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Benchmarking sustainable urban mobility: The case of Curitiba, Brazil

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ABSTRACT

Transportation planning is currently being confronted with a broader planning view, which is given by the concept of mobility. The Index of Sustainable Urban Mobility (I_SUM) is among the tools developed for supporting this new concept implementation. It is a tool to assess the current mobility conditions of any city, which can also be applied for policy formulation. This study focus on the application of I_SUM in the city of Curitiba, Brazil. Considering that the city is known worldwide as a reference of successful urban and transportation planning, the index application must confirm it. An additional objective of the study was to evaluate the index itself, or the subjacent assessment method and reference values. A global I_SUM value of 0.747 confirmed that the city has indeed very positive characteristics regarding sustainable mobility policies. However, some deficiencies were also detected, particularly with respect to non-motorized transport modes. The application has also served to show that a few I_SUM indicators were not able to capture some of the positive aspects of the city, what may suggest the need of changes in their formulation. Finally, the index application in parts of the city suggests that the city provides fair and equitable mobility conditions to all citizens throughout the city. This is certainly a good attribute for becoming a benchmark of sustainable mobility, even if it is not yet the ideal model.

1. Introduction

The urban space is composed by a complex network of systems that interact in an integrated fashion, therefore influencing one another. The traditional urban planning process, however, is quite often concentrated in just a few parts of the systems. By ignoring transversal impacts found in those systems' parts, this approach may result in poor and inefficient policies. This is also the case of transportation planning, as suggested by Litman (1999). He listed some of the problems that can be caused by a transport system: it serves nondrivers poorly; it distributes benefits and costs inequitably; it is financially burdensome to households, governments, and businesses; it is increasingly inefficient due to traffic congestion and dispersed land use; it is a major cause of death and disability; it contradicts environmental and quality-of-life objectives; and it relies on nonrenewable resources that may become scarce in the future.

The problems aforementioned are a consequence of an incorrect view of conventional planning regarding transport progress. According to Litman and Burwell (2006), conventional planning tends to assume that transport progress is linear, consisting of newer, faster modes that displace older, slower modes. This model assumes that the older modes are less important than the newer modes, even if the latter are private cars that cause congestion delays to public transit or create a barrier to pedestrian travel.

In the particular case of transportation, those negative conditions led to the appearance of a new planning paradigm, which is worldwide known as sustainable mobility planning. One of the first concepts of sustainable urban mobility, applied by OECD and later complemented by the European Commission Group of Specialists in Transport and Environment, defines sustainable transport as that which "contributes positively to the economic and social state without prejudicing human health and the environment. Integrating the social, economic and environmental dimensions, it can be defined as that which

- Permits the satisfaction of the basic necessities of access and mobility of people, companies and society, of a form compatible with human health and the equilibrium of the ecosystem, promoting intra and inter-generational equality;
- Has acceptable costs, functions efficiently, offers the possibility to choose transport modes and supports a dynamic economy and regional development;
- Limits emissions and residues in function of the earth's capacity to absorb them, utilizes renewable resources at a rate below or equal to their regeneration, utilizes non-renewable resources at a rate below or equal to the development of renewable substitutes and reduces land use and sound emissions to the minimum level possible" (MOURELO, 2002).

According to Gudmundsson (2004), sustainable urban mobility is represented by the displacement of persons and goods in the urban space not only by automobiles, but also autonomously or by non-motorized modes. In this way, it plays an important role

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in the urban context, given it promotes social inclusion and balanced urban development. Nevertheless, the new paradigm creates many challenges to the municipalities for using urban spaces and streets in more efficient and dynamic ways in order to reduce the negative impacts of their actions. According to Litman (1999), sustainable development requires significant changes in existing transportation systems for increasing economic efficiency, equity, and environmental security. Also, individual transport decisions must be subordinate to community's long-term strategic objectives.

If we had to state one overall objective for urban planning, the goal would be "quality of life" instead of "sustainable mobility". However, given the current conditions of our cities, where a significant part of the population can spend hours only to reach the daily destinations, it is very difficult to separate the two goals. The consequence of this is a growing public support to the concept of sustainable mobility or at least to measures that lead to the concept. But, as stated by Banister (2008), "effective implementation of sustainable mobility requires the engagement of key stakeholders, so that they can understand the reasoning behind different policy initiatives and support their introduction". In summary, planning sustainable transportation requires fundamental changes in the existing transportation planning practices, which includes more comprehensive analysis of impacts (as stated by Berger (1998)).

The impacts of the human actions on the environment can be explained by cause-effect relationships. So, conventional planning choices accumulated throughout time have usually resulted in chronic urban problems. Those impacts can be precisely evaluated through indicators. According to Maclaren (1996), indicators are simplifications of complex phenomena and they often provide only an indication of the condition or state of a given element. Thus, a better picture is only obtained through a combination of indicators, in order to capture the different dimensions and aspects of any particular problem (Gudmundsson, 2000). Several researchers (such as OECD (1999), Gudmundsson (2000), Black et al. (2002), Nicolas et al. (2003), Gudmundsson (2004), SUMMA (2004), Rodrigues da Silva et al. (2008), Litman (2009a,b), Black (2010)) search for indicators suitable for the assessment of urban sustainable mobility, although they may have divergences about the best number and combination of indicators. Black (2010), for example, suggests the use of essentially one indicator, which is vehicle miles traveled. Nevertheless, most of them agreed upon the importance of considering economic, social and environmental aspects (see, for instance, Litman and Burwell (2006), Johnston (2008), May and Crass (2007)). Planners and public administrators in general face several difficulties for dealing with those challenges in the absence of tools for performance evaluation tailored to the case of sustainable mobility. As a consequence, the Index of Sustainable Urban Mobility (I_SUM) was developed as a strategy to overcome this problem. In order to be as comprehensive as needed, the method relies on eighty-seven indicators that cover thirty-seven themes. Those themes can be further grouped into nine main areas, or domains.

