up-to-date data of sufficient quality at higher spatial levels. The very few Latin American case studies are all located in Brazil. One study develops a model for PT sustainability evaluation in Florianápolis (Barbosa et al., 2016) and two more studies focus on the ex-post evaluation of PT services in downtown Rio de Janeiro and Niterói (Guimaraes & Leal, 2017; Guimarães et al., 2018).

The traditional reference dimensions for assessing sustainability of different systems are environment, society, and economy. However, urban public transport systems cannot be sustainable if they do not balance demand and supply, if they do not incorporate the various local stakeholders' perspectives and preferences and if they are not well integrated into the long-term urban planning instruments. These aspects should be addressed in an evaluation framework with defined goals to monitor progress and tackle adequate measures (Gerike & Koszowski, 2017). The characteristics of PT demand and supply and their interaction as the core mechanism of the system to achieve effective services are considered in many of the researched studies in a system effectiveness dimension (Diana & Daraio, 2014; Miller et al., 2016). Governance and participatory aspects are included in some references as single indicators or as dedicated dimensions which are called e.g., urban planning (Karjalainen & Juhola, 2019) or governance and public policies (Ribeiro et al., 2020; Zhang et al., 2018).

Velasco Arevalo et al. (2023) identify more than 160 different indicators in their review on PT sustainability evaluation frameworks. Indicators are mostly organized along sustainability dimensions, most frameworks include indicators for the system effectiveness dimension, very few frameworks cover governance and planning issues. Indicators in the environmental dimension are most consistent with greenhouse gas emissions, air pollutants and energy consumption being the most frequently used (see e.g. (Currie & de Gruyter, 2018)). Typical indicators in the economic dimension include revenues (Awasthi et al., 2018), operating cost (Dawda et al., 2021) and travel costs for users (Keshavarz-Ghorabaee et al., 2021). The highest numbers of indicators are found in the social and system effectiveness dimensions showing the importance of these aspects but also the diversity of indicators used to measure similar effects such as service quality. Average travel time and speed (Awasthi et al., 2018), PT service reliability (Karjalainen & Juhola, 2019), frequency (Dawda et al., 2021), fleet size and ridership (Currie & de Gruyter, 2018) are the most frequently used indicators in the system effectiveness dimension. For the social dimension, these are vehicle occupancy (Rasca & Hogli Major, 2021), coverage of PT networks (Dawda et al., 2021), safety (Currie & de Gruyter, 2018), affordability and accessibility particularly for people with reduced mobility (Awasthi et al., 2018). Indicators on urban planning and governance are rarely included in the existing indicator systems. This is a deficit from the sustainability point of view seeing that the success of PT systems heavily depends on land-use pattern and effective political decision making. Karjalainen and Juhola (2019) include public participation, transparency in decision making, regional cooperation and transit-oriented development in their indicator system which is a promising approach to address this deficit. Relevant indicators addressing the specific characteristics of Latin American PT systems such as paratransit, gender violence or low technology are missing.

In Latin America, very few cities and/or countries apply evaluation frameworks for public transport. Velasco Arevalo et al (2023) identify six evaluation frameworks produced by local or national governments in this region (Fonadin, 2016; Ministerio de Transporte de Colombia, 2009; Ministerio de Transportes y Telecomunicaciones de Chile, 2018; Protransporte, 2014; Secretaría de Movilidad DMQ, 2021; ANTP, 2017). None of these frameworks include governance, the linkage between sustainable transport plans and land use plans, paratransit, or gender issues, which are persistent problems in the region.

Three main types of PT sustainability evaluation frameworks can be distinguished, this is (1) Multi-Criteria Decision Making (MCDM), (2) Assessment Indicator Models (AIM) and (3) Performance Evaluation Models (PEM) (Velasco Arevalo et al., 2023). MCDM is the most diverse group of techniques for generating preferences among different possible alternatives based on pairwise comparisons e.g., in Analytical Hierarchy Processes (AHP) (Awasthi et al., 2018), distance measurements to pre-defined goals such as TOPSIS (Technique for Order Performance by Similarity to Ideal Solution) (Hamurcu & Eren, 2020) or outranking models like PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation) (Farooq et al., 2019).

AIM combine different indicators to composite single-level indices, multi-level indices or multi-dimensional matrices (Awasthi et al., 2018). One of the most common methods is the Composite Index (CI) that relies on the use of techniques for normalization, weighting and aggregation (Miller et al., 2016). Normalization as the first step means the mathematical transformation of the individual indicators with their different units of measurement into one common unit or to dimensionless entities (Illahi & Mir, 2020). The most common normalization methods in the literature are the simple reversion method, z-score method, the distance to reference based approach, and the minimum–maximum method (Haghshenas & Vaziri, 2012; Miller et al., 2016; Lopez-Carreiro & Monzon, 2018; Sałabun et al., 2020). Z-score transformations are often applied, they convert the individual indicators to a common scale with a mean of zero and standard deviation of one (El Gibari et al., 2019). Minimum – maximum scales are often used as normalization approach when no reference values are available. Second, the normalized indicators need to be weighted before they can be aggregated in the third step to the final AIM scores. The Equally Weighted Average method (EWA) which assigns equal weights to all indicators or groups of indicators (Currie et al., 2018) and the Budget Allocation Process (BAP) are the two most common techniques for weighting. BAP requires stakeholders to allocate a "budget" of points to the whole set of indicators reflecting their individual knowledge and preferences (Alonso et al., 2015; Dobranskyte-Niskota et al., 2009). The Weighted Sum Model (WSM) as the additive aggregation and the Weighted Product Model (WPM) as the geometric aggregation are the two identified techniques in AIM for aggregating the standardized individual indicator values (Triantaphyllou, 2000). The WSM is a fully compensatory method where sum-up techniques are applied to construct the composite index. With this technique, bad performance in certain single indicators can be compensated by

Table 1
Selected dimensions and goals for the SPTI-LATAM.

Dimension	PT sustainability goals
Environmental	Minimize negative environmental effects from PT system operation including emissions of air pollutants, greenhouse gases and noise, use of energy and natural resources, space consumption
Social	Provide accessibility with PT to all destinations and areas for all user groups at any time, minimize negative social effects such as gender violence, crime or accidents
Economic	Provide efficient services from the operator perspective in terms of cost-benefit ratios and revenues, from society perspective in terms of cost for service provision, from user perspective in terms of affordability and prices, strengthen local economies
System Effectiveness	Provide PT services that are tailored to user needs and that maximize uptake
Governance and Integrated Transport Planning	Develop governance frameworks that promote citizen engagement and that allow for integrated, comprehensive, and inclusive PT planning as one component within urban and regional sustainable development ambitions

good performances in others (El Gibari et al., 2019). Its mathematical expression is $A_i^{WSM} = \Sigma\, W_j X_{ij}$, meaning that for alternative *i* the A_i^{WSM} is equal to the sum of the product of each indicator X_{ij} multiplied by its weight W_j. In contrast, the WPM is a partial compensatory technique (El Gibari et al., 2019) where the geometric product of the indicator values is obtained by assigning weights in the power function to each indicator and by subsequently multiplying all weighted indicator values to get the final score: $A_i^{WPM} = \Pi\, X_{ij}^{Wi}$.

PEM optimize target functions such as PT performance or profit given specific constraints such as limited financial or environmental resources (Di Yao et al., 2019). Data Envelopment Analysis (DEA) is a frequently applied type of PEM, that seeks to maximize the efficiency of Decision-Making Units (DMUs) measured as the ratio of outputs over inputs (Dawda et al., 2021).

3. Methods for a sustainability index for public transport in Latin America

The presentation of methods and data in the following Section 3 is divided into 6 sub-sections: The concept for the SPTI-LATAM is developed in Sections 3.1–3.3 in a top-down approach. First, the Assessment Indicator Model (AIM) is chosen as the framework and five dimensions are selected in Section 3.1. Second, the three levels of SPTI-LATAM are introduced in Section 3.2 and third, the indicators for each of the three levels are selected in Section 3.3. Sections 3.4–3.6 describe then the implementation of the SPTI-LATAM concept including the approaches for normalization (Section 3.5), weighting and aggregation (Section 3.6) as well as the description of the study areas and data collection (Section 3.4).

3.1. Evaluation framework and dimensions

We choose an Assessment Indicator Model (AIM) because the goal of this research is to compare and benchmark PT sustainability performance by means of performance indicators arranged in multi-level indices. Specifically, we use a Composite Index as the most frequently used AIM approach which is also easier to use and to interpret than MCDM or PEM methods thanks to the three steps of normalization, weighting and aggregation of the individual indicators (Miller et al., 2016).

Besides the three traditional sustainability dimensions (*Environmental*, *Social*, and *Economic*), we incorporate two additional dimensions in the index as shown in Table 1. This is (1) *System Effectiveness*, and (2) *Governance and Integrated Transport Planning* since sustainable urban PT cannot be achieved without integrated planning approaches, coordination with urban and regional planning and citizen engagement.

3.2. Three levels of SPTI-LATAM

Due to the different levels of development and evolution of PT systems in Latin American cities, a flexible approach is needed to intentionally leave room for cities to monitor progress towards sustainability goals according to local capacities and data availability. The SPTI-LATAM is therefore set up with three levels: The basic index at the lowest level already measures PT sustainability comprehensively but is limited to the core indicators needed to meet this ambition. The extended and global indices at the second and third level add further indicators and give overall a complete picture of all relevant aspects of PT sustainability:

- **The Basic Sustainable Public Transport Index (BSPTI):** The BSPTI includes 32 indicators in all five sustainability dimensions that are based on commonly available standard data sources. The indicators are chosen from the most cited indicators in the literature (Velasco Arevalo et al., 2023), as well as based on considerations of data availability and the relevance of the indicators for sustainability. Since 55 % of PT users in Latin America are women (Linke et al., 2018), we propose the inclusion of actions for female safety in PT systems (y/n) as one simple indicator on gender equity into the BSPTI in order to consider this aspect already in the lowest level of the SPTI and to monitor the policy measures taken by authorities and/or operators to reduce gender violence at PT systems.
- **The Extended Sustainable Public Transport Index (ESPTI):** This index includes 11 further indicators in all five sustainability dimensions. The ESPTI adds characteristics of paratransit services and their impacts, indicators on vehicle technologies and on effects that are already covered by the BSPTI but that are now measured in more detail.

Table 2
Sustainable Public Transport Index for Latin America – SPTI-LATAM.

Specific goals	Category	Selected indicators	↑↓ Sust*	Basic	Extended	Global
System effectiveness Dimension						
To provide PT services that are tailored to user needs and that maximize uptake	a. PT usage	Formal PT share (%)	↑	x		
		Average trip time (min)	↓	x		
		Index passenger per km IPK (pass/km)	↑	x		
		Paratransit mode share (%)	↓		x	
	b. PT supply	PT fleet size (# veh/1,000 inh)	↑	x		
		Payment automatization (E-ticketing veh/total PT fleet)	↑	x		
		Operating time of formal PT (hours/day)	↑	x		
		Average speed (km/h)	↑	x		
		Exclusive lanes for PT (km/100,000 inh)	↑	x		
		Frequency (veh/hour)	↑		x	
Social Dimension						
To improve accessibility to PT services and connections to all destinations and areas and promote social equity through user's affordability	a. PT accessibility & affordability	PT network coverage (km/ urban area in km^2)	↑	x		
		Average user trip distance (km)	↓	x		
		Accessible PT stations/stops (%)	↑	x		
		Accessible PT vehicles (%)	↑	x		
		Income devoted to PT (%)	↓	x		
		Average household distance to nearestPT stop/station (m)	↓		x	
To reduce accidents, crime exposure and gender violence and promote intergenerational inclusion in PT systems	b. PT safety, security & gender inclusion	Fatalities/injured people in formal PT (#fatalities/injured people per 1,000 pkm)	↓	x		
		Fatalities/injured people at paratransit (%)	↓		x	
		Ratio of annual recorded crime incidents/total pkm (%)	↓			x
		Actions for female safety in PT system (y/n)	↑	x		
		Gender violence in PT (% female aggression/total female users)	↓		x	
		Female drivers in PT fleet (%)	↑		x	
		Drivers between 50 and 65 y-o (%)	↑			x
To provide high quality service for customers	c. Rider comfort & customer services	PT fleet with air conditioning (%)	↑	x		
		Average PT occupancy rate (%)	↓		x	
		PT vehicles with on-board information systems (%)	↑	x		
		PT stops/terminals with passenger information (%)	↑	x		
Environmental Dimension						
To preserve environmental quality and public health	a. Air pollution & climate change	CO_2 emissions (g/pkm)	↓	x		
		PM_{10} emissions (g/pkm)	↓	x		
		NOx emissions (g/pkm)	↓	x		
		CO emissions (g/pkm)	↓		x	
To promote clean technologies and reduce energy consumption and the use of fossil fuels in PT systems	b. Clean technologies & reduced energy consumption	Average PT fleet age (y)	↓	x		
		Low-or zero emissions PT vehicles (% /total PT fleet)	↑	x		
		Share of pkm travelled by low/zero emissionvehicles (% pkm)	↑		x	
		Electricity from renewable energies consumption (MJ/pkm)	↑		x	
		Fuel/oil consumption (MJ/pkm)	↓		x	
Economic Dimension						
To maximize cost recovery and minimize cost expenditures	a. PT operation efficiency	Passenger km per capita (pkm/inh)	↑	x		
		Annual costs recovery ($USD passenger revenues/total operating costs in $USD)	↑	x		

(*continued on next page*)

Table 2 (*continued*)

Specific goals	Category	Selected indicators	↑↓ Sust*	Basic	Extended	Global
		Vehicle productivity (Veh-km/day)	↑	x		
	b. PT operators̕ revenues and expenditures	Annual operating cost per pkm ($USD/pkm)	↓	x		
		Users' costs ($USD/trip)	↓	x		
		PT subsidies (%/total PT cost)	↑	x		
To create job opportunities and foster sustainable economic development	c. Jobs creation	Direct jobs in formal PT (#jobs/million passenger-trips)	↑			x
		Direct jobs in paratransit (# jobs/million passenger-trips)	↓			x
Governance and Integrated Transport Planning Dimension						
To enhance the coordination with urban planning	a. Integrated and inclusive transport planning	OD surveys in the last 5 years for the city (y/n)	↑	x		
		SUMP based on OD survey results and aligned with SDGs and Land Use Plans (y/n)	↑	x		
		Regular monitoring and evaluation for PT systems (y/n)	↑	x		
	b. Regional planning	Existence of regional integration plans (y/n)	↑			x
To promote active citizen participation in transport planning	c. Citizen Engagement	Transport projects that follow a public participation plan (%)	↑			x

*"↑" refers to an indicator for which a higher value is desirable for sustainability, while "↓" refers to an indicator for which a lower value is desirable for sustainability.
Inh = inhabitants; pkm = passenger-kilometer; OD = origin–destination; SUMP = Sustainable Urban Mobility Plan; SDG = Sustainable Development Goal.
Source: Adapted from Gruyter et al., 2017; Currie & de Gruyter, 2018; Currie et al., 2018; Oses et al., 2018, Jeon et al., 2013; Sdoukopoulos et al., 2019; Ribeiro et al., 2020; TCRP, 2019; Diana & Daraio, 2014; Eboli & Mazzulla, 2012; Nardo, 2005; Alonso et al., 2015; Gerike & Koszowski, 2017; Velasco Arevalo et al., 2023.

- **The Global Sustainable Public Transport Index (GSPTI):** The GSPTI with overall 49 indicators is the most demanding level of the SPTI in terms of data availability. It adds indicators on job opportunities in the economic dimension, on crime and PT drivers' age in the social dimension and on regional planning and citizen engagement in the governance dimension. All these indicators address important aspects of PT sustainability, but their measurement is demanding, and few cities have the capacities to collect the necessary data.

In each of the three SPTI-levels, a maximum score of 100 points can be achieved. The overall score indicates the progress towards the final sustainability ambition for local PT systems.