Once having set the index, the recognition of actual reference values can be quite useful to provide elements for comparison between cities, the so-called benchmarking. Our initiative is supported by the work of several authors. López-Lambas et al. (2010), for instance, stated that the creation of a common and homogeneous set of indicators, which allow a consistent monitoring of the sustainable urban transport plans, using common methods, is very important. Those authors also emphasize that the development of proper benchmarking techniques that allow authorities to learn from one another is equally important. According to Gudmundsson et al. (2005), benchmarking is usually understood as a method to compare the performances of similar organizations or processes in order to learn for the best performers. This is a clever strategy to improve one's own performance.

Thus, when it comes to sustainable urban mobility, it is also very important to find cities to serve as benchmarks. We do assume I_SUM can be used to identify cities meeting that condition. In addition, we also believe any application of the index to cities that are extensively known as good examples of sustainable urban mobility can help improve the index itself. This is the case when contradictions are found, i.e., the index results are poor despite a good reputation of the city. Thus, the objective of this work is to test the index performance in a city that is worldwide known by the quality of its transportation solutions, which is Curitiba, Brazil, in order to confirm if the index results suggest that the current conditions of sustainable mobility are indeed good. Therefore, there are two goals involved in the present study: the first one is to verify if the city of Curitiba can be used as a benchmark of sustainable mobility, and the second one is to evaluate the index itself, or the subjacent assessment method and reference values. The importance of finding cities to serve as benchmarks, even if we assume that the index can show the level of sustainable mobility in any particular city, is the possibility of learning about the strategies applied in the reference cities to reach a good performance in most indicators. The method relies then on a careful application of the Index in the city selected. The paper is structured as follows: after a brief introduction of the city in the next section, the methodology applied in this study is presented, followed by a discussion of the main results of the case study. This provides enough elements for a discussion about using Curitiba as a benchmark for sustainable urban mobility and also about the performance of the index itself, what is done in the concluding section.

2. Curitiba's urban and transportation planning

Located in the southern part of Brazil, Curitiba is the capital of the state of Paraná. The city is also the heart of a metropolitan region formed by twenty-six municipalities and over 3.1 million inhabitants (IBGE, 2012). The city's 1.8 million inhabitants are spread in 430 km^2, which are divided in nine administrative regions encompassing seventy-five neighborhoods (or 'bairros', in Portuguese). Curitiba became, in 2010, the eighth largest city in Brazil in terms of population.

The fifth position in the Brazilian rank of Gross Internal Product (IBGE, 2009) helps to explain the prosperity of Curitiba. Notwithstanding the importance of the automobile production for the local industrial sector, the metropolitan region has a diversified economy. Furthermore, the well-known quality of life standards in the city and surroundings attracted migrants form several parts of Brazil. As a consequence, Curitiba has experienced an intense development in the 1970s. Only a continuous planning process throughout consecutive administrative terms was capable of controlling the urban growth.

Curitiba's transport system became famous because of the successful association of land use and streets hierarchy aiming at a consistent public transport demand. The process started back in 1965, when the Curitiba Research and Urban Planning Institute (IPPUC) was founded. The institute was created to implement the city master plan, which later on became the preliminary mass transport plan. A trinary road system concept was then proposed. The concept is formed by a set of three parallel streets, in which the external streets are used to provide direct and fast connections between the CBD and the city periphery (and vice-versa) for the general traffic. Conversely, the central streets are reserved for express transit routes (internal lanes) and access to the local traffic (external lanes). Services and commercial activities are allowed and stimulated in the central streets, as well as higher buildings, what concentrated a transit demand along those corridors. The five transit corridors became physical references for the city development (IPPUC, 2008). The city growth was organized along those axes in a linear high-density pattern from the CBD to the outer neighborhoods, which concentrated many urban facilities and infrastructure.

The municipal public transport system, named RIT (i.e., the acronym for Integrated Transportation Network, in Portuguese) is a trunk-feeder system with physical integration provided mainly by terminals and tube stations. The latter are bus stops of the trunk and express routes. The RIT is currently connected to other cities of the metropolitan region, summing up 28 terminals, 2200 vehicles, 355 routes and 2.38 million passengers per day (L. Filla, personal communication, July 16, 2009). The routes have different colors and vehicle types depending on the function they have in the system. Express routes, for instance, are operated with bi-articulated red buses while feeder routes use orange regular buses or even micro-buses.

Despite having a public transportation system that is a worldwide reference, the motorization trend is a serious issue in the city. According to DENATRAN (2012), Curitiba reached, in 2010, over 700 vehicles per 1000 inhabitants, which is the highest motorization rate of the country. This has stimulated the municipal planning and operation agencies to think about measures to improve the circulation conditions of the streets network. Small scale interventions, such as the creation of traffic binaries, are currently considered to allow higher traffic speeds in critical parts of the network. However, the most controversial measure under discussion is the construction of a first subway line, essentially because it somehow goes against the successful transport planning philosophy built in the city along the last four decades.

3. Method

This study focus on the application of I_SUM in the city of Curitiba. Considering that the city is a reference of good transportation planning, the index application must confirm it. The application will also serve to evaluate the index itself, or the subjacent assessment method and reference values. In short, I_SUM is a method to assess the mobility conditions in any city by taking into consideration the inherent complexity of the urban space. Therefore, I_SUM can be used as a supporting tool for mobility management and for the formulation of sustainable policies. The index hierarchy of criteria was essentially structured on the top of a comprehensive set of indicators that are relatively easy to calculate and to analyze (Rodrigues da Silva et al., 2010). In addition, the index covers several aspects associated to the new paradigm of sustainable mobility while simultaneously considering traditional issues of transportation planning (Miranda et al., 2009). The index structure is described in the sequence, as well as the application method.

3.1. The index of sustainable urban mobility (I_SUM) framework

According to Costa (2008), I_SUM is an assessment tool that can be used to reveal current urban mobility conditions or to anticipate the impacts of measures and strategies aiming at sustainable mobility. The index is formed by nine domains covering thirty-seven themes, which are further subdivided into eighty-seven indicators. It was designed to cover both traditional transportation topics and questions related to the new paradigm of sustainable mobility. In addition, it is flexible enough to be adapted to different urban contexts, as a result of the diversified and comprehensive structure of the index.

The index of Sustainable Urban Mobility was developed in several stages, as described in Rodrigues da Silva et al. (2010), and summarized in the sequence. The first step was the definition of the concept of sustainable urban mobility that could be adopted in urban and transportation planning and management activities in selected Brazilian cities. The process involved the organization of several workshops with technicians, planners and decision-makers working for the public administration sector at the municipal or metropolitan level between May 2005 and November 2006. The outcome of the analyses of the aspects discussed in the eleven cities in which the workshops were organized was a list of fifty-five Alternatives. They reflected the main areas of concern regarding the issue of sustainable mobility.

The hierarchy of criteria of I_SUM started with the fifty-five Alternatives, which were defined after successive rounds of analyses, comparisons and combinations of concepts that expressed similar ideas. The final outcome of the process was the identification of nine groups, individually named to represent the main idea behind each group. Given the comprehensiveness of the concepts involved, the new groups derived from the Alternatives were then called Domains. The ninety-six original Fundamental Points of View (FPVs) obtained during the workshops with a constructivist Multicriteria Decision Analysis approach were consequently reduced to thirty-seven Themes in the I_SUM hierarchy of criteria. Finally, the I_SUM hierarchy of criteria was completed with the relocation, in the Themes, of the Indicators originally associated to the FPVs. The selection of indicators to be used in I_SUM for monitoring each one of the Themes was based on the analysis of two sets of information: (i) a reference system with roughly 2700 urban indicators organized by the authors after looking at experiences developed in Brazil and abroad; and (ii) the complete set of indicators obtained in the workshops conducted in the Brazilian cities. The process described above resulted in a final set of 87 indicators. Even considering the large number of indicators, we tried as much as possible to avoid redundancy. The process used to define the set of indicators was very helpful in that, because we started with large number of indicators and than narrowed it down to a final number that was large enough to cover the domains considered relevant but not too large that it would impossible to calculate. A guide containing procedures for their development and application was thereafter developed by Costa (2008).

The weights for Themes and Domains were obtained through a panel of experts, who work in the fields of urban planning, transportation planning, mobility and sustainability in Brazil as well as in other countries (Portugal, Germany, United States, and Australia). The experts were also asked, in the case of Themes, to assess their relative contribution directly to each one of the three Dimensions usually considered as the main parts of sustainability (i.e., Social, Economic, and Environmental). The weights of the Themes and of the sustainability Dimensions for each Theme were obtained directly from the average of the values given by the experts. In the case of the Domains, their weights were obtained from the average of the values coming from all Themes that are a part of it. The weights of the Indicators were equal and they had to sum up one within each Theme. The complete list of Domains, Themes and Indicators used in I_SUM and their respective weights can be seen in Table 1.

Considering that each Indicator may be assessed in a particular way, the resulting values of different indicators usually cannot be directly combined. In order to overcome this problem, it was necessary to define a normalization process to each of the indicators applied in I_SUM. In the case of I_SUM, the suggested normalization process is essentially based on a lookup table defined for each indicator. The reference values adopted in the lookup tables were proposed based either on Brazilian or

Table 1
The index of sustainable urban mobility (I_SUM) framework.