3.3. Selection of indicators

Indicators should be selected based on a sound theoretical understanding of PT sustainability. Indicators should cover all relevant aspects in the five sustainability dimensions, they should be consistent, measurable, understandable and applicable for communication to the wider public, accessible in terms of data availability, and suitable for formulating reference values in the form of thresholds or goals (Haghshenas & Vaziri, 2012; Sdoukopoulos & Pitsiava-Latinopoulou, 2017). As a basis, we select the most frequent indicators cited by authors included in the literature review for sustainable public transport in Velasco Arevalo et al (2023). Then we consider the specific conditions and challenges for Latin American PT systems such as paratransit, obsolete vehicle technologies and gender violence as core requirements for a comprehensive set of indicators focussing on this region. In addition to the selection of indicators, the direction of sustainability ambitions needs to be assigned. For example, lower levels of CO_2 emissions but higher PT ridership are beneficial for sustainability. Table 2 summarizes the indicators for all three levels of the SPTI including the sustainability dimensions, specific goals, and categories as well as the direction of the sustainability ambition. A complete summary with the description of categories and indicators included in the BSPTI, which is applied for the case studies in this research, is presented in the Appendix A.

For the final calculation of the SPTI for public transport in Latin America, we establish a four-step procedure: 1) the generation of the indicator values, 2) normalization of the original values, 3) weighting of the normalized values, and 4) the calculation of the weighted sum of normalized values for each dimension.

3.4. Study areas and data collection

In this study we analyze eleven cities with the BSPTI as shown in Table 3. The selected cities are part of the Urban Observatory of Mobility of the Andean Development Corporation (CAF, 2016) and represent typical Latin American cities: some are very large and highly populated cities, others are medium-sized cities, some are coastal cities, and others are located in the mountains, also

Table 3
General data of the case study cities in Latin America.

	Abbreviation	Urbanized area (km^2)	Population (2019)	Urban population density (inh/km^2)	Per capita income of the bottom quintile ($USD) (2019)
Área Metropolitana de Buenos Aires	**BA**	3,830	12,801,365	3,342	139
Bello Horizonte	**BH**	603	2,512,070	7,619	158
Bogotá	**BOG**	478	7,181,469	4,907	224
León	**LE**	537	1,721,215	1,409	90
Lima	**LI**	731	9,674,755	13,235	73
Medellín	**MED**	376	2,376,337	5,820	180
Mexico City	**MEX**	2,609	9,209,944	3,530	125
Montevideo	**MON**	201	1,382,579	6,889	350
Quito	**QUI**	372	2,501,011	5,401	87
Río de Janeiro	**RIO**	1,200	6,626,511	4,781	86
Santiago de Chile	**SAN**	641	7,014,702	8,497	126

population density varies largely. In addition to a good representation of typical Latin American cities, data availability was also one relevant criterion for the selection of the case study cities.

For collecting data on the indicators in the BSPTI, the authors approached all cities and asked for support. Data was provided by the municipalities of Bogotá, Belo Horizonte, Medellín, Montevideo, and Quito. The missing data was obtained from various publicly available online secondary sources. Data was collected between 2020 and 2022. The sources consulted for the eleven cities are shown in Table 4, they are the basis for the analysis in Section 4.

3.5. Normalization and reference values for indicators

Normalization is done based on international standards or benchmarks. International standards for air pollutant emissions or noise are prominent examples which are set by legitimized organizations and are usually legally binding. International benchmarks are created by expert organizations such as UITP or ONU-Habitat based on comparisons of specific indicators for different case studies (e. g. cities or countries). Indicator values for the case studies with the best performance are usually chosen as benchmarks which serve as target values for the others.

Standards respectively benchmarks exist in two directions: Standards for air pollutant emissions are examples for minimum objectives; sustainability performance improves when air pollutant emissions decrease; sustainability ambitions are met when the standards are achieved. The opposite holds for maximum objectives such as PT fleet size; sustainability performance improves with increasing indicator values until the benchmark or standard is reached and the sustainability ambition is met. Maximum or minimum objectives are one boundary of the normalization function, the second boundary (maximum value or minimum value) is set by the authors based on the literature or indicator values from the own sample of case study cities. Minimum or maximum values from the own sample are also used as proxies for objectives if no standards or benchmarks could be identified for specific indicators.

Equations (1) and (2) illustrate the approach for computing the normalized indicator values X^n for variables with interval scale, discrete values are set for indicators with ordinal scale such as the existence of instruments for regular monitoring and evaluation of PT policies. Equation (1) is applied for maximum objectives when the indicator is proportional to sustainable PT and equation (2) for minimum objectives when the indicator is inversely proportional to sustainable PT.

$$\begin{cases} 1 \text{ if } X_i & \geqslant \text{maximum } objective \\ \dfrac{X_i - \text{minimum } value}{\text{maximum } objective - \text{minimum } value} & for \text{ minimum } value < X_i < \text{maximum } objective \\ 0 \text{ if } X_i & \leqslant \text{minimum } value \end{cases} \quad (1)$$

$$\begin{cases} 1 \text{ if } X_i & \leqslant \text{minimum } objective \\ 1 - \dfrac{X_i - \text{minimum } objective}{\text{maximum } value - \text{minimum } objective} & \text{for maximum } value > X_i > \text{minimum} objective \\ 0 \text{ if } X_i & \geqslant \text{maximum } value \end{cases} \quad (2)$$

The use of international standards or benchmarks as reference values for the normalization function allows to measure progress towards the sustainability ambition which is met when the maximum or minimum objectives are achieved. The maximum achievable points X^n are limited to one hundred, no more points can be achieved when the target value is exceeded to avoid compensation between indicators with very strong performance reaching out far beyond the pre-defined objectives and other indicators with very low performance.

For some indicators the minimum objective might be difficult to achieve in developing countries because of their low standards in vehicle technology and infrastructures in combination with dynamically growing volumes of motorized vehicles. Emissions of air pollutants are again one example; international strict standards should be used as maximum objective, but these standards require

Table 4
Data sources per city and type of data.

BA	BH	BOG	LE	LI	MED	MEX	MON	QUI	RIO	SAN
PT usage / PT supply / Rider comfort & customer services										
Bondorevsky & Estupiñán, 2018; Ministerio de Transporte de Argentina, 2018	ANTP, 2017; Data provided by authorities	Data provided by authorities; Alcaldía de Bogotá, 2019	CAF, 2016	CAF, 2016	CAF, 2016	Secretaría de Movilidad de la Ciudad de México, 2019	Intendencia de Montevideo, 2019; Rivas et al., 2019	Data provided by authorities	Instituto Pereira Passos, 2017	DTPM, 2019; Rivas et al., 2019
PT accessibility& affordability										
Buenos Aires Ciudad, 2020	ANTP, 2017	Transmilenio, 2022	Dirección de Movilidad de León, 2022	Lima Cómo Vamos, 2021; Rivas et al., 2019	Alcaldía de Medellín, 2020	Gobierno de la Ciudad de México, 2022	Data provided by authorities; Rivas et al., 2019	Data provided by authorities	Instituto Pereira Passos, 2017; Summit Mobilidade Urbana, 2021, 2019	DTPM, 2019
PT safety, security & gender inclusion										
Ministerio de Transporte de Argentina, 2018; Buenos Aires Ciudad, 2020	Prefeitura Belo Horizonte, 2019; Data provided by authorities	Transmilenio, 2022	Zona Franca, 2019	MTC Perú, 2021	Data provided by authorities	IDOM, 2019; Reyes Flores, 2018	Intendencia de Montevideo, 2018	MDMQ, 2009; BID, 2010	Instituto Pereira Passos, 2017	DTPM, 2019
Air pollution & climate change/ Clean technology & energy consumption										
CAF, 2016	CAF, 2016	Data provided by authorities	CAF, 2016	CAF, 2016	Data provided by authorities	CAF, 2016	Intendencia de Montevideo, 2019	Secretaría de Ambiente de Quito, 2015	CAF, 2016	DTPM, 2019
PT operation efficiency / PT operatorś revenues and expenditures										
CAF, 2016	CAF, 2016	Data provided by authorities	CAF, 2016	CAF, 2016	Data provided by authorities	CAF, 2016	Intendencia de Montevideo, 2019	CAF, 2016	CAF, 2016	DTPM, 2019
Integrated and inclusive transport planning										
Buenos Aires Ciudad, 2020	Prefeitura Belo Horizonte, 2020	Secretaria de Movilidad de Bogotá, 2021	Dirección de Movilidad de León, 2022	JICA, 2013	AMVA, 2020	Secretaría de Movilidad de la Ciudad de México, 2019	Intendencia de Montevideo, 2019	MDMQ, 2009	Prefeitura Do Rio & de Janeiro, 2016	SECTRA, 2012

Table 5
Normalization method and thresholds for indicators in BSPTI-LATAM.

Indicator and units	Threshold value	Threshold source	Type of source
System Effectiveness Dimension			
Formal PT share (%)	$X \leq 6 \rightarrow 0X \geq 65 \rightarrow 1$	ONU-Habitat, 2016	IB
Average trip time (min)	$X = 20 \rightarrow 1$ $X \geq 60 \rightarrow 0$	the authors	own definition
Index passenger per km IPK (pass/km)	$X \leq 1.2 \rightarrow 0X \geq 7.7 \rightarrow 1$	Embarq, 2023	IB
PT Fleet Size (# veh/1,000 inh)	$X \leq 0.5 \rightarrow 0X \geq 1.2 \rightarrow 1$	PPIAF, 2006	IB
Payment automatization (E-ticketing veh/total PT fleet)	$X = 0 \rightarrow 0X = 100 \rightarrow 1$	min & max values of sample	own definition
Operating time of formal PT (hours/day)	$X \leq 12 \rightarrow 0X = 24 \rightarrow 1$	the authors	own definition
Average speed (km/h)	$X \leq 15 \rightarrow 0X \geq 30 \rightarrow 1$	UITP, 2012 adapted by the authors	IB
Exclusive lanes for PT (km/100,000 inh)	$X = 0 \rightarrow 0X \geq 10 \rightarrow 1$	BID, 2016	IB
Social Dimension			
PT network coverage (km/ urban area in km^2)	$X \leq 0.2 \rightarrow 0X \geq 4.9 \rightarrow 1$	min & max values of sample	own definition
Average user trip distance (km)	$X \leq 5.9 \rightarrow 1X \geq 16 \rightarrow 0$	UITP, 2012	IB
Accessible PT stations/stops (%)	$X = 0 \rightarrow 0X = 100 \rightarrow 1$	100 % as max value, 0 % as min value	own definition
Accessible PT vehicles (%)	$X = 0 \rightarrow 0X = 100 \rightarrow 1$	100 % as max value, 0 % as min value	own definition
Income devoted to PT (%)	$X \leq 4 \rightarrow 1X \geq 26 \rightarrow 0$	BID, 2016	IB
Fatalities/injured people in formal PT (#fatalities/injured people per 1,000 pkm)	$X \geq 0.1 \rightarrow 0X = 0 \rightarrow 1$	BID, 2016	IB
Actions for female safety in PT system (y/n)	$X = y \rightarrow 1X = n \rightarrow 0$	100 % as max value, 0 % as min value	own definition
PT fleet with air conditioning (%)	$X = 0 \rightarrow 0X = 100 \rightarrow 1$	100 % as max value, 0 % as min value	own definition
PT vehicles with on-board information systems (%)	$X = 0 \rightarrow 0X = 100 \rightarrow 1$	100 % as max value, 0 % as min value	own definition
PT stops/terminals with passenger information (%)	$X = 0 \rightarrow 0X = 100 \rightarrow 1$	100 % as max value, 0 % as min value	own definition
Environmental Dimension			
CO_2 emissions (g/pkm)	$X \leq 30 \rightarrow 1X \geq 60 \rightarrow 0$	Sims et al., 2014	IS
PM_{10} emissions (g/pkm)	$X \leq 0.005 \rightarrow 1X \geq 0.01 \rightarrow 0$	Sims et al., 2014	IS
NO_x emissions (g/pkm)	$X \leq 0.08 \rightarrow 1X \geq 0.16 \rightarrow 0$	Sims et al., 2014	IS
Average PT fleet age (y)	$X \leq 12 \rightarrow 1X \geq 24 \rightarrow 0$	BID, 2016	IB
Low-or zero emissions PT vehicles (% /total PT fleet)	$X = 0 \rightarrow 0X = 100 \rightarrow 1$	100 % as max value, 0 % as min value	own definition
Economic Dimension			
Passenger km per capita (pkm/inh)	$X \geq 30.4 \rightarrow 1X \leq 2.9 \rightarrow 0$	min & max values of sample	own definition
Annual costs recovery ($USD passenger revenues/total operating costs in $USD)	$X = 0 \rightarrow 0X \geq 110 \rightarrow 1$	PPIAF, 2006	IB
Vehicle productivity (veh-km/day)	$X \geq 300 \rightarrow 1X \leq 150 \rightarrow 0$	PPIAF, 2006	IB
Annual operating cost per pkm ($USD/pkm)	$X \leq 5 \rightarrow 1X \geq 40 \rightarrow 0$	min & max values of sample	own definition
Users' costs ($USD/trip)	$X \geq 1.73 \rightarrow 0X \leq 0.18 \rightarrow 1$	CAF, 2016	IB
PT subsidies (%/total PT cost)	$X > 0 \rightarrow 1X = 0 \rightarrow 0$	min & max values of sample	own definition
Governance and Integrated Transport Planning Dimension			
OD surveys in the last 5 years (y/n)	$X = y \rightarrow 1$ $X =$ process ongoing $\rightarrow 0.5$ $X = n \rightarrow 0$	min & max values of sample	own definition
SUMP based in OD survey and aligned with SDGs and land use plans (y/n)	$X = y \rightarrow 1$ $X =$ process ongoing $\rightarrow 0.5$ $X = n \rightarrow 0$	min & max values of sample	own definition
Regular monitoring and evaluation for PT systems (y/n)	$X = y \rightarrow 1$ $X =$ only KPI $\rightarrow 0.5$ $X = n \rightarrow 0$	min & max values of sample	own definition

OD = Origin – destination; **SUMP** = Sustainable Urban Mobility Plans; **SDG** = Sustainable Development Goals; **pkm** = passenger-kilometer; **y/n** = yes/no; **IB** = International Benchmark; **IS** = International Standard.

clean vehicles technologies and fuels which cannot be accomplished in developing countries in the short term. Buffer ranges are defined for these cases when X_i values exceed the objective up to a maximum "tolerable" limit which is set to two times the international standard. This means that X^n gets zero if X_i exceeds two times the standard. The upper limits of the buffer range might be modified for individual applications if a decline to zero points for X^n at a slower or faster rate is more suitable. Table 5 gives an overview of the threshold values and sources for each indicator in BSPTI-LATAM.