Domains (weights)	Dimensions weights			Themes (weights)	Indicators	Indicators weights
	Soc	Eco	Env			
Accessibility (0.108)	0.38	0.36	0.26	Accessibility to transport systems (0.29)	Accessibility to transit	0.33
					Public transportation for users with special needs	0.33
					Transport expenses	0.33
	0.40	0.32	0.27	Universal accessibility (0.28)	Street crossings adapted to users with special needs	0.20
					Accessibility to open spaces	0.20
					Parking spaces to users with special needs	0.20
					Accessibility to public buildings	0.20
					Accessibility to essential services	0.20
	0.38	0.30	0.32	Physical barriers (0.22)	Urban fragmentation	1.00
	0.46	0.28	0.27	Legislation for users with special needs (0.21)	Actions towards universal accessibility	1.00
Environmental aspects (0.113)	0.29	0.28	0.43	Control of environmental impacts (0.52)	CO Emissions	0.25
					CO_2 Emissions	0.25
					Population exposed to traffic noise	0.25
					Studies of environmental impacts	0.25
	0.26	0.32	0.42	Natural resources (0.48)	Fuel consumption	0.50
					Use of clean energy and alternative fuels	0.50
Social aspects (0.108)	0.40	0.31	0.29	Support to the citizens (0.21)	Information available to the population	1.00
	0.45	0.30	0.25	Social inclusion (0.20)	Vertical equity (income)	1.00
	0.39	0.30	0.31	Education and active citizenship (0.19)	Education for sustainable development	1.00
	0.41	0.27	0.32	Public participation (0.19)	Participation in decision-taking	1.00
	0.35	0.30	0.35	Quality of life (0.21)	Quality of life	1.00
Political aspects (0.113)	0.33	0.34	0.32	Integration of political actions (0.34)	Integration of different government levels	0.50
					Public-private partnerships	0.50
	0.33	0.40	0.27	Acquisition and management of resources (0.33)	Acquisition of resources	0.25
					Investments in transport systems	0.25
					Distribution of resources (public x private)	0.25
					Distribution of resources (motorized x non-motorized)	0.25
	0.34	0.33	0.32	Urban mobility policy (0.34)	Urban mobility policy	1.00
Transport infrastructure (0.120)	0.28	0.41	0.31	Provision and maintenance of transport infrastructure (0.46)	Density of the street network	0.25
					Paved streets	0.25
					Maintenance expenditures in transport infrastructure	0.25
					Streets signaling	0.25
	0.33	0.35	0.33	Distribution of transport infrastructure (0.54)	Transit lanes	1.00
Non-motorized modes (0.110)	0.32	0.29	0.39	Bicycle transportation (0.31)	Length and connectivity of cycleways	0.33
					Bicycle fleet	0.33
					Facilities for bicycle parking	0.33
	0.33	0.28	0.39	Pedestrians (0.34)	Pathways for pedestrians	0.50
					Streets with sidewalks	0.50
	0.28	0.32	0.40	Trips reduction (0.35)	Travel distance	0.25
					Travel time	0.25
					Number of trips	0.25
					Measures to reduce motorized traffic	0.25
Integrated planning (0.108)	0.31	0.37	0.32	Managers training (0.12)	Expertise of technicians and managers	0.50
					Training for technicians and managers	0.50
	0.35	0.30	0.35	Central areas and historical sites (0.11)	Vitality of the central area	1.00
	0.31	0.34	0.35	Regional integration (0.12)	Intercity partnerships	1.00
	0.38	0.32	0.31	Planning process transparency (0.12)	Transparency and responsibility	1.00
	0.31	0.32	0.36	Planning and control of land use (0.14)	Vacant land	20
					Urban growth	0.20
					Urban population density	0.20
					Mixed land use	0.20
					Illegal settlements	0.20
	0.32	0.35	0.33	Strategic and integrated planning (0.14)	Integrated urban. environmental and transport planning	0.50
					Implementation and sequence of planed actions	0.50
	0.31	0.39	0.30	Infrastructure and urban facilities planning (0.13)	Parks and green areas	0.33
					Urban facilities (schools)	0.33
					Urban facilities (hospitals)	0.33
	0.31	0.35	0.35	Master Plan and urban legislation (0.12)	Master Plan	0.33

Table 1 (*continued*)

Domains (weights)	Dimensions weights			Themes (weights)	Indicators	Indicators weights
	Soc	Eco	Env			
					Urban legislation	0.33
					Urban legislation actual application	0.33
Urban circulation traffic (0.107)	0.37	0.38	0.26	Traffic accidents (0.21)	Traffic accidents	0.33
					Accidents with pedestrians and cyclists	0.33
					Accident prevention	0.33
	0.39	0.31	0.30	Traffic education program (0.19)	Traffic education program	1.00
	0.29	0.35	0.36	Freedom of movements and circulation (0.19)	Congestion	0.50
					Average traffic speed	0.50
	0.34	0.33	0.33	Traffic operation and enforcement (0.20)	Violation of traffic rules	1.00
	0.32	0.31	0.36	Private transport (0.21)	Motorization rate	0.50
					Vehicle occupation	0.50
Urban transport systems (0.112)	0.35	0.33	0.32	Transit availability and quality (0.23)	Total extension of the transit network	0.13
					Transit service frequency	0.13
					On-time performance	0.13
					Transit average speed	0.13
					Transit fleet age	0.13
					Passengers per kilometer	0.13
					Annual number of passengers	0.13
					User satisfaction with the transit service	0.13
	0.31	0.34	0.34	Diversity of transportation modes (0.18)	Diversity of transportation modes	0.33
					Public versus private transport	0.33
					Motorized versus non-motorized modes	0.33
	0.34	0.35	0.31	Transit regulations and enforcement (0.18)	Contracts and limitations	0.50
					Informal transport	0.50
	0.37	0.33	0.30	Transit integration (0.22)	Intermodal terminals	0.50
					Transit integration	0.50
	0.38	0.37	0.25	Fare policy (0.19)	Discounts and free rides	0.33
					Transit fares	0.33
					Public subsidies	0.33

international standards found in the literature or on the experience of the index developers, who adapted the existing reference values to the context of Brazilian cities. After all indicators were individually normalized to values between zero and one, they could be aggregated according to a decision rule. The aggregation method proposed to I_SUM was based on a weighted linear combination, in which all the criteria were combined through a weighted average. This method allows for a total trade-off among criteria. It means that a very poor attribute, translated as a low score obtained for one criterion, can be compensated by a number of good attributes, translated as higher scores obtained for some other criteria. Given the adopted structure of Domains, Themes and Indicators, and the insertion of the sustainability Dimensions, the criteria aggregation process resulted in a global index and in three sectorial indexes, one for each Dimension.

The structure suggested to I_SUM also allows evaluations based on a reduced number of indicators. This is the case when the data needed for the calculation of all eighty-seven indicators are not reliable or simply do not exist. However, if a reduced number of indicators is used, it is necessary to redistribute the weights of the indicators within each Theme. The same procedure may be needed for Themes and for Domains, in order to assure that the weights in each hierarchy level always sum up one.

The association of the hierarchical structure formed by the domains, themes and indicators with a weighing system allows the identification of the relative contributions of each of these components to the global index. This index feature can be used in the formulation of policies directed exclusively to mobility issues or integrated with other planning areas, which can result in a more rational and efficient use of the available resources (Miranda et al., 2009). The application of the index may help identify critical factors likely to produce a significant impact on global and partial aspects of urban mobility. As stated by Costa (2008), this information can be very useful in the design of strategies and policies aiming at sustainable mobility.

3.2. Input data

Due to its comprehensive structure, the Index of Sustainable Urban Mobility requires a substantial amount of data and information for the applications. These inputs can be obtained from many different data sources, but the municipal administrations usually have most of what is needed. However, as some data may not be easily obtained anywhere, it is important to carry out a previous availability evaluation of the data required for the calculation of each one of the index indicators. If a particular indicator cannot be calculated, it has to be removed from the index hierarchical structure and the weights of the remaining indicators within the same theme have to be redistributed to still sum up one. The overall index value is obviously more representative if a large number of indicators is calculated.

The data applied in the calculation may vary significantly. Some are statistical figures (e.g., number of inhabitants in a certain area) while other are physical attributes of urban elements (e.g., the location of transit stops). In Curitiba, the main data sources for an I_SUM application are two municipal agencies: Curitiba Research and Urban Planning Institute (IPPUC) and Curitiba Urbanization (URBS). These important institutions are in charge of planning, implementation and management of the city's transportation systems. Also, other departments and secretaries, public institutions at federal, state or municipal levels, as well as websites, are supplementary data sources.

3.3. Index calculation

A consequence of the large number of I_SUM indicators is the diversity of calculation procedures. The scores of some indicators are easily obtained, because they depend only on direct information or simple mathematical operations. This is the case of the indicator urban population density, which is simply the division of the number of inhabitants in the urban area by that area. However, some indicators require complex procedures. The indicator urban growth, for example, is the division of the area of new developments (projected or under implementation) in urban regions with existing transport services and infrastructure by the area of new developments (projected or under implementation) in urban regions without transport services and infrastructure (Costa, 2008). The complexity resides here in the fact that many municipalities do not have a prior and complete knowledge of the private sector urban development projects. Also, the inventory of existing infrastructures and transport services is quite often outdated or not available in either digital or even paper maps. Actually, the lack of reliable spatial data is a general problem that can result in a poor evaluation of the index.

A preliminary examination has shown that only a few indicators could not be calculated in Curitiba due to data unavailability. The calculation of all other indicators, their conversion into scores and standardization procedures followed the original recommendations of the Guide for the Calculation of I_SUM Indicators (Costa, 2008).

3.4. Evaluation of the results

In addition to an overall score, the numerical result obtained for each I_SUM indicator directly reflects the condition of the topic under analysis. Low scores (i.e., close to zero) show that the service or condition analyzed is unsatisfactorily serving the population. Conversely, high scores (i.e., close to one) indicate a satisfactory situation. The straightforward information provided by the indicators scores make it simple to assess the positive and negative aspects affecting the sustainable urban mobility conditions of any city. This was exactly the approach adopted when applying I_SUM to Curitiba. After the indicator scores were calculated, those with the best and worst scores were separately analyzed.

In the case of negative results, the following question was also considered. Would it be possible that particular conditions of the city could have produced biased or unfair results? The explanation for that procedure is simple. The indicators and respective reference values used in I_SUM consider general conditions applicable to any city. However, all cities have differences and particularities that may produce distinct outcomes even when they are subjected to the same policies, procedures or conditions. Once confirmed that an indicator is not allowing a fair evaluation of any mobility aspect of the city, an analysis of the indicator calculation method must be conducted, as we have done in the present study.

As a final step of the process, Curitiba was submitted to a regional evaluation, i.e. the index was calculated again for the nine administrative subdivisions of the city. This was a process with some limitations, though, because not all data needed for the calculations was available at the same aggregation level. When this was the case, the indicators scores found for the entire municipality were simply transferred to all subdivisions.