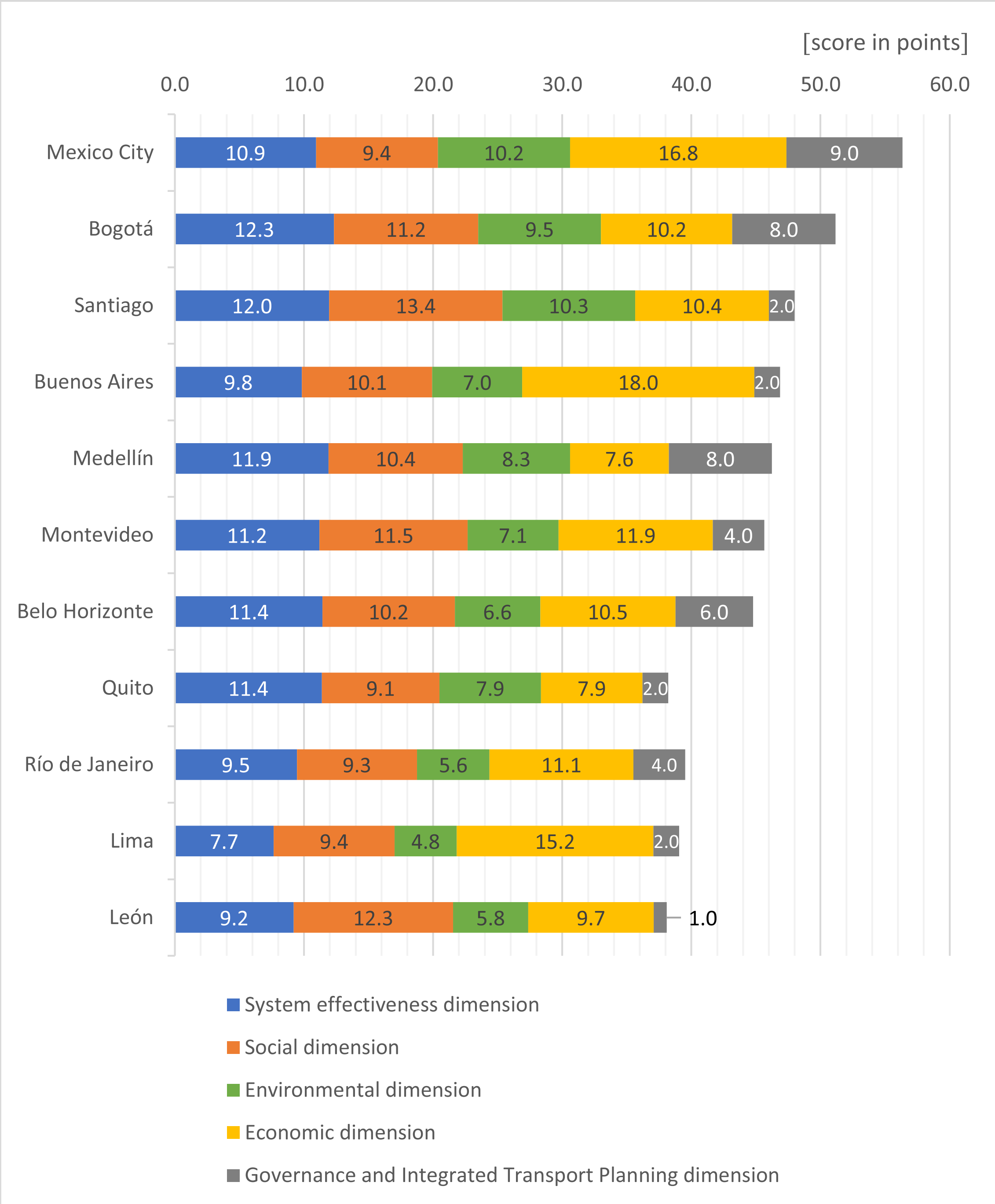

Fig. 1. Overall scores for the BSPTI-LATAM in eleven cities.

3.6. *Weighting and aggregation*

Indicator weights allocate relative importance to each indicator; they help to consider policy priorities in a transparent way (Jeon, 2007). For the SPTI-LATAM, we recommend applying the Equal Weighting Aggregation method (EWA) as a neutral approach that is suitable to compare PT systems between cities with their varying contexts in terms of stakeholders and stakeholder interests (Sałabun et al., 2020). The EWA method is also applied to the 11 cities in this study to achieve comparability as the basis for benchmarking the cities and also for monitoring PT sustainability performance over time. The Budget Allocation Process (BAP) can be used as an alternative when the focus is on local stakeholder priorities (e.g., for decisions on specific policies to improve PT systems) and

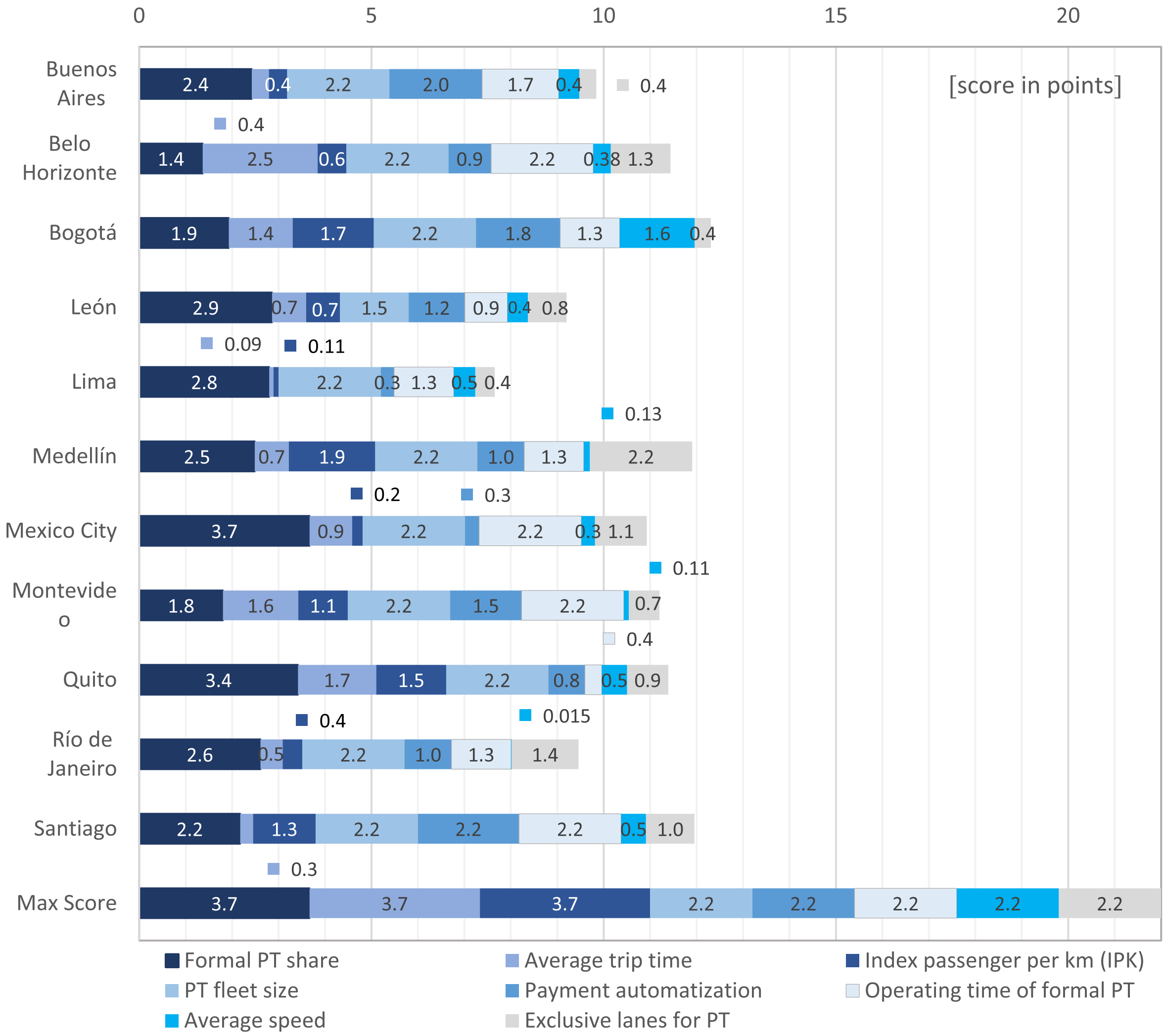

Fig. 2. Indicator performance in the System Effectiveness dimension per city.

comparability between cities or between years within a city is less important.

In this study, all five sustainability dimensions get the same weight except *Governance and Integrated Transport Planning* which gets half of the weight of the other dimensions. The reason behind this is that there is only one category with three ordinal indicators in this dimension which would get too much influence on the overall results if *Governance and Transport Planning* got assigned the same weight as the other dimensions. Within one dimension, all categories have the same weight, and this also holds for all indicators within one category. The final weights for this study are shown in Table 6 in Appendix B. The aggregation of the weighted indicators is the final step to get the overall score for the SPTI-LATAM. In this study we apply the Weighted Sum Model (WSM) to see the effect of a fully compensatory technique in the final ranking of cities. We multiply the individual indicator values (Table 7) with the weights (Table 6) and finally receive for each city a score between 0 and 100 (Table 8).

4. Sustainability calculations and results for the 11 case study cities

4.1. Overall scores of the BSPTI-LATAM index

Fig. 1 shows the overall scores of the final BSPTI-LATAM index for each of the 11 case study cities also including the partial scores in each dimension. The scores are computed based on the data sources as listed in Table 4, the numerical values behind the figure are listed in Appendix B, Table 6. All data inputs used for computing the scores are shown in Appendix B, Table 7.

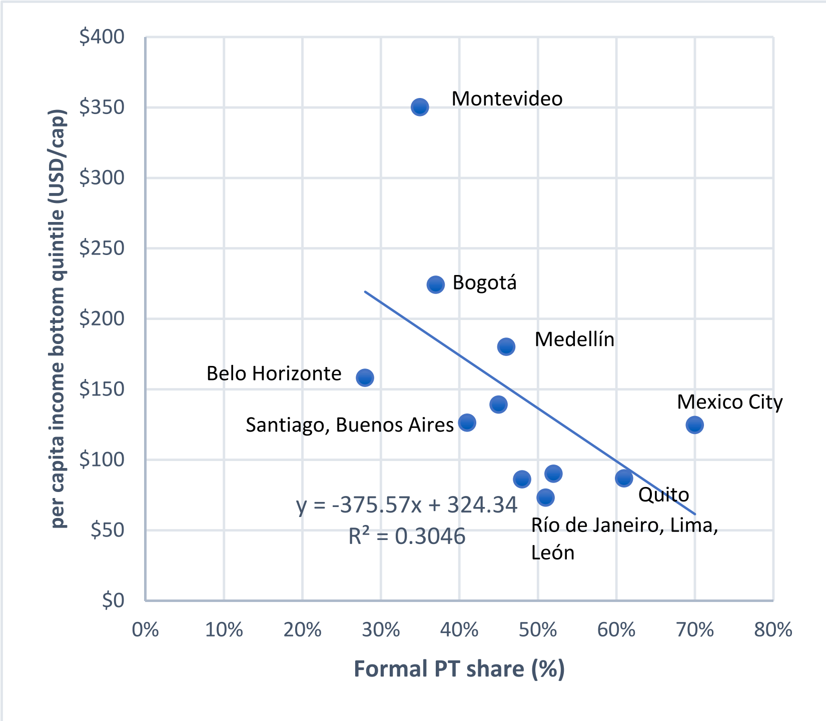

Fig. 3. Relationship between formal PT share and per capita income.

Mexico City scores highest with 56 out of 100 points while Río de Janeiro, Lima, and León have the lowest scores (39, 39, and 38 points respectively). The overall variation between the cities is moderate which indicates stability of the approach and shows that all case study cities have some strengths and weaknesses in their PT systems and that these compensate each other due to the WSM approach. The overall average score is 45 out of a possible 100 points which shows substantial room for improvement in the PT sustainability performance. In absolute terms, the *Economic* dimension has the highest mean score across all cities with 12.2 points, followed by the *System Effectiveness* and the *Social* dimensions with 10.6 points and 10.6 points, respectively. The *Environmental*, and the *Governance and Integrated Transport Planning* dimensions have the lowest mean scores (7.6 out of 22 points and 4.3 points out of 12 maximal achievable points, respectively). Variation is between 1.4 and 1.9 points for the *System Effectiveness*, *Social* and *Environment* dimensions and substantially higher for the *Economic* and the *Governance and Integrated Transport Planning* dimensions (2.7 and 2.9 points). Cities with overall low performance consistently have weaknesses in *Governance and Integrated Transport Planning* practices except Medellin and Santiago. Strengths in data collection, integrated strategic planning and monitoring seem to be one main driver for the overall performance of cities. The high variation in the *Economic* and *Governance and Integrated Transport Planning* dimensions demonstrates that change is possible. The low variation in the *System Effectiveness* and the *Social* dimensions show that PT systems in the 11 cities are providing overall good services and are one backbone of equitable and affordable transport provision for all user groups.

4.2. Detailed scores of the BSPTI-LATAM index per sustainability dimension

In the *System Effectiveness* dimension, the variables with the best performance are formal PT share, PT fleet size and PT operating hours as shown in Fig. 2. Mexico City and Quito have (almost) the full scores for formal PT shares with 70 % in Mexico City and 61 % in Quito. The other cities follow with values around 50 % which is still very high compared to many other cities in the world. These high values impressively show the relevance of PT in our 11 case study cities, PT is a backbone of the urban transport systems and holds a great potential for their overall sustainability. All cities except Leon have the full score for PT fleet size, four cities have the full score for the operating time of formal PT which means a 24-hour service. The high values of these three indicators demonstrate that the case study cities have functioning PT systems in place and that people are also used to using public transport. Deficits exist for the indicators that describe the quality of the PT services. The low scores for the average PT speed are particularly problematic. Bogotá is the only city which scores high for this indicator which shows that change is possible. The scores for the exclusive PT lanes are generally low and there is no correlation with PT speed. This means that more exclusive PT lanes with consequent prioritization at signalized intersections are needed in order to achieve a visible impact on the overall PT speed in the system.

Significant correlations have been identified between formal PT share and income as shown in Fig. 3. This is one prominent determinant of PT usage and residents' overall travel behavior. In addition, this correlation shows the urgent need to improve the

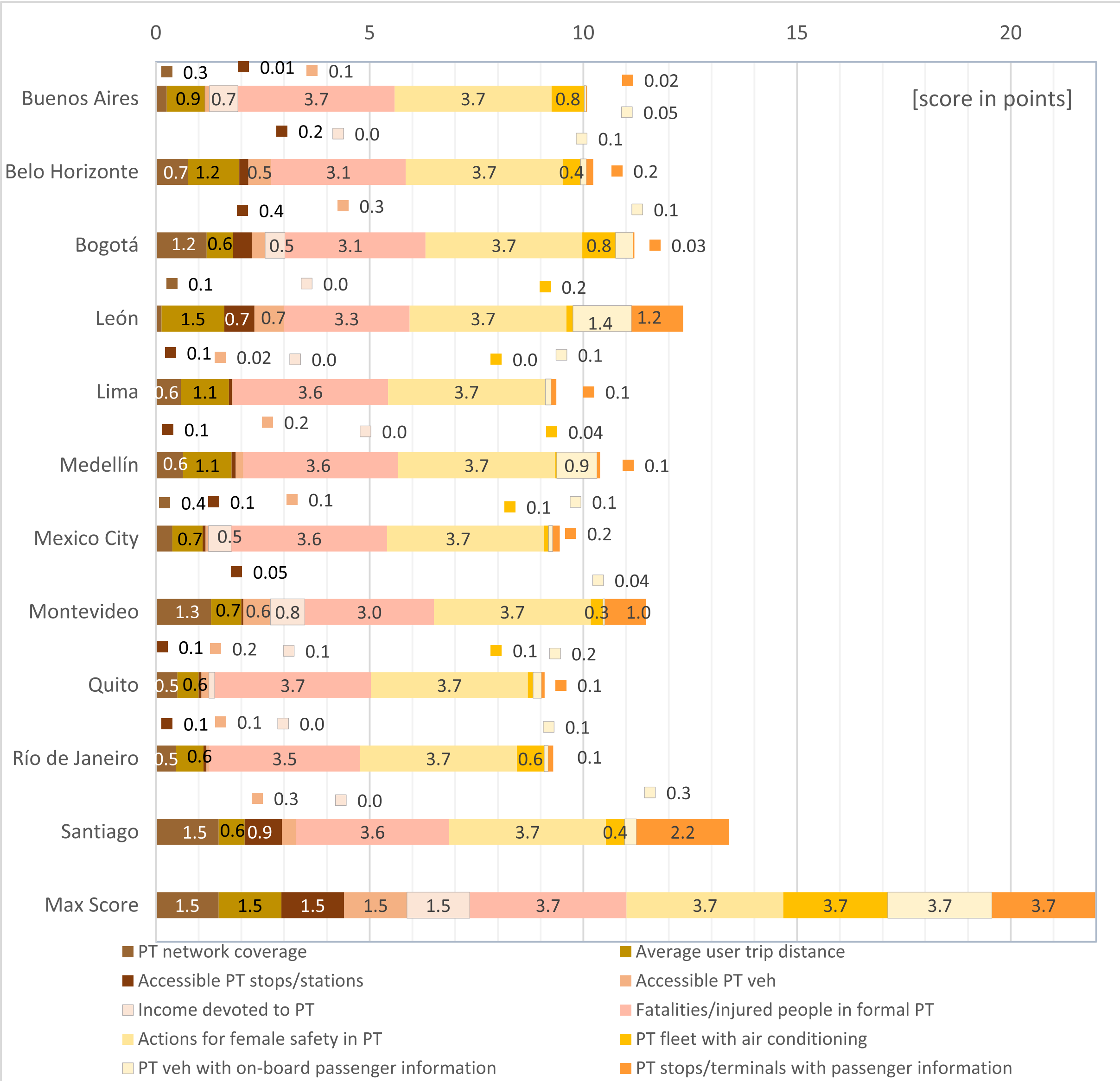

Fig. 4. Indicator performance in the social dimension per city.

quality of PT systems in Latin American cities. PT ridership is high today but with increasing income, people will switch to the private motorized modes if PT is not competitive in terms of speed, reliability, and comfort.