4. I_SUM results in Curitiba

The main results of the I_SUM application in the city of Curitiba are presented in this section, along with the analyses of some of the most important outcomes.

4.1. The overall performance of the city

Seventy-two of the eighty-seven indicators that compose I_SUM were calculated in the city of Curitiba. The fifteen indicators that could not be calculated are distributed in all Domains but Political Aspects, as shown in Table 2. Six of those indicators would have been calculated with the results of an origin-destination survey. Unfortunately this helpful transportation planning tool used to identify the population travel patterns was not available for the index calculation. In reality, Curitiba never conducted a complete origin-destination survey. However, there is no doubt that even without it the city has managed to meet the transport demand with efficiency and effectiveness. The explanation for that success may be in the long term planning efforts carried out in the city, where the implementation of successive municipal Master Plans was not discontinued by administrative or political changes (Lindau et al., 2010). Strong and active planning agencies, such as IPPUC and URBS, play an important role in that process by assuring the established goals are really reached.

The planning process always focused on a controlled city growth that was essentially oriented by the public transportation supply. Therefore, as the main desire lines were somehow induced, the planning agencies were not dependent on surveys (and more specifically, O–D surveys) to identify them. However, useful additional information (e.g., the modal split, and travel times and distances) was also not available since detailed surveys were not conducted. As a consequence, we were not able to calculate the indicators that rely on this information.

The global I_SUM value for Curitiba resulting from the calculation of the 72 remaining indicators was 0.747. A result that is about three-quarters of the maximum possible value suggests that even Curitiba, despite the several merits of the urban and transportation planning processes, is not a perfect example of sustainable mobility. Curitiba has many characteristics of a large urban area, including the physical dimensions, what results in many problems with the same level of complexity of most metropolitan areas in Brazil. Nevertheless, the city has successfully managed those problems, as shown by many results found during the calculation of the I_SUM indicators. In summary, the city can be seen as a reference in many aspects. Table 3 has the

Table 2
I_SUM indicators that could not be calculated in the city of Curitiba.

Domain	Indicator
Accessibility	Accessibility to public buildings
Environmental aspects	CO Emissions
	CO_2 Emissions
Social aspects	Vertical equity (income)
Transport infrastructure	Street signaling
Non-motorized modes	Travel distance
	Travel time
	Number of trips
Integrated planning	Expertise of technicians and managers
	Training for technicians and managers
Urban circulation and traffic	Accidents prevention
	Congestion
	Violation of traffic rules
Urban transport systems	Public versus private transport
	Motorized versus non-motorized modes

Table 3
The final scores of the I_SUM indicators in Curitiba.

Domains	Themes	Indicators	Scores
Accessibility	Accessibility to transport systems	Accessibility to transit	0.95
		Public transportation for users with special needs	1.00
		Transport expenses	0.82
	Universal accessibility	Street crossings adapted to users with special needs	0.60
		Accessibility to open spaces	0.82
		Parking spaces to users with special needs	**0.20**
		Accessibility to public buildings	not available
		Accessibility to essential services	0.85
	Physical barriers	Urban fragmentation	**0.00**
	Legislation for users with special needs	Actions towards universal accessibility	1.00
Environmental aspects	Control of environmental impacts	CO Emissions	not available
		CO_2 Emissions	not available
		Population exposed to traffic noise	0.96
		Studies of environmental impacts	1.00
	Natural resources	Fuel consumption	0.99
		Use of clean energy and alternative fuels	0.35
Social aspects	Support to the citizens	Information available to the population	1.00
	Social inclusion	Vertical equity (income)	not available
	Education and active citizenship	Education for sustainable development	0.75
	Public participation	Participation in decision-taking	1.00
	Quality of life	Quality of life	0.80
Political aspects	Integration of political actions	Integration of different government levels	0.75
		Public-private partnerships	1.00
	Acquisition and management of resources	Acquisition of resources	0.31
		Investments in transport systems	1.00
		Distribution of resources (public x private)	0.25
		Distribution of resources (motorized x non-motorized)	0.25
	Urban mobility policy	Urban mobility policy	1.00
Transport infrastructure	Provision and maintenance of transport infrastructure	Density of the street network	1.00
		Paved streets	0.89
		Maintenance expenditures in transport infrastructure	1.00
		Streets signaling	not available
	Distribution of transport infrastructure	Transit lanes	0.90
Non-motorized modes	Bicycle transportation	Length and connectivity of cycleways	0.25
		Bicycle fleet	1.00
		Facilities for bicycle parking	**0.00**
	Pedestrians	Pathways for pedestrians	0.25
		Streets with sidewalks	1.00
	Trips reduction	Travel distance	not available
		Travel time	not available
		Number of trips	not available
		Measures to reduce motorized traffic	0.25
Integrated planning	Managers training	Expertise of technicians and managers	not available
		Training for technicians and managers	not available
	Central areas and historical sites	Vitality of the central area	0.51
	Regional integration	Intercity partnerships	1.00
	Planning process transparency	Transparency and responsibility	1.00
	Planning and control of land use	Vacant land	0.91
		Urban growth	0.94
		Urban population density	0.00
		Mixed land use	1.00
		Illegal settlements	1.00
	Strategic and integrated planning	Integrated urban. environmental and transport planning	1.00
		Implementation and sequence of planed actions	1.00
	Infrastructure and urban facilities planning	Parks and green areas	1.00
		Urban facilities (schools)	1.00
		Urban facilities (hospitals)	**0.00**
	Master Plan and urban legislation	Master Plan	1.00
		Urban legislation	1.00
		Urban legislation actual application	1.00
Urban circulation and traffic	Traffic accidents	Traffic accidents	0.99
		Accidents with pedestrians and cyclists	1.00
		Accident prevention	not available
	Traffic education program	Traffic education program	1.00
	Freedom of movements and circulation	Congestion	not available
		Average traffic speed	0.38
	Traffic operation and enforcement	Violation of traffic rules	not available
	Private transport	Motorization rate	**0.00**
		Vehicle occupancy	**0.15**