The comparably high scores of the *Social* dimension as shown in Fig. 4 are mainly driven by the indicators *Fatalities/ injured people in formal PT*, which reaches almost the full score for all cities, and *Actions for female safety in PT*, which reaches the full score for all cities. Safety of PT passengers is high, almost no PT user gets killed in crashes in our 11 case study cities. A weakness of this indicator is that injuries other than PT passengers and particularly the vulnerable road users (pedestrians and cyclists) in crashes with PT vehicles being involved are not covered. All 11 cities have actions for improving female safety in PT vehicles and stations in place. This is a strength and urgently needed but obviously not sufficient seeing that still today, a high proportion of female PT users reports harassment and sexual aggression in PT (Galiani & Jaitman, 2016). All other indicators in the *Social* dimension score low on average with significant correlations between the indicators describing the accessibility of PT stations and vehicles as well as their equipment with passenger information services. Cities working to improve these indicators appear to be working jointly on vehicles and infrastructure. Santiago is an example city with high scores in these indicators. Santiago also reaches the maximum score for PT network coverage, followed by Montevideo and Bogota. This indicator correlates with PT fleet size and operating time in the *System Effectiveness* dimension. The affordability of PT, measured as the proportion of income devoted to PT, scores low in most cities except Buenos Aires, Bogota, Mexico City and Montevideo. These low scores are problematic seeing that many low income people are captives and have no alternative to using PT services.

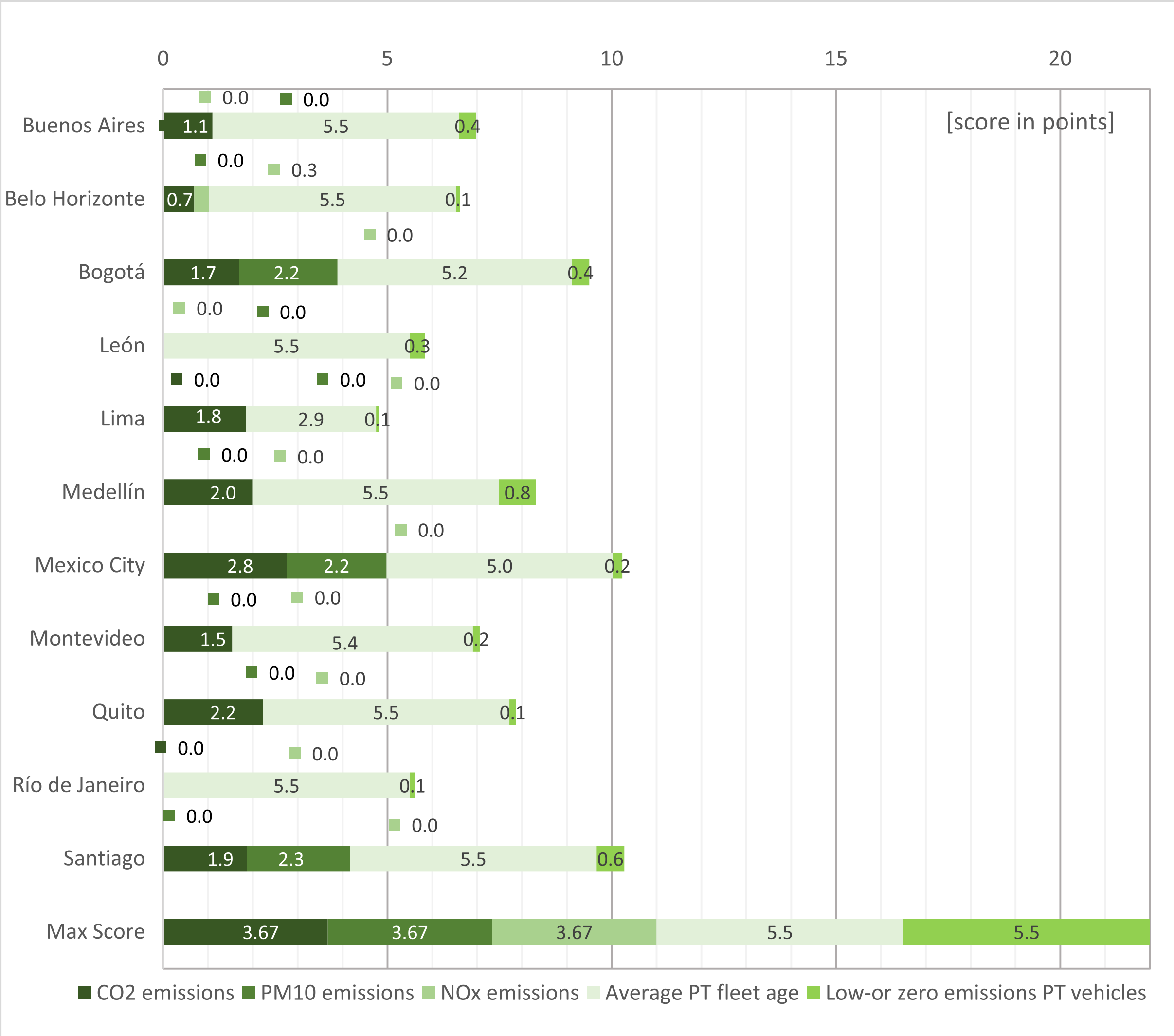

Fig. 5. Indicator performance in the environmental dimension per city.

Indicators in the *Environmental* dimension as shown in Fig. 5 score low on average, indicating a substantial need for action. Almost all cities reach the full score for the average PT fleet age which corresponds to a value of 12 years. Lima is the only exception with an average fleet age of 17.7 years. The high performance of most cities in the average PT fleet age is not sufficient to reach high scores in the other environmental indicators. Emissions of CO_2 and PM_{10} have high variation: Mexico City, Bogota and Santiago score highest whereas Leon and Rio de Janeiro score zero even though they have young PT vehicle fleets with an age of 6,5 and 6,0 years respectively. The scores of NO_x emissions are close to zero for all 11 cities. The international standards (Sims et al., 2014) are obviously very ambitious for all our case study cities even though the thresholds chosen for the SPTI-Latam index are twice as high as the Euro VI technology (0.16 g/km for NO_x and 0.01 g/km for PM_{10}). Differences between performance in PM_{10} and NO_x can be explained with technology. For example, 82 % of the bus fleet in Santiago has particulate filters (Plataforma Urbana, 2016) while SCR or EGR systems are less present. Despite an average age of 11 years for the PT fleet in our case study cities, the bus technology is predominantly Euro III which leads to higher emissions per kilometer. The percentage of low or zero emission PT vehicles scores also very low for all cities. The high scores for PT fleet age indicate that investments in new vehicles are done but the purchased vehicles obviously do not meet sustainability ambitions. Cleaner technologies represent less than 6 % of the PT fleet in Latin America (4,128 electric buses including hybrid and trolleybuses), except in Santiago de Chile with 849 electric buses which corresponds to 11 % of their total PT fleet (Labmob, 2021). Bad quality of fuels is an external factor that negatively impacts on PT environmental performance.

The *Economic* dimension is characterized by high variation between the case study cities but overall, it has comparably high scores as shown in Fig. 6. Annual cost recovery scores high for all cities, it is correlated with the low scores for PT subsidies. PT systems in our case study cities need to cover major parts of their cost on their own because support from governments is limited. Low investments in technology and the renewal of buses in combination with high levels of travel demand are behind the high levels of cost recovery but

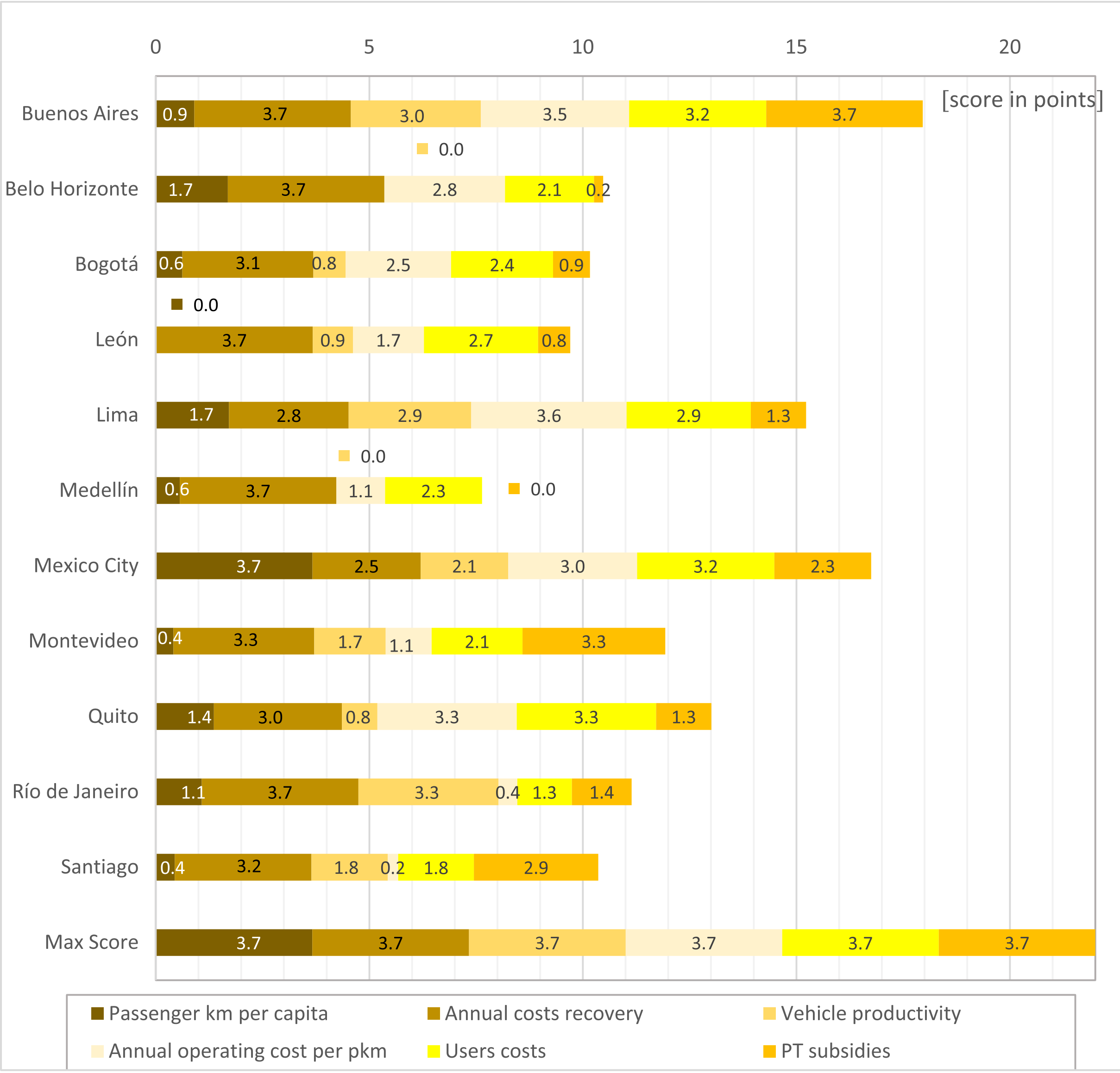

Fig. 6. Indicator performance in the economic dimension per city.

generate problems in the environmental dimension. Economic efficiency might also relate to the inadequate labor rights of drivers, meaning that operators diminish operating costs by not providing social security or not formal labor contracts to drivers (GSD Plus - MDMQ, 2017). Vehicle productivity and annual operating cost show high variation between the cities with no significant correlations between these variables. User cost score high in Buenos Aires, Mexico City and Quito which shows that low fares are possible even with limited subsidies.

Finally, in the Governance and Integrated Transport Planning dimension, the three selected indicators as shown in Fig. 7 represent relevant aspects of the planning process. They show the extent to which it is evidence-based and regular monitoring takes place. The average score on this dimension is 4.36 out of 12 points. Only three out of the eleven cities reach the full scores for at least two of the three indicators, these are Mexico City (9 points), Medellín (8 points) and Bogota (8 points). All these three cities score also high over all five dimensions. Belo Horizonte has the fourth highest score in the *Governance and Integrated Transport Planning* dimension but ranks only fifths over all dimensions, mainly because of the low environmental performance of its PT system. Four cities report OD-surveys but only one city reports a SUMP based on an OD-survey (Medellín: AMVA, 2020) and one city regular monitoring (Bogotá: Secretaria de Movilidad de Bogotá, 2021). This shows the urgent need to action in this dimension.

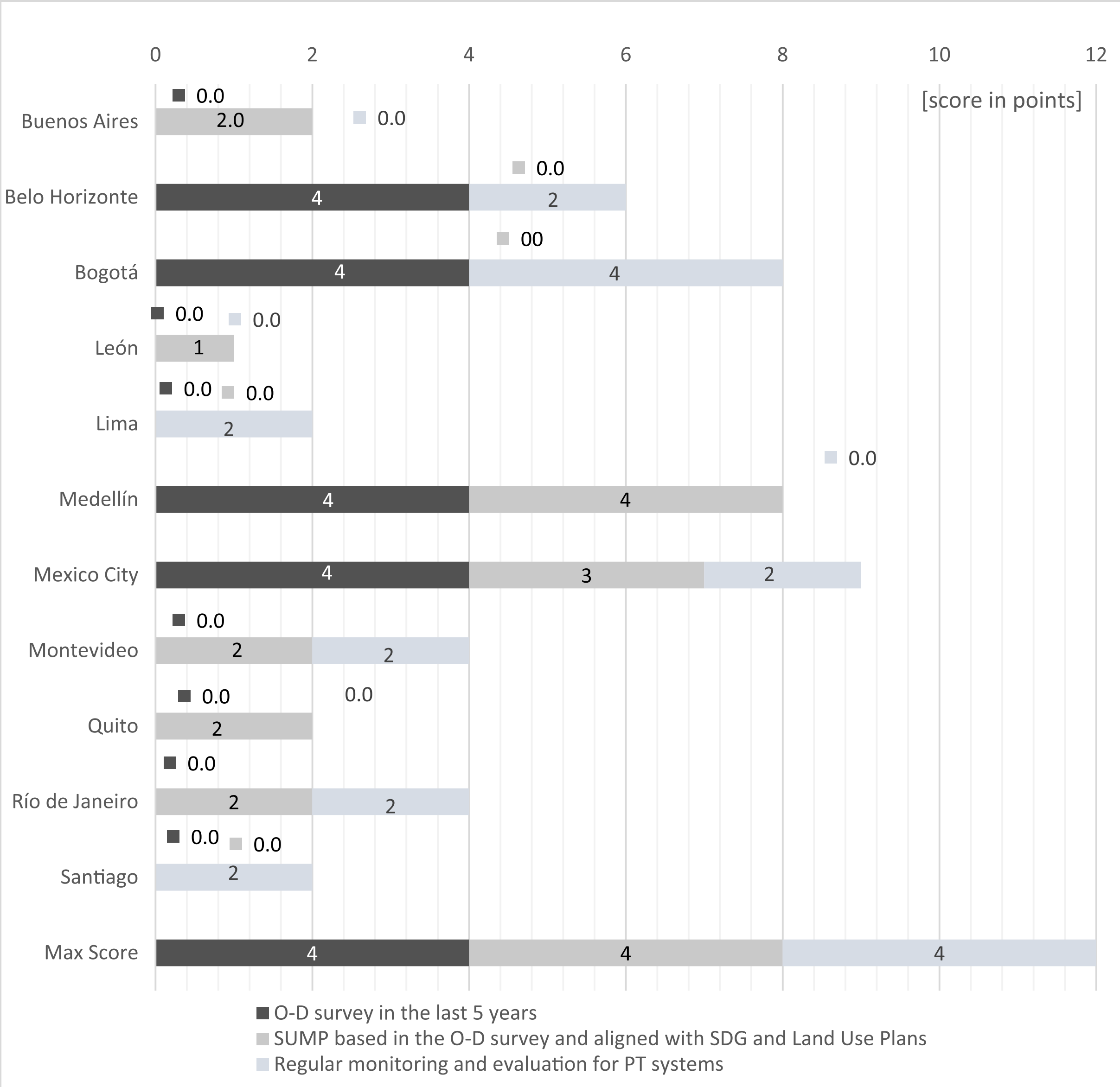

Fig. 7. Indicator performance in the governance and integrated transport planning dimension per city.

5. Discussion

The application of the BSPTI-LATAM for the 11 case study cities provides a clear picture of the overall strengths and weaknesses of the local PT systems and their specific characteristics. The results show an average score of 45 points for the 11 cities, this is less than half of the full sustainability performance. Only 2 cities scored more than 50 points, Mexico and (56 points) and Bogotá (51points), which indicates that even the highest-ranking cities have considerable potential for improvement. The remaining 9 cities obtained scores between 38 and 49 points, being León and Lima with the lowest scores under 40 points. These generally low values for the overall sustainability performance of Latin American PT systems confirms the few studies that exist for this region and that consistently find substantial need for action (Barbosa et al., 2016; Guimarães et al., 2018; Santos & Ribeiro, 2013).

The detailed analysis of the indicators in the five dimensions shows that deficits mainly exist in quality and less in quantity of PT systems. PT systems with suitable fleet sizes and network coverage exist in all our 11 study areas and their usage is high with a formal PT share of up to 70 %. Formal PT share and usage correlate with supply-side indicators such as PT network coverage. Correlations also exist between the various supply-side indicators, e.g., between PT network coverage, PT fleet size and operating time. No clear correlations could be identified between PT supply and its quality but between the different indicators describing PT quality such as the accessibility of PT stops and vehicles or on-board information.

Table 6
Indicator weights assigned with the EWA method for the BSPTI.

Dimension	Dimension weight in the index	Categories	Categories weighting within the dimension	Indicators	Variable weight within the category	Variable weight within the dimension
System effectiveness	**0.22**	PT usage	**11**	Formal PT share	0.3	3.7
				Average trip time	0.3	3.7
				Index passenger per km (IPK)	0.3	3.7
		PT supply	**11**	PT fleet size	0.2	2.2
				Operating hours of formal PT	0.2	2.2
				Average PT speed	0.2	2.2
				Exclusive lanes for PT	0.2	2.2
				Payment automatization	0.2	2.2
SUBTOTAL			**22**			22
Social	**0.22**	PT accessibility & affordability	**7.4**	PT network coverage	0.2	1.5
				Average user trip distance	0.2	1.5
				Accessible PT stations/ stops	0.2	1.5
				Accessible PT vehicles	0.2	1.5
				Income devoted to PT	0.2	1.5
		PT safety, security & gender inclusion	**7.4**	Fatalities/injured people in formal PT	0.5	3.7
				Actions for female safety in PT system	0.5	3.7
		Rider comfort & customer services	**7.4**	PT fleet with air conditioning	0.3	2.4
				PT vehicles with on-board information systems	0.3	2.4
				PT stops/terminals with passenger information	0.3	2.4
SUBTOTAL			**22**			22
Environmental	**0.22**	Air pollution & climate change	**11**	CO2 emissions	0.3	3.7
				PM10 emissions	0.3	3.7
				NOx emissions	0.3	3.7
		Clean technologies & energy consumption	**11**	Average PT fleet age	0.5	5.5
				Low-or zero emissions PT vehicles	0.5	5.5
SUBTOTAL			**22**			20
Economic	**0.22**	PT operation efficiency	**11**	Passenger km per capita	0.3	3.7
				Annual costs recovery	0.3	3.7
				Vehicle productivity	0.3	3.7
		PT operatorś revenues and expenditures	**11**	Annual operating cost per pkm	0.3	3.7
				Users' costs	0.3	3.7
				PT subsidies	0.3	3.7
SUBTOTAL			**22**			22
Governance and integrated transport planning	**0.12**	Integrated and inclusive transport planning	**12**	O-D survey in the last 5 years	0.3	4
				SUMP based in the O-D survey and aligned with SDG and Land Use Plans	0.3	4
				Evaluation and monitoring of the PT system	0.3	4
SUBTOTAL			**12**			**12**
FINAL SCORE			**100**			**100**

The *Social, Environmental* and *Governance* dimensions had the lowest results by obtaining between 34 % and 36 % of the 100 % full performance. Indicators related with passenger comfort, user services and accessibility scored the lowest in the social dimension, while for the *Environmental* dimension the scores are consistently low in all cities and are in addition mainly driven by the average PT fleet age. This shows the challenges that PT systems in Latin America face in terms of environmental quality. Improvements in the environmental performance, service quality and in the efficiency of vehicles are urgently needed in order to keep the high levels of PT usage. The identified correlation between income and formal PT share reveals the risk that current PT users switch to individual motorized transport modes as soon as they can afford a car or a motorcycle. This upward trend in car use is the typical first part of the peak car cycle, which could be shortened by a strong public transport system combined with restrictive measures on individual car use (Wittwer et al., 2019). The income variable is also an example for the manifold external factors that impact on PT performance and that need to be considered to fully understand the mechanisms and to purposefully shape future PT systems.

The *Governance and Integrated Transport Planning* dimension has the lowest mean score and the highest variation across the 11 cities.

Table 7
Data inputs used for the calculation of the SPTI - LATAM.

Category	Indicator	BA	BH	BOG	LE	LI	MED	MEX	MON	QUI	RIO	SAN
System Effectiveness Dimension												
PT Usage	Formal PT split/share (%)	45 %	28 %	37 %	52 %	51 %	46 %	70 %	35 %	61 %	48 %	41 %
	Average trip time (min)	56	33	45	52	59	52	50	42	42	55	57
	Index passenger per km IPK (pass/km)	1.9	2.3	4.3	2.5	1.4	4.5	1.6	3.1	3.9	2.0	3.6
PT Supply	PT Fleet Size (# veh/1000 inh)	1.5	3.0	2.6	1.0	3.7	2.4	3.7	1.2	1.3	3.2	1.3
	Payment automatization (E-ticketing veh/total PT fleet)	91 %	42 %	82 %	55 %	13 %	46 %	14 %	70 %	36 %	46 %	99 %
	Operating time of formal PT (hours/day)	21	24	19	17	19	19	24	24	14	19	24
	Average speed (km/h)	18	18	26	18	18	16	17	16	19	15	19
	Exclusive lanes for PT (km/100.000 inh)	2	6	2	4	2	17	5	3	4	7	5
Social Dimension												
PT accessibility & affordability	PT network coverage (km/ urban area in km2)	1.0	2.6	4.0	0.6	2.1	2.2	1.4	4.3	1.8	1.7	4.9
	Average user trip distance (km)	9.9	7.7	11.8	5.1	8.3	8.2	11.1	11.1	12.6	11.6	11.8
	Accessible PT stations/stops (%)	1 %	14 %	30 %	48 %	5 %	7 %	5 %	3 %	5 %	5 %	59 %
	Accessible PT vehicles (%)	7 %	36 %	21 %	47 %	1 %	12 %	5 %	43 %	12 %	5 %	22 %
	Income devoted to PT (%)	16 %	32 %	19 %	40 %	41 %	26 %	18 %	14 %	24 %	83 %	47 %
PT safety, security & gender inclusion	Fatalities/injured people in formal PT (#fatalities/1000 pkm)	0.000	0.028	0.021	0.040	0.002	0.002	0.001	0.035	0.001	0.008	0.005
	Actions for female safety in PT system (y/n)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Rider comfort & Customer services	PT fleet with air conditioning (%)	31 %	17 %	32 %	6 %	1 %	2 %	4 %	12 %	5 %	26 %	18 %
	PT vehicles with on-board information systems (%)	2 %	6 %	17 %	56 %	6 %	39 %	4 %	2 %	8 %	4 %	11 %
	PT stops/terminals with reliable passenger information (%)	1 %	7 %	1 %	50 %	5 %	3 %	7 %	40 %	3 %	5 %	90 %
Environmental Dimension												
Air pollution & Climate Change	CO2 emissions (g/pkm)	42.0	48.7	32.3	79.1	29.8	27.5	15.0	34.8	23.7	160.8	29.4
	PM10 emissions (g/pkm)	0.019	0.024	0.004	0.039	0.016	0.080	0.004	0.017	0.033	0.034	0.004
	NOx emissions (g/pkm)	0.36	0.15	0.44	0.75	0.24	2.49	0.22	0.42	0.30	0.65	0.22
Clean technology & energy consumption	Average PT fleet age (y)	7.0	9.7	11.4	6.5	17.7	7.0	13.0	12.3	12.0	6.0	7.9
	% Low-or zero emissions PT vehicles	7 %	2 %	7 %	6 %	1 %	15 %	4 %	3 %	3 %	2 %	11 %
Economic Dimension												
PT operation efficiency	Passenger km per capita (pkm/ihn)	9.7	15.6	7.6	3.0	15.8	7.1	30.4	6.0	13.1	11.0	6.2
	Annual costs recovery ($USD pass revenues/total operating costs in $USD)	165 %	212 %	92 %	150 %	84 %	111 %	76 %	99 %	90 %	135 %	96 %
	Vehicle productivity (Veh-km/day)	274.5	146.0	181.0	188.4	267.5	137.6	233.9	218.3	184.0	284.3	223.1
PT operators' revenues and expenditures	Annual operating cost per pkm ($USD/pkm)	$6.88	$13.03	$16.43	$24.12	$5.28	$29.12	$11.20	$29.71	$8.87	$35.81	$37.68
	Users' costs ($USD/trip)	$0.37	$0.85	$0.72	$0.60	$0.50	$0.77	$0.37	$0.83	$0.35	$1.19	$0.98
	PT subsidies (%/total PT cost)	37 %	5 %	11 %	10 %	15 %	3 %	24 %	34 %	15 %	16 %	30 %
Governance and Integrated Transport Planning												
Integrated and inclusive transport planning	OD surveys in the last 5 years (y/n)	0 %	100 %	100 %	0 %	0 %	100 %	100 %	0 %	0 %	0 %	0 %
	SUMP based in OD survey and aligned with SDG and Land Use Plans (y/n)	50 %	0 %	0 %	25 %	0 %	100 %	75 %	50 %	50 %	50 %	0 %
	Regular monitoring and evaluation for PT systems (y/n)	0 %	50 %	100 %	0 %	50 %	0 %	50 %	50 %	0 %	50 %	50 %

BA = Buenos Aires; BH = Belo Horizonte; BOG = Bogotá; LE = León; LI = Lima; MED = Medellín; MEX = México City; MON = Montevideo; QUI = Quito; RIO = Rio de Janeiro; SAN = Santiago.

Table 8
SPTI – LATAM normalized by EWA and aggregated by WSM.

Category	Indicator	BA	BH	BOG	LE	LI	MED	MEX	MON	QUI	RIO	SAN
System Effectiveness Dimension												
PT Usage	Formal PT share	2.4	1.4	1.9	2.8	2.8	2.5	3.6	1.8	3.4	2.6	2.2
	Average trip time	0.4	2.5	1.4	0.7	0.09	0.7	0.9	1.6	1.7	0.5	0.3
	Index passenger per km (IPK)	0.4	0.6	1.8	0.7	0.12	1.9	0.2	1.1	1.5	0.4	1.4
PT Supply	PT fleet size	2.2	2.2	2.2	1.5	2.2	2.2	2.2	2.2	2.2	2.2	2.2
	Payment automatization	2.0	0.9	1.8	1.2	0.3	1.0	0.3	1.5	0.8	1.0	2.2
	Operating time of formal PT	1.7	2.2	1.3	0.9	1.3	1.3	2.2	2.2	0.4	1.3	2.2
	Average speed	0.4	0.38	1.6	0.4	0.5	0.13	0.3	0.11	0.5	0.015	0.5
	Exclusive lanes for PT	0.4	1.3	0.4	0.8	0.4	2.2	1.1	0.7	0.9	1.4	1.0
Partial score for the SE dimension over 22 points		**9.8**	**11.4**	**12.3**	**9.2**	**7.6**	**11.9**	**10.9**	**11.2**	**11.4**	**9.4**	**12.0**
Social Dimension												
PT accessibility & affordability	PT network coverage	0.3	0.7	1.2	0.1	0.6	0.6	0.4	1.3	0.5	0.5	1.5
	Average user trip distance	0.9	1.2	0.6	1.5	1.1	1.1	0.7	0.7	0.5	0.6	0.6
	Accessible PT stops/stations	0.01	0.2	0.4	0.7	0.1	0.1	0.1	0.05	0.1	0.1	0.9
	Accessible PT veh	0.1	0.5	0.3	0.7	0.02	0.2	0.1	0.6	0.2	0.1	0.3
	Income devoted to PT	0.7	0.0	0.5	0.0	0.0	0.0	0.5	0.8	0.1	0.0	0.0
PT safety, security & gender inclusion	Fatalities/injured people in formal PT	3.7	3.1	3.3	2.9	3.6	3.6	3.6	3.0	3.7	3.5	3.6
	Actions for female safety in PT	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7
Rider comfort & customer services	PT fleet with air conditioning	0.8	0.4	0.8	0.1	0.0	0.04	0.1	0.3	0.1	0.6	0.4
	PT vehicles with on-board passenger information	0.05	0.1	0.4	1.4	0.1	1.0	0.1	0.04	0.2	0.1	0.3
	PT stops/terminals with passenger information	0.02	0.2	0.03	1.2	0.1	0.1	0.2	1.0	0.1	0.1	2.2
Partial score for the social dimension over 22 points		**10.1**	**10.2**	**11.2**	**12.4**	**9.4**	**10.4**	**9.5**	**11.5**	**9.1**	**9.3**	**13.4**
Environmental Dimension												
Air pollution & Climate Change	CO2 emissions	1.1	0.7	1.7	0.0	1.8	2.0	2.7	1.5	2.2	0.0	1.9
	PM10 emissions	0.0	0.0	2.2	0.0	0.0	0.0	2.2	0.0	0.0	0.0	2.3
	NOx emissions	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Clean technology & energy consumption	Average PT fleet age	5.5	5.5	5.2	5.5	2.9	5.5	5.0	5.4	5.5	5.5	5.5
	Low-or zero emissions PT vehicles	0.4	0.1	0.4	0.3	0.1	0.8	0.2	0.2	0.1	0.1	0.6
Partial score for the ENV dimension over 22 points		**7.0**	**6.6**	**9.5**	**5.8**	**4.8**	**8.3**	**10.2**	**7.0**	**7.8**	**5.6**	**10.2**
Economic Dimension												
PT operation efficiency	Passenger km per capita	0.9	1.7	0.6	0.0	1.7	0.6	3.6	0.4	1.3	1.1	0.4
	Annual costs recovery	3.6	3.6	3.0	3.6	2.8	3.6	2.5	3.3	3.0	3.6	3.2
	Vehicle productivity	3.1	0.0	0.8	1.0	2.9	0.0	2.1	1.7	0.8	3.3	1.8
PT operators' revenues and expenditures	Annual operating cost per pkm	3.5	2.9	2.5	1.7	3.7	1.2	3.1	1.1	3.3	0.4	0.2
	Users' costs	3.2	2.1	2.4	2.6	2.9	2.2	3.2	2.1	3.2	1.3	1.8
	PT subsidies	3.6	0.2	0.9	0.7	1.3	0.0	2.2	3.3	1.3	1.4	2.9
Partial score for the economic dimension over 22 points		**18.0**	**10.5**	**10.2**	**9.7**	**15.3**	**7.6**	**16.7**	**11.9**	**13.0**	**11.1**	**10.3**
Governance and Integrated Transport Planning												
Integrated and inclusive transport planning	O-D survey in the last 5 years	0.0	4.0	4.0	0.0	0.0	4.0	4.0	0.0	0.0	0.0	0.0
	SUMP based in the O-D survey and aligned with SDG and Land Use Plans	2.0	0.0	0.0	1.0	0.0	4.0	3.0	2.0	2.0	2.0	0.0
	Regular monitoring and evaluation for PT systems	0.00	2.04	4.08	0.00	2.04	0.00	2.04	2.04	0.00	2.04	2.04
Partial score for the GOV dimension over 12 points		**2.0**	**6.0**	**8.0**	**1.0**	**2.0**	**7.9**	**9.0**	**4.0**	**2.0**	**4.0**	**2.0**
Final Score over 100 points		**47**	**45**	**51**	**38**	**39**	**46**	**56**	**46**	**43**	**40**	**48**
Ranking		**4**	**7**	**2**	**11**	**10**	**5**	**1**	**6**	**8**	**9**	**3**

In addition, it has the lowest number of indicators and the simplest indicators. This dimension has hardly been covered in any of the existing indicator schemes that were identified in the literature research, it is one of the main innovations of this study (Karjalainen & Juhola, 2019; Ribeiro et al., 2020). The three indicators in the *Governance and Integrated Transport Planning* dimension show the diversity between the cities and the weaknesses in planning processes and institutions. Despite being simple so far, this dimension proved of high importance for the overall sustainability performance of PT systems. Strengths in governance are a driver for the overall PT sustainability, more competencies in city administrations and governments are one core success factor for better sustainability performance. More research is needed on how to measure performance in this dimension more comprehensively.