Table 3 (*continued*)

Domains	Themes	Indicators	Scores
Urban transport systems	Transit availability and quality	Total extension of the transit network	**0.13**
		Transit service frequency	1.00
		On-time performance	0.99
		Transit average speed	0.45
		Transit fleet age	0.83
		Passengers per kilometer	1.00
		Annual number of passengers	0.50
		User satisfaction with the transit service	0.59
	Diversity of transportation modes	Diversity of transportation modes	0.75
		Public versus private transport	not available
		Motorized versus non-motorized modes	not available
	Transit regulations and enforcement	Contracts and limitations	1.00
		Informal transport	1.00
	Transit integration	Intermodal terminals	**0.00**
		Transit integration	1.00
	Fare policy	Discounts and free rides	1.00
		Transit fares	0.66
		Public subsidies	0.75

entire list of indicators and their final scores. The scores with high values (i.e., close or equal to one) are displayed in italics while the scores with low values (i.e., close or equal to zero) are shown in bold.

4.2. Indicators with good performances

The city had an excellent performance in the indicators that show the accessibility conditions to public services and facilities for persons with mobility constraints. In the domain Environmental Aspects, four indicators have been effectively calculated and indicate a clear concern of the municipality to preserve the natural environment manifested through measures and actions. An example is the use of clean energy and alternative fuels. The city is gradually introducing public transport buses operating with biodiesel. The announced strategy is to replace the entire fleet within the next few years, given that all new buses will always come with biodiesel engines. In this way, the city will soon reach the maximum score for the indicator use of clean energy and alternative fuels.

Social issues are also a concern of the city planners, as shown by the good scores obtained in Curitiba for the indicators of the domain Social Aspects. The population is not only generally well informed about the activities of the municipal administration, but also has opportunities to participate in the decision taking process. In addition to public consults, the city benefits from: an urban mobility policy, investments in the transport systems, and public–private partnerships (all part of the Domain Political Aspects). The city also had an excellent performance regarding the Transport Infrastructure, with a dense and highly connected street network. The high level of investments in the maintenance of the transportation system is another positive city aspect. A large number of streets with sidewalks and a good bicycle fleet are the highlights regarding non-motorized transport modes, although cycling is mainly seen as a leisure activity in the city.

Curitiba is recognized as an example of successful urban and transportation planning, as well as a model of policy continuity despite successive administrative changes. Those characteristics are typical of high-quality planning leading to actual plans and effective enforcement of the legislation. Clear consequences of it are (i) the high proportion of green public areas for leisure and (ii) less illegal settlements than usually found in most large Brazilian cities.

Regarding urban public transportation, Curitiba obtained good scores for the indicators associated to service frequency, system integration, contracts and licitations, just to mention some. One of the city highlights, though, was the inexistence of informal transport, a critical issue in most Brazilian cities of the same size.

4.3. Critical Indicators

In addition to provide elements for a detailed analysis of the mobility conditions in virtually any city, another positive feature of I_SUM as a planning tool is the possibility of using it to detect potential points for improvement. The indicators that have the lowest scores are undoubtedly those with the biggest deficiencies. They are, therefore, the ones that deserve immediate attention regarding mobility planning. In the case of Curitiba, some indicators of the domain Non-motorized Modes are in that condition, if compared to most indicators of the other domains. The city cycleways, for example, do not constitute a large network and are designed to serve mainly leisure purposes. Also, the lack of specific places for bicycles storage in public transportation terminals, just a few exclusive pedestrian malls, and practically no measures to restrict the motorized traffic are conditions that suggest the city preference for the circulation of motorized vehicles, both public and private. The performance in that particular domain shows that despite the excellent initiatives adopted to improve the urban public transportation system, the city still has to change some conditions regarding the private car for moving towards sustainable mobility.

The poor performance in indicators such as motorization rate and average car occupancy reflect a global problem with social implications: the automobile culture. Even in a city like Curitiba, which has a very effective public transportation system, a large share of the population still chooses to use the automobile for the regular trips. In addition to a massive use of the automobile, the reduced average car occupancy rate (i.e., 1.44 persons per vehicle) contributes to increase the number of private vehicles in circulation.

In practice, it is certainly not easy to change the current condition of the indicator that looks for measures to reduce the motorized traffic, because restrictions on the use of private cars are usually not well accepted by the population. This is a political burden that most administrators are not willing to take. Finally, the average traffic speed indicator reflects another complex mobility issue, which is congestion. Apparently there is no short-term solution for this problem, which does not happen only in Curitiba but in most large cities of the planet.