6. Conclusions and outlook for further research

This study developed with the SPTI-LATAM the first sustainability index for benchmarking PT systems from the societal perspective which is tailored to the specific local conditions in Latin America. The SPTI-LATAM contains conceptual innovations in normalization and reference values. It consciously applies with equal weighting of dimensions and indicators the simplest but most suitable approach for ensuring comparability between cities and over time. The selection of indicators was the main way in which SPTI-LATAM was adapted to the specific Latin American context. Indicators have been included for the specific characteristics of Latin American PT systems, e.g., for vehicle technology (air conditioning, PT fleet age etc.), gender violence and modified thresholds for air pollutant emissions. The newly added *Governance and Integrated Transport Planning Dimension* is of particular relevance. It contains only few and simple indicators so far but is already powerful and influential for the overall city scores.

The application of the SPTI-LATAM to 11 study areas in Latin America with different size, urban form, external framework conditions and PT systems demonstrates its applicability for benchmarking cities with different characteristics. The application complements the few previous studies carried out for this region, specifically in Brazil, where only the three traditional sustainability dimensions (environmental, economic, social) were considered (Barbosa et al., 2016; Guimaraes & Leal, 2017; Guimarães et al., 2018). Furthermore, Barbosa et al. (2016) considered only the user perspective in Florianápolis, and Guimaraes and Leal (2017) and Guimarães et al. (2018) evaluate the general performance of PT systems in Rio de Janeiro without considering the normative sustainability framework. The SPTI-LATAM broadens this perspective to assess not only the performance of PT systems, but also their sustainability as a balance between providing accessibility to all person groups in society while minimizing the related negative impacts.

Future research that computes the BSPTI for smaller cities and also the two higher levels of the SPTI-LATAM (ESPTI, GSPTI) will give more insights and further improve benchmarking between the cities. The consideration of paratransit services will be particularly insightful as this is a complement to formal PT services that differs widely in terms of quantity and quality between the cities but that is hardly covered by publicly available statistics so far. More detailed indicators in the *Governance dimension* will be helpful to better map and understand this part of the overall PT sustainability performance which is of core relevance but insufficiently considered so far.

Sensitivity analyses can help to investigate the stability of BSPTI-scores. Equal weights have been assigned to dimensions, categories, and indicators in this study to support benchmarking and comparability between cities. Budget allocation processes (BAP) assigning weights according to local stakeholder preferences as one possible alternative to EWA in combination with the systematic variation of weights will give further insights and a more comprehensive picture of sensitivities and mechanisms. The variation of indicator thresholds could be included into sensitivity analysis.

The integration of instruments such as the SPTI-LATAM into planning processes and decision making is another avenue for future research. Research can contribute to better understanding which support local stakeholders in terms of data, monitoring and evaluation need and how instruments should be designed so that they actually help to make progress towards the sustainability ambition.

Overall, Latin-American PT systems can be considered best practice in terms of coverage and high usage levels but at the same time, there is an urgent need for action in terms of service quality and environmental performance. PT systems in Latin-American systems hold a great potential for becoming sustainable and for being a backbone of overall sustainable urban transport systems. The SPTI-LATAM helps to better understand strengths and weaknesses and to tell success stories when cities succeed in establishing regular monitoring of their PT systems. It thus offers municipalities, operators, users and other stakeholders the basis for discussing about what sustainability in public transport means and for supporting their work in the development of plans and policies for a more sustainable approach in planning and operation.

Funding

This research received no external funding.

CRediT authorship contribution statement

Alexandra Velasco: Conceptualization, Methodology, Writing – original draft, Investigation. **Regine Gerike:** Validation, Writing – review & editing.

Declaration of competing interest

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

Acknowledgments

The authors would like to acknowledge the Municipalities of Belo Horizonte, Montevideo, Santiago de Chile, Quito, Bogotá, and México City, for their direct contribution with the necessary data for the index.

Declaration of generative AI in scientific writing

The authors declare no use of AI tools to analyze and draw insights from data as part of the research process.

Appendix A

Categories and indicators in the system effectiveness dimension

The system effectiveness dimension is composed by two categories: PT usage and PT supply.

PT usage: it indicates the system's ability to attract riders and generate trips as a proxy indicator for level of service of the PT system and is expressed by three indicators: 1) *Formal PT mode share*; 2) *Average trip time* (Miller et al., 2016; Jasti & Ram, 2019b), and 3) *Index Passenger Km (IPK)* (Ribeiro et al., 2020). A high modal share in PT reflects the capacity of the system to attract and maintain users while PT trip time is a key factor to attract or loose users. There are external and internal conditions that affect travel time. Traffic conditions or accidents in the road network are external conditions that reduce speed and reliability for PT, these can hardly be controlled by the operator. Internal conditions are the absence of timetables, insufficient driving skills, inefficient passengers take-on and take-off, among others (Litman, 2015; Miller et al., 2016; Gruyter et al., 2017). The *Index Passenger Km (IPK)* is the number of passengers a bus is able to attract and retain defines the success of a bus system (ANTP, 2017; Ribeiro et al., 2020). It is calculated as the ratio between the total number of passengers who have travelled during a certain period of time and the total distance covered by the entire fleet within a system, line, or route. This ratio is important for sustainability as it demonstrates the intensity of usage of a public transport system. The more passengers there are, the better it is for all aspects, including social, environmental, and economic.

PT supply: This category expresses the capacity of a PT system to provide a service. Five indicators are chosen for this category and for the basic index: 1) *PT fleet size*: The existing number of vehicles represents a considerable share of the operation expenses of PT-supply (Gruyter et al., 2017; Currie et al., 2018). Here buses, trains, metro cables gondolas, trams, and other vehicles operating in the formal PT system should be counted. Shortage of transport capacity may be due to inadequate fleet size. Often, the number of available vehicles would be adequate if they were more effectively utilized. Inefficient operating practices, such as full vehicle dispatching, may result in inadequate capacity even if there are surplus vehicles. On the other hand, surplus vehicles may cause severe traffic congestion in terminals and in the surrounding streets if there is insufficient parking space in the terminals (PPIAF, 2006); 2) *Payment automatization:* The elimination of on-board payments reduces time at a bus stop or terminal. Automatization allows a better passenger control and a centralized budget that could be distributed among the operators, eliminating the "war of the cent" and increasing coverage service in less profitable routes (Lopez-Carreiro & Monzon, 2018). It is calculated as the ratio of vehicles with E-ticketing and the total PT fleet; 3) *Operating time of formal PT*: The number of hours in which at least one service is offered (TCRP, 2019 Cervero & Golub, 2007 Brussel et al., 2019). A good level of service (LOS) of a PT system is between 20 and 21 h a day, 17 – 18 h/day is level C and less than 16 h/day is LOS D (Friedrich et al., 2010). 4) *Average speed*: High average speed in PT reduces the operating costs (lower expenses e.g., for purchasing fuel) and increases the bus efficiency (lower delays) (Protransporte, 2014; Ribeiro et al., 2020; TCRP, 2019). On the other hand, excessive driving speed comes with risks for passengers and street users, PT drivers should therefore comply with the maximum legally allowed speed. GPS systems on vehicles allow a better controlling of speed and location; they are also a suitable basis for the optimization of vehicle schedules; 5) *Exclusive lanes for PT*: Giving priority to the circulation of public transport is a prerequisite for high-speed, safer and reliable systems and with this also for a more efficient PT supply (Lin et al., 2021; Liu et al., 2020). It is considered here by the ratio of kilometers of exclusive lanes over 100,000 inhabitants.

Categories and indicators in the social dimension

PT accessibility and affordability: For this study, we define accessibility based on Gertz and Peter (2017) (see also Biazzo et al., 2019; Bocarejo et al, 2012) as the ease of reaching desired destinations from a certain location with PT and including all user groups, particularly people with reduced mobility and by guaranteeing equity and equal access to personal and professional opportunities generated as a result of both transport supply and land use characteristics. We include indicators for the ease of reaching desired destinations, and the ease of access in PT infrastructure: 1) *PT network coverage:* This indicator is measured by the overall length of the PT network per square kilometer in each city (Alonso et al., 2015) (Tan & Chen, 2011). The length is calculated by the sum of kilometers of roads and streets that have at least one PT line service, including rail systems. A higher PT network coverage is desirable for sustainability since it creates access to different social groups to citýs services and infrastructures. 2) *Average user trip distance:* This indicator takes the user perspective and reflects the average distance each PT passenger travels on the system to get to his or her destination. A lower average PT trip length is desirable (Miller et al., 2016) including the two aspects of short distances from origins to desired destinations and the directness of the PT supply (Currie & de Gruyter, 2018). 3) *Accessible PT stations/stops* and 4) *Accessible PT vehicles* reflect the number of PT vehicles and bus stops, stations and terminals adapted for people with reduced mobility (Jasti & Ram, 2019a). Accessibility not only includes the coverage of a public transport infrastructure within the city, but also the ease of access to the transport infrastructure by individuals, especially those with reduced mobility such as children, the elderly, and people with disabilities, providing them with the same opportunity and right to travel as other social groups (López et al., 2019).

With regards to affordability it refers to the extent to which the financial cost of journeys require an individual or household to make sacrifices to travel or the extent to which they can afford to travel when they want to (ONU-Habitat, 2016). In developing cities, the travel cost in PT is a very sensitive parameter affecting especially low incomers. Therefore, the indicator number five *Income devoted to PT* calculates the total amount of budget per month per person, invested in PT in relation to the per capita income for the lowest income quintile (ONU-Habitat, 2016).

PT safety, security and gender inclusion*:* Generally, the term "safety" is used to indicate the possibility of being involved in a road accident, while the term "security" refers to the possibility of becoming the victim of a crime (Eboli & Mazzulla, 2012). A sustainable PT system should guarantee safety to all citizens (PT users and road users, including cyclists and pedestrians) and at the same guarantee security to all PT users, especially women since they are the primary victims of sexual harassment in public transport services (Pereyra et al., 2018). For the safety variable we included the indicator *Fatalities/injured people in formal PT* expressed as the ratio of fatalities and injured people in a traffic accident caused by a PT vehicle, every 1000 pkm. This indicator shows the level of safety of a PT system depending on the driving behaviour, the mechanical state of vehicles, but also how safe are crossings and intersections where PT lines are operating. A comprehensive planning of PT diminishes the risk of fatalities and casualties for PT users, other vehicles and road users, including pedestrians and cyclists. With regards to gender inclusion, the corresponding indicator is *Actions for female safety in PT system* since female users are more exposed to sexual harassment or other type of gender violence (Pereyra et al., 2018). Therefore, the indicator expresses the availability of campaigns, call centers, hot lines and special services that are implemented to fight against any type of sexual aggression in PT systems. It is calculated as a yes or no question, stating whether a municipality or an operator has taken actions to reduce gender violence in the PT system.

Rider comfort and customer services: *1) PT fleet with air conditioning:* In some Latin American cities at sea level or in subtropics with high humidity and temperatures above 30 °C, the in-vehicle temperature can be very uncomfortable. Providing air conditioning inside the vehicles could increase comfort and therefore, ridership among users (Güner, 2018; Litman, 2015). It is calculated as the ratio of PT vehicles with air condition and the total vehicle fleet. 2) *PT vehicles with on-board information systems*: Travelers significantly value on-board information or printed and posted schedules, especially when there is heavy congestion, because it reduces stress and allows passengers to better use their time and coordinate activities (Litman, 2015). A couple of Latin American cities (e.g., Lima and Quito) included this parameter in their guidelines; the latter one intended for visually and hearing impaired users (Protransporte, 2014;Secretaría de Movilidad DMQ, 2021). 3) *PT stops/terminals with passenger information*: Timetables, LED panels and other services with the schedules, bus lines and stops are the basic information that a passenger expects to have when arriving to a bus stop or terminal for a better planning of his or her trip. Both indicators are calculated as a ratio of vehicles and stops with these services and the total fleet/number of terminals and PT stops.

Categories and indicators in the environmental dimension

Air pollution and climate change: *1) CO_2 emissions*: Reductions of greenhouse gas emissions are paramount seeing the high political ambitions for mitigating climate change at all levels. PT services can greatly contribute to achieve these reductions in the overall transport systems while still providing accessibility for all user groups (Romero-Ania et al., 2021); *2) PM_{10} Emissions:* Particulate matter is mainly related to diesel and older Euro engine technologies. It has been associated with short term and long term increases in mortality and increases in respiratory symptoms, greater use of drug treatments in people with asthma, reduction in lung function, and admissions to hospital for respiratory and cardiovascular disease (Barassa, 2021); *3) NOx emissions*: NOx refers to a group of highly reactive gases knows as oxides of nitrogen. A high concentration of these gases in the air can irritate airways in the human respiratory system. Short periods exposures can aggravate respiratory diseases, particularly asthma, leading to respiratory symptoms (such as coughing, wheezing or difficulty breathing), hospital admissions and visits to emergency rooms. Longer exposures to elevated concentrations of NOx may contribute to the development of asthma and potentially increase susceptibility to respiratory infections. People with asthma, as well as children and the elderly are generally at greater risk for the health effects of NOx (EPA, 2021). Therefore, a decrease of nitrogen oxides in the atmosphere is desirable. *CO_2, PM_{10} and NO_X* emissions are measured by emission inventories, if they are not available, emissions factors specific for countries or cities, plus network length, pkm, average speed and fleet characteristics can ease its calculation as grams per pkm (Guzman & Orjuela, 2017).

Clean technology and energy consumption: *1) Average PT fleet age* is an important factor for rider comfort, reduced emissions, and improves safety. It also reflects the economic status of the country (Dobranskyte-Niskota et al., 2009). Surveys to authorities and databases of operators are the primary source of information. All types of PT vehicles should be included, and its average age calculated. We include this variable as an environmental indicator since old technologies in buses are a great cause of air pollution and climate change in Latin America (Hidalgo & Huizenga, 2013); *2) Low-or zero emissions PT vehicles*: In recent years the number of electric buses in Latin America has increased enormously. Santiago de Chile, Montevideo, Bogotá are examples of cities intending to decarbonize their PT fleets. This helps to reduce GHG emissions and air pollutants coming from PT sector. Therefore, we include this indicator as the ratio of cleaner technology to total PT fleet (Hahn et al., 2017).