The challenges to be faced in order to reach sustainable mobility are enormous. They include a change in the current population perception of mobility, in which the society is no longer dependent on the automobile. Apparently only in this condition people will accept measures to restrict the car use.

4.4. Indicators that are not adequately adjusted to the city conditions

The indicator urban fragmentation must be discussed in more details for the purpose of this study. According to the original definition of Costa (2008), urban fragmentation is the proportion of continuous urbanized land in the total urbanized area of a municipality. This refers to the land that is not crossed by any major transportation infrastructure (e.g., freeways, railways, fully segregated transit corridors, large terminals), or any other natural or artificial physical barriers that produce a discontinuity in the urban fabric. Nevertheless, it is certainly not very easy to find cities without any of those interferences, given that even natural elements can become physical barriers. In the case of large cities, this is even more likely to happen. In the particular case of Curitiba, the urban fragmentation condition is intensified by the widespread presence of parks and green areas. It is difficult to consider, though, that parks and green areas are a problem, given that they clearly improve the overall population's quality of life. Based on this, the indicator seems inappropriate to be applied in Curitiba, at least as it was originally formulated.

Another indicator that had an unexpected score for the city was population density. Curitiba is not only known because of the city planning process, but also because it has followed what was proposed in the successive plans. In the case of zoning, that resulted in very specific patterns of high density along the transport corridors, which are also development axes. The densities are intentionally lower far from those corridors, where green areas are combined with single-family dwellings. The distinct development patterns created a large variation of population densities within the city. This goes against what is recommended by I_SUM, i.e., overall high densities. One could certainly argue that the city was then unfairly penalized for the planning choices regarding land use, given that the actual land use patterns do not jeopardize the citizens' quality of life. On the contrary, the low density areas are in this case usually combined with green areas and leisure facilities that improve the population's quality of life.

Also, another apparent contradiction of the application is the fact that the city was penalized because its transportation planning has always been concentrated on a public transportation system based only on buses. Despite the number and functionality of the bus terminals, they are not integrated with other transport modes, not even the bicycle. Therefore, the indicator intermodal terminals had a null score. Another problem of the bus alternative is the system operational speed. Differently from rail modes, buses operational speeds are limited by the number of bus stops and interferences along the way, such as at level crossings, etc.

The indicator total extension of the transit network also presented an unexpected result, when calculated according to the I_SUM method. A transit network does not necessarily need to have a total extension equivalent to the entire city's street network for assuring a total coverage of the urban area. In the case of Curitiba, for example, this assumption was confirmed by the indicator accessibility to transit, which is part of the Accessibility domain. The calculation of this indicator has shown that 95% of the city is covered by the public transportation system, despite the fact that the transit network extension is only around 30% of the total length of the city's street network (i.e., a poor performance in the indicator total extension of the transit network). A geographical coverage of 100% is just reasonable in the case of radial or diametral transit systems, in which several routes converge to the central area of the city. This certainly means a high percentage of coincident routes, which is an undesirable misuse of resources and infrastructure. The trunk-feeder transit system of Curitiba does not face the same problem, but the I_SUM indicator was not able to capture that positive feature of the system. Therefore, it needs to be revised.

If the indicators are not separately analyzed, the identified problems seem a consequence of the city size and of the single mode of public transportation. It may indicate that the city must carefully think about sustainable development, since the simple but important issues were already solved. Using exclusively buses as the transit alternative is not necessarily a problem. Even some of the I_SUM indicators have shown that the city's system is effective and efficient. Rail solutions, which are often seen as the best option for cities as big as Curitiba, may not be really needed in that case. The fact that I_SUM deals with general topics that are common to virtually any city does not mean that the indicators and reference values cannot be adjusted to accommodate context specificities, given that no two cities are exactly the same.

4.5. Local I_SUM values

The application of I_SUM in Curitiba was also separately done in each one of the nine administrative subdivisions. An interesting outcome of that procedure is the possibility of easily comparing the results, given that the same databases were available for all subdivisions. If this was not the case, a direct comparison would not be advisable. This recommendation also applies when considering comparison between cities.

A problem for the index application in sectors of the city was the lack of disaggregated data in the case of several indicators. Many variables needed for the calculations were only available at the city level. As a consequence, only indicators relying on data with spatial reference, which could be obtained with geographical information systems, were recalculated. This restricted the index variation to those 19 indicators (Table 4), since all other indicator values were similar to the overall city values. The results found in the calculation of the local I_SUM values have shown only small differences in the mobility conditions of the distinct subdivisions. Also, the local values are not very different from the overall city value of 0.747. This is shown in Fig. 1, which contains the spatial distribution of the subdivisions and the respective local I_SUM values.

Table 4
Indicators considered when calculating local values of I_SUM in the city of Curitiba.

Domains	Indicators
Accessibility	Accessibility to transit
	Accessibility to open spaces
	Accessibility to essential services
	Urban fragmentation
Environmental aspects	Population exposed to traffic noise
Transport infrastructure	Density of the street network
	Paved streets
	Transit lanes
Non-motorized modes	Length of cycleways
	Pathways for pedestrians
Integrated planning	Vacant land
	Urban growth
	Urban population density
	Mixed land use
	Illegal settlements
	Parks and green areas
	Urban facilities (schools)
	Urban facilities (hospitals)
Urban transport systems	Total extension