Categories and indicators in the economic dimension

PT operation efficiency: *1) Passenger km per capita* helps to understand the progress of the PT sector, which in turn explains the patronage of the system and the current market in a city (Diana & Daraio, 2014). It is calculated as the multiplication of average daily passenger trips in a line or a PT system and the average daily distance per person (obtained through e-ticketing system data mining, O-D surveys and/or mobile applications), and then as the division to the total population in the city; *2) Annual costs recovery*: Fare revenues is an operation cost effectiveness indicator that shows the percentage of recovery of total costs operation, in other words, the net earnings the whole PT system has (Hassan et al., 2013). *3) Vehicle productivity:* It is measured in kilometers per PT vehicle per day. A PT vehicle should be used as intensively as possible (operating hours and coverage) if passenger demand is sufficient to cover the direct operation costs (Illahi & Mir, 2020). Otherwise, when there is lower passenger demand, PT operation should be organized to reduce unnecessary trips, costs, emissions, and energy consumption.

PT operators' revenues and expenditures: *1) Annual operating cost per pkm:* Total operation costs of a line or a network divided by the total amount of passenger-kilometers per year. It reflects the economic efficiency of the system. Lower annual operating cost is desirable without diminishing the quality and quantity of service (Gruyter et al., 2017). 2) *Users' costs:* This indicator represents the economic costs incurred on the traveller using the system. That means the average price for a single ticket that each user pays per trip. Fares are benefits to PT operators and costs to passengers (Miller et al., 2016). 3) *PT Subsidies* are financial aids that cover partially PT operation costs. They could be of two types: 1) supply and 2) demand subsidies. The supply subsidies for PT are given by national or local governments to finance partially the costs of operation. Subsidies of this type could be fuel subsidies, exception of taxes and fees, loans for new PT fleet or payments made directly to the operators. The demand subsidies are reductions in the fare made directly to vulnerable groups, such as children, students, elderly, or people with reduced mobility. When PT approaches 100 % costs recovery for operation by fares and subsidies it will trend toward economic sustainability (Papacostas & Prevedouros, 2001; Litman, 2009).

Categories and indicators in the governance and integrated transport planning dimension

Integrated and inclusive transport planning: This category refers to actions and plans taken by the authorities that includes not only transport data for all modes, but also land use planning and international commitments. Three indicators are included for this category: 1) *Origin-Destination (OD) surveys in the last 5 years for the city*: Up-to-date information about residents' travel behavior including the origins and destinations of all trips made by residents for all purposes (work, education, leisure, etc.) with all transport modes is a key element for a comprehensive urban transport planning including the design of public transport services; 2) *SUMP based on OD survey results and aligned with SDGs and land use plans* refers to the existence of Sustainable Urban Mobility Plans (SUMP), then if they are based on the results of OD surveys, and finally, if they are aligned to the Sustainable Development Goals (SDGs) and land use plans to foster the progress of cities towards sustainable development and climate change mitigation goals; 3) *Regular monitoring and evaluation for PT systems*: a public transport system cannot achieve sustainability if permanent monitoring and evaluation are not carried out. Tools and methods for this goal should be developed to avoid economic loses and to increase customers loyalty to the service. Key performance indicators (KPIs) measurement is essential for the regular evaluation of the system effectiveness. Examples are IPK, passengers per hour/direction, average user trip time and distance, vehicle productivity, annual operating costs and revenues. Customer satisfaction might be derived by yearly surveys collecting information about rider comfort, cleanliness, accessibility, air conditioning and other services in the PT infrastructure and vehicles. Finally, mandatory yearly vehicle technical inspection guarantees that safety and emissions standards are accomplished. Data given by authorities and official SUMPs and other transport plans were used to determine the completion of this indicator.

Appendix B

See Tables 6-8.

References

Alcaldía de Bogotá, 2019. Encuesta de Movilidad 2019: Indicadores Preliminares. http://ieu.unal.edu.co/images/Resultados_Preliminares_EncuestaMovilidad_2019.pdf.

Alcaldía de Medellín, 2020. Conductores de transporte público de Medellín se capacitan para prevenir el acoso y la violencia sexual. https://www.medellin.gov.co/movilidad/component/k2/conductores-de-transporte-publico-de-medellin-se-capacitan-para-prevenir-el-acoso-y-la-violencia-sexual.

Alonso, A., Monzón, A., Cascajo, R., 2015. Comparative analysis of passenger transport sustainability in European cities. Ecol. Ind. 48, 578–592. https://doi.org/10.1016/j.ecolind.2014.09.022.

Ammenberg, J., Dahlgren, S., 2021. Sustainability assessment of public transport, Part I—a multi-criteria assessment method to compare different bus technologies. Sustainability 13 (2), 825. https://doi.org/10.3390/su13020825.

AMVA, 2020. Plan Maestro de Movilidad para el Valle de Aburrá. https://www.metropol.gov.co/movilidad/PlanMaestro/Plan%20Maestro%20de%20Movilidad.pdf.

ANTP, 2017. Sistema de Informações da Mobilidade Urbana da Associação Nacional de Transportes Públicos -Simob/ANTP: Relatório geral 2017.

Awasthi, A., Omrani, H., Gerber, P., 2018. Investigating ideal-solution based multicriteria decision making techniques for sustainability evaluation of urban mobility projects. Transp. Res. A Policy Pract. 116, 247–259. https://doi.org/10.1016/j.tra.2018.06.007.

Barassa, E. e. a., 2021. 1st-Brazilian-Electric-Mobility-Annual-Report: Changing the landscape towards fleet electrification Brazilian EV Outlook 2020 In the way to boosting electrification.

Barbosa, S.B., Ferreira, M.G.G., Nickel, E.M., Cruz, J.A., Forcellini, F.A., Garcia, J., Guerra, J.B., Osório, S., de Andrade,, 2016. Multi-criteria analysis model to evaluate transport systems: an application in Florianópolis, Brazil. Transp. Res. A Policy Pract. 96, 1–13. https://doi.org/10.1016/j.tra.2016.11.019.

Biazzo, I., Monechi, B., Loreto, V., 2019. General scores for accessibility and inequality measures in urban areas. Roy. Soc. Open Sci. 6 (8) https://doi.org/10.1098/rsos.190979.

BID, 2016. Anexo de indicadores de la guía metodológica del Programa de Ciudades Emergentes y Sostenibles. Banco Interamericano de Desarrollo. https://publications.iadb.org/es/guia-metodologica-programa-de-ciudades-emergentes-y-sostenibles-tercera-edicion-anexo-de.

BID, 2010. Inclusión de Género. https://tglab.iadb.org/quito.

Bocarejo, J.P., Oviedo, H., D. r., 2012. Transport accessibility and social inequities: a tool for identification of mobility needs and evaluation of transport investments. J. Transp. Geogr. 24, 142–154. https://doi.org/10.1016/j.jtrangeo.2011.12.004.

Bondorevsky, D., Estupiñán, N., 2018. Quién, qué y cómo se financia el sistema de transporte público en la Región Metropolitana de Buenos Aires. Caracas. https://scioteca.caf.com/bitstream/Costos-Transporte.pdf.

Brundtland, G. H. (1987). Our Common Future: Report of the World Commission on Environment and Development. Oxford University Press, Oxford, UK. World Commission on Environment and Development. https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf.

Brussel, M., Zuidgeest, M., Pfeffer, K., van Maarseveen, M., 2019. Access or Accessibility? A Critique of the Urban Transport SDG Indicator. ISPRS Int. J. Geo Inf. 8 (2), 67. https://doi.org/10.3390/ijgi8020067.

Buenos Aires Ciudad, 2020. Qué es el Plan de Movilidad Sustentable?.

Caf, 2011. Desarrollo Urbano y Movilidad en América Latina. CAF.

Caf, 2016. Observatorio de Movilidad Urbana: Informe 2015–2016. Caracas, CAF Banco de Desarrollo de América Latina.

Cervero, R., Golub, A., 2007. Informal transport: a global perspective. Transp. Policy 14 (6), 445–457. https://doi.org/10.1016/j.tranpol.2007.04.011.

Chen, F.an, Wu, Z.H., 2013. Comprehensive evaluation for urban public transport network based on TOPSIS. Appl. Mech. Mater. 361–363, 1998–2001. https://doi.org/10.4028/www.scientific.net/AMM.361-363.1998.

Currie, G., de Gruyter, C., 2018. Exploring links between the sustainability performance of urban public transport and land use in international cities. J. Transp. Land Use 11 (1), 325–342. https://doi.org/10.5198/jtlu.2018.957.

Currie, G., Truong, L., de Gruyter, C., 2018. Regulatory structures and their impact on the sustainability performance of public transport in world cities. Res. Transp. Econ. 69, 494–500. https://doi.org/10.1016/j.retrec.2018.02.001.

Dawda, N.H., Gajera, H., Joshi, G.J., Arkatkar, S.S., Dave, S.K.M., 2021. Efficiency based evaluation of public transport and paratransit systems with a view to integrating transportation. Transport. Res. Rec.: J. Transport. Res. Board 2675 (3), 17–32. https://doi.org/10.1177/0361198120980322.

de Gruyter, C., Currie, G., Rose, G., 2017. Sustainability measures of urban public transport in cities: a world review and focus on the asia/middle east region. Sustainability 9 (1), 43. https://doi.org/10.3390/su9010043.

Intendencia de Montevideo, 2019. Catálogo de Datos abiertos.

Secretaría de Movilidad de la Ciudad de México. (2019). *Plan estratégico de movilidad de la Ciudad de México 2019*. https://www.movilidad-integrada.tianguisdigital.cdmx.gob.mx/docs/plan-estrategico-de-movilidad-2019.pdf.

Diana, M., Daraio, C., 2014. Evaluating the Effectiveness of Public Transport Operations: A Critical Review and some Policy Indicators, 41(1), 75–107.

Dirección de Movilidad de León, 2022. Sistema Integrado de Transporte. https://www.leon.gob.mx/movilidad/.

Dobranskyte-Niskota, A., Perujo, J., Jesinghaus, J., Jensen, P., 2009. Indicators to Assess Sustainability of Transport Activities - Part 2: Measurement and Evaluation of Transport Sustainability Performance in the EU27. Doi: 10.2788/46618.

DTPM, 2019. Informe de Gestión 2019. Santiago de Chile. DTPM. http://www.dtpm.gob.cl/descargas/memoria/InformeGestion_2019_DTPM.pdf.
Eboli, L., Mazzulla, G., 2012. Performance indicators for an objective measure of public transport service quality. Eur. Transport - Trasporti Europei 51, 1–21.
El Gibari, S., Gómez, T., Ruiz, F., 2019. Building composite indicators using multicriteria methods: a review. J. Bus. Econ. 89 (1), 1–24. https://doi.org/10.1007/s11573-018-0902-z.
Embarq, 2023. Global BRT data. WRI Brasil Ross Center for Sustainable Cities.
EPA, 2021. Basic Information about NO2. https://www.epa.gov/no2-pollution/basic-information-about-no2.
European Commission, 2020. Sustainable Urban Mobility Indicators (SUMI). European Commission.
Farooq, A., Xie, M., Stoilova, S., Ahmad, F., 2019. Multicriteria Evaluation of transport plan for high-speed rail: an application to Beijing-Xiongan. Math. Probl. Eng. 2019, 1–23. https://doi.org/10.1155/2019/8319432.
Fonadin, 2016. ANEXO 1 - Guía para la Presentación y Evaluación de Proyectos de Transporte Masivo. Fondo Nacional de Infraestructuras. http://www.fonadin.gob.mx/wp-content/uploads/2016/08/Guia_Presentacion_EvaluacionPROTRAM.pdf.
Zona Franca. (2019). *Leonesas optan por asociaciones civiles para denunciar acoso en el transporte público*. https://zonafranca.mx/politica-sociedad/movilidad/leonesas-optan-por-asociaciones-civiles-para-denunciar-acoso-en-el-transporte-publico/.
Friedrich, M., Schlaich, J., Schleupen, G., 2010. Bewertung des ÖPNV aus Kundensicht. Methodik des ADAC-ÖPNV-Tests in europäischen Großstädten. Internationales Verkehrswesen 62 (12), 11–16.
Galiani, S., Jaitman, L., 2016. El transporte público desde una perspectiva de género: percepción de inseguridad y victimización en Asunción y Lima. https://publications.iadb.org/publications/spanish/document/El-transporte-público-desde-una-perspectiva-de-género-Percepción-de-inseguridad-y-victimización-en-Asunción-y-Lima.pdf.
Gerike, R [R.], Koszowski, C., 2017. Sustainable Urban Transportation. In: Encyclopedia of Sustainable Technologies (pp. 379–391). Elsevier. Doi: 10.1016/B978-0-12-409548-9.10176-9.
Gertz, C., Peter, M., 2017. Leitprojekt Regionale Erreichbarkeitsanalysen: Abschlussbericht und Erreichbarkeitsatlas. Hamburg. Metropolregion Hamburg. https://metropolregion.hamburg.de/erreichbarkeitsanalysen.
Gobierno de la Ciudad de México, 2022. Sistema de Transporte Colectivo de Cd de México: Parque vehicular. https://www.metro.cdmx.gob.mx/parque-vehicular.
GSD Plus - MDMQ. (2017). ESTRUCTURACIÓN DE COSTOS OPERACIONALES, FINANCIEROS Y DE INVERSIÓN ASOCIADOS A LA OPERACIÓN DE LOS CUATRO SUBSISTEMAS DEL DISTRITO METROPOLITANO DE QUITO (DMQ). Quito. Municipio del Distrito Metropolitano de Quito.
Guimaraes, V.D., Leal, I.C., 2017. Performance assessment and evaluation method for passenger transportation: a step toward sustainability. J. Clean. Prod. 142, 297–307. https://doi.org/10.1016/j.jclepro.2016.05.071.
Guimarães, V.d.A., Leal Junior, I.C., Da Silva, M.A.V., 2018. Evaluating the sustainability of urban passenger transportation by Monte Carlo simulation. Renew. Sustain. Energy Rev. 93, 732–752. https://doi.org/10.1016/j.rser.2018.05.015.
Güner, S., 2018. Measuring the quality of public transportation systems and ranking the bus transit routes using multi-criteria decision making techniques. Case Stud. Transp. Pol. 6 (2), 214–224. https://doi.org/10.1016/j.cstp.2018.05.005.
Guzman, L.A., Orjuela, J.P., 2017. Linking a transport dynamic model with an emissions model to aid air pollution evaluations of transport policies in Latin America. Transport. B: Transp. Dyn. 5 (3), 265–280. https://doi.org/10.1080/21680566.2016.1169954.
Haghshenas, H., Vaziri, M., 2012. Urban sustainable transportation indicators for global comparison. Ecol. Ind. 15 (1), 115–121. https://doi.org/10.1016/j.ecolind.2011.09.010.
Hahn, J.-S., Kho, S.-Y., Choi, K., Kim, D.-K., 2017. Sustainability evaluation of rapid routes for buses with a network DEA model. Int. J. Sustain. Transp. 11 (9), 659–669. https://doi.org/10.1080/15568318.2017.1302022.
Hamurcu, M., Eren, T., 2020. Strategic planning based on sustainability for urban transportation: an application to decision-making. Sustainability 12 (9), 3589. https://doi.org/10.3390/su12093589.
Hassan, M.N., Hawas, Y., Ahmed, K., 2013. A multi-dimensional framework for evaluating the transit service performance. Transp. Res. A Policy Pract. 50, 47–61. https://doi.org/10.1016/j.tra.2013.01.041.
Hidalgo, D.[Dario], Huizenga, C., 2013. Implementation of sustainable urban transport in Latin America. Res. Transp. Econ. 40 (1), 66–77. https://doi.org/10.1016/j.retrec.2012.06.034.
IDOM, 2019. PROGRAMA INTEGRAL DE SEGURIDAD VIAL 2020 - 2024. https://semovi.cdmx.gob.mx/storage/app/media/Diagnostico_PISVI_2020.pdf.
Illahi, U., Mir, M.S., 2020. Sustainable Transportation Attainment Index: multivariate analysis of indicators with an application to selected states and National Capital Territory (NCT) of India. Environ. Dev. Sustain.. Advance online publication. Doi: 10.1007/s10668-020-00734-w.
Instituto Pereira Passos, 2017. Data Rio: Transporte. Rio Prefeitura. https://www.data.rio/.
Intendencia de Montevideo, 2018. Montevideo libre de acoso. https://montevideo.gub.uy/montevideo-libre-de-acoso.
Jasti, P.C., Ram, V.V., 2019a. Integrated and sustainable benchmarking of metro rail system using analytic hierarchy process and Fuzzy Logic: a case study of Mumbai. Urban Rail Transit 5 (3), 155–171. https://doi.org/10.1007/s40864-019-00107-1.
Jasti, P.C., Ram, V.V., 2019b. Sustainable benchmarking of a public transport system using analytic hierarchy process and fuzzy logic: a case study of Hyderabad, India. Public Transport 11 (3), 457–485. https://doi.org/10.1007/s12469-019-00219-8.
Jeon, C.M., Amekudzi, A.A., Guensler, R.L., 2013. Sustainability assessment at the transportation planning level: performance measures and indexes. Transp. Policy 25, 10–21. https://doi.org/10.1016/j.tranpol.2012.10.004.
Jeon, C.M., 2007. Incorporating sustainability into transportation planning and decision making: definitions, performance measures, and evaluation. Georgia Institute of Technology.
JICA, 2013. Encuesta de Recolección de Información Básica del Transporte Urbano en el Área Metropolitana de Lima y Callao: Informe Final. https://openjicareport.jica.go.jp/pdf/12087532_01.pdf.
Karjalainen, L., Juhola, S., 2019. Framework for assessing public transportation sustainability in planning and policy-making. Sustainability 11 (4), 1028. https://doi.org/10.3390/su11041028.
Keshavarz-Ghorabaee, M., Amiri, M., Hashemi-Tabatabaei, M., Ghahremanloo, M., 2021. Sustainable public transportation evaluation using a novel hybrid method based on fuzzy BWM and MABAC. The Open Transport. J. 15 (1), 31–46. https://doi.org/10.2174/1874447802115010031.
Labmob, U., 2021. E-Bus Radar: Electric buses in Latin America. https://www.ebusradar.org/en/.
Lima Cómo Vamos, 2021. ¿Cómo vamos en Lima y Callao? Reporte urbano de indicadores de calidad de vida 2021.
Lin, G., Wang, S., Lin, C., Bu, L., Xu, H., 2021. Evaluating performance of public transport networks by using public transport criteria matrix analytic hierarchy process models—case study of Stonnington, Bayswater, and Cockburn Public Transport Network. Sustainability 13 (12), 6949. https://doi.org/10.3390/su13126949.
Linke, C.C., Rocha, M.J., Alcalá, A., Palacios, A., Suárez, M., Gómez, M., Pardo, C., 2018. Transporte y desarrollo en America Latina volumen 2. Caracas, CAF http://scioteca.caf.com/handle/123456789/1348.
Litman, T., 2009. A Good Example of Bad Transportation Performance Evaluation. Victoria Transport Policy Institute (Www. Vtpi. Org/perind. Pdf), 1(October 2008), 15. http://www.vtpi.org/per_ind.pdf.
Litman, T., 2015. Valuing transit service quality improvements: Considering comfort and convenience in transport project evaluation.
Liu, Y., Chien, S., Hu, D., Wang, N., Zhang, R., 2020. Developing an extenics-based model for evaluating bus transit system. J. Adv. Transp. 2020, 1–13. https://doi.org/10.1155/2020/8879664.
López, C., Ruíz-Benítez, R., Vargas-Machuca, C., 2019. On the environmental and social sustainability of technological innovations in urban bus transport: the EU case. Sustainability 11 (5), 1413. https://doi.org/10.3390/su11051413.
Lopez-Carreiro, I., Monzon, A., 2018. Evaluating sustainability and innovation of mobility patterns in Spanish cities. analysis by size and urban typology. Sustain. Cities Soc. 38, 684–696. https://doi.org/10.1016/j.scs.2018.01.029.
MDMQ, 2009. Plan Maestro de Movilidad para el Distrito Metropolitano de Quito: 2009 -2025. https://biblio.flacsoandes.edu.ec/shared/biblio_view.php?bibid=118765&tab=opac.

Miller, P., G.de Barros, A., Kattan, L., Wirasinghe, S.C., 2016. Analyzing the sustainability performance of public transit. Transp. Res. Part D: Transp. Environ. 44, 177–198. https://doi.org/10.1016/j.trd.2016.02.012.
Ministerio de Transporte de Argentina, 2018. Situación de la Seguridad Vial en Argentina: Datos y análisis para un abordaje integral del problema [Información disponible hasta el año 2016].
Ministerio de Transportes y Telecomunicaciones de Chile. (2018). Resolución No. 3166. http://www.dtpm.cl/descargas/contratos/cc/un1/Establece%20Condiciones%20Especificas%20de%20Operación_(RES.%20EX.%20N%203166%2019-10-2018).pdf.
Nardo, M & M. Saisana. (2005). *OECD/JRC Handbook on constructing composite indicators. Putting theory into practice.* https://ec.europa.eu/eurostat/documents/1001617/4398416/S11P3-OECD-EC-HANDBOOK-NARDO-SAISANA.pdf.
ONU-Habitat, 2012. Estado de las Ciudades de América Latina y El Caribe 2012: Rumbo a una nueva transición urbana.
ONU-Habitat. (2016). *Measurement of City Prosperity: Methodology and Metadata*. https://unhabitat.org/sites/default/files/2019/02/CPI-METADATA.2016.pdf.
Oses, U., Rojí, E., Cuadrado, J., Larrauri, M., 2018. Multiple-criteria decision-making tool for local governments to evaluate the global and local sustainability of transportation systems in urban areas: case study. J. Urban Plann. Dev. 144 (1), 4017019. https://doi.org/10.1061/(ASCE)UP.1943-5444.0000406.
Papacostas, C.S., Prevedouros, P.D., 2001. Transportation Engineering and Planning, 3rd. ed. Pearson Prentice Hall.
Pereyra, L. P., Gutiérrez, A., & Nerome, M. M. (2018). La inseguridad en el transporte público del Área Metropolitana de Buenos Aires. Experiencias y percepciones de mujeres y varones. *Territorios*(39), 71–95. Doi: 10.12804/revistas.urosario.edu.co/territorios/a.6310.
MTC Perú. (2021). *MTC lanza la campaña contra el acoso sexual en el transporte público "No va Sola"*. Ministerio de Transportes y Comunicaciones de Perú.
PPIAF, 2006. Urban Bus Toolkit. The World Bank Group & PPIAF. https://ppiaf.org/sites/ppiaf.org/files/documents/toolkits/UrbanBusToolkit/assets/1/1c/1c.html.
Prefeitura Belo Horizonte, 2019. Grupo de combate à importunação sexual no transporte público.
Prefeitura Belo Horizonte, 2020. PlanMob-BH. https://prefeitura.pbh.gov.br/bhtrans/informacoes/planmob-bh.
Protransporte., 2014. Manual de Operaciones de los corredores complementarios. Protransporte.
Rao, S.-H., 2021. Transportation synthetic sustainability indices: a case of Taiwan intercity railway transport. Ecol. Ind. 127, 107753 https://doi.org/10.1016/j.ecolind.2021.107753.
Rasca, S., Hogli Major, J., 2021. Applicability of Existing Public Transport Sustainability Indicators to Norwegian Small Cities and Towns. In: In 2021 Smart City Symposium Prague (SCSP). IEEE, pp. 1–6. https://doi.org/10.1109/SCSP52043.2021.9447387.
Reyes Flores, A., 2018. Atención y prevención del acoso sexual en el Sistema de Transporte Colectivo Metro (STCM). http://bibliodigitalibd.senado.gob.mx/bitstream/handle/123456789/4206/CI_54.pdf?sequence=1&isAllowed=y.
Ribeiro, P., Fonseca, F., Santos, P., 2020. Sustainability assessment of a bus system in a mid-sized municipality. J. Environ. Plan. Manag. 63 (2), 236–256. https://doi.org/10.1080/09640568.2019.1577224.
Prefeitura Do Rio de Janeiro, 2016. Plano de Mobilidade Urbana Sustentável da Cidade do Rio de Janeiro.
Rivas, M.E., et al., 2019. Stylized Urban Transportation Facts in Latin America and the Caribbean: Infrastructure and Energy (TECHNICAL NOTE N° IDB-TN-1640). Inter-American Development Bank. https://publications.iadb.org/publications/english/viewer/Stylized_Urban_Transportation_Facts_in_Latin_America_and_the_Caribbean_en_en.pdf.
Romero-Ania, A., Rivero Gutiérrez, L., de Vicente Oliva, M.A., 2021. Multiple criteria decision analysis of sustainable urban public transport systems. Mathematics 9 (16), 1844. https://doi.org/10.3390/math9161844.
Sałabun, W., Wątróbski, J., Shekhovtsov, A., 2020. Are MCDA methods benchmarkable? A comparative study of TOPSIS, VIKOR, COPRAS, and PROMETHEE II methods. Symmetry 12 (9), 1549. https://doi.org/10.3390/sym12091549.
Santos, A.S., Ribeiro, S.K., 2013. The use of sustainability indicators in urban passenger transport during the decision-making process: the case of Rio de Janeiro, Brazil. Curr. Opin. Environ. Sustain. 5 (2), 251–260. https://doi.org/10.1016/j.cosust.2013.04.010.
Sdoukopoulos, A., Pitsiava-Latinopoulou, M., 2017. Assessing urban mobility sustainability through a system of indicators: the case of Greek cities. In: Brebbia, C.A. (Ed.), WIT Transactions on Ecology and the Environment, Sustainable Development and Planning IX. WIT PressSouthampton UK, pp. 617–631. https://doi.org/10.2495/SDP170541.
Sdoukopoulos, A., Pitsiava-Latinopoulou, M., Basbas, S., 2019. Measuring progress towards transport sustainability through indicators: Analysis and metrics of the main indicator initiatives. Transp. Res. Part D: Transp. Environ. 67, 316–333. https://doi.org/10.1016/j.trd.2018.11.020.
Secretaría de Ambiente de Quito, 2015. Inventario Huella de Carbono: Sectores: Energía estacionaria. Transporte y Residuos. http://www.quitoambiente.gob.ec/ambiente/images/Secretaria_Ambiente/red_monitoreo/informacion/inventario_03.pdf.
Secretaria de Movilidad de Bogotá, 2021. Plan de Movilidad Sostenible y Segura de Bogotá - PMSS: 2022 -2035. https://www.movilidadbogota.gov.co/web/sites/default/files/Paginas/28-12-2021/anexo_3_202112117_comite_sectorial_sdmpptx_1.pdf.
Secretaría de Movilidad DMQ, 2021. Manual para la Implementación de Indicadores de Calidad de Servicio de Transporte Público de Pasajeros del DMQ. Secretaría de Movilidad DMQ.
SECTRA, 2012. Planes de Transporte Urbano. http://www.sectra.gob.cl/planes_transporte_urbano/planes_stu.htm.
Sims, R., Schaeffer, F., Creutzig, X., Cruz-Núñez, M., D'Agosto, D., Dimitriu, M. J., Figueroa Meza, L., Fulton, S., & Kobayashi, O., 2014. Transport. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter8.pdf.
Summit Mobilidade Urbana 2021, 2019. Mulher no transporte público: dificuldades e soluções. https://summitmobilidade.estadao.com.br/guia-do-transporte-urbano/mulher-no-transporte-publico-dificuldades-e-solucoes/.
Tan, X., Chen, Y., 2011. The Sustainable Development of Multi-Level Public Transit Network Fuzzy Evaluation of New City Transit Based on TRANSCAD. In: Yin, Y., Wang, Y., Lu, J., Wang, W. (Eds.), ICCTP 2011. American Society of Civil Engineers, pp. 2581–2590. https://doi.org/10.1061/41186(421)258.
TCRP, 2019. Social and Economic Sustainability Performance Measures for Public Transportation: Final Guidance Document. The National Academics of Sciences, engineering and Medicine. http://www.trb.org/Main/Blurbs/179093.aspx Doi: 10.17226/25461.
Transmilenio S.A., 2022. Historia de Transmilenio. https://www.transmilenio.gov.co/publicaciones/146028/historia-de-transmilenio/.
Triantaphyllou, E., 2000. Multi-criteria Decision Making Methods: A comparative Study. SPRINGER-SCIENCE+BUSINESS MEDIA B.V. Doi: 10.1007/978-1-4757-3157-6.
UITP, 2012. Mobility in cities database. https://www.uitp.org/publications/mobility-in-cities-database/.
United Nations, 2016. SDG Indicators: Metadata repository.
Plataforma Urbana, 2016. Transantiago: 18% de los buses no posee filtros antiesmog.
Velasco Arevalo, A., Gerike, R., [Regine],, 2023. Sustainability evaluation methods for public transport with a focus on Latin American cities: A literature review. Int. J. Sustain. Transp. 1–18 https://doi.org/10.1080/15568318.2022.2163208.
Venter, C., Jennings, G., Hidalgo, D., [Darío], Valderrama Pineda, A.F., 2018. The equity impacts of bus rapid transit: a review of the evidence and implications for sustainable transport. Int. J. Sustain. Transp. 12 (2), 140–152. https://doi.org/10.1080/15568318.2017.1340528.
Victoria Transport Policy Institute, 2021. Evaluating Public Transit Benefits and Costs: Best Practices Guidebook. Victoria Transport Policy Institute.
WBCSD, 2016. Integrated sustainable mobility in cities - a practical guide: Sustainable Mobility Project 2.0. Geneva, Switzerland. https://docs.wbcsd.org/2016/04/Integrated_Sustainable_Mobility_Cities_practical_guide.pdf.
Wittwer, R., Gerike, R [Regine], Hubrich, S., 2019. Peak-car phenomenon revisited for urban areas: microdata analysis of household travel surveys from five European capital cities. Transport. Res. Record: J. Transport. Res. Board, 2673(3), 686–699.
Di Yao, Xu, L., Li, J., 2019. Evaluating the performance of public transit system: a case study of eleven cities in China. Sustainability, 11(13), 3555. Doi: 10.3390/su11133555.

Alexandra Velasco Arévalo is Doctoral candidate at TUD Dresden University of Technology, Germany. Her research topic is on sustainable public transportation and electromobility in Latin American cities. She completed her master's degree in Infrastructure Planning at the University of Stuttgart in 2015. She worked as sustainable

urban mobility advisor at the German International Cooperation GIZ in Ecuador from 2016 to 2019 and before as non-motorized transport Coordinator in the Municipality of Quito for two years. She has more than 7 years-expertise on sustainable mobility policy making, non-motorized transport, traffic simulation models and travel demand. Her current research interests are planning of sustainable public transport and infrastructures, feasibility of electric buses in BRT corridors and urban form, and active mobility.

Regine Gerike is the Dean of the “Friedrich List” Faculty of Transport and Traffic Sciences and head of the chair of Integrated Transport Planning and Traffic Engineering at TUD Dresden University of Technology, Germany. Before joining TUD Dresden, she chaired the Institute for Transport Studies at the University of Natural Resources and Life Sciences (BOKU) in Vienna, Austria. Regine Gerike did her PhD at TUD Dresden University of Technology in the field of modelling transport and its environmental effects. From 2008 to 2012 she was assistant professor at Technische Universität München, head of the Research centre mobility and transport (mobil.TUM) and of the PhD-program “mobil.LAB – Sustainable Mobility in the Metropolitan Region of Munich”. Her research interests include various aspects of transport planning, safety, and traffic engineering, including modelling, empirical research and holistic approaches to evaluate sustainable mobility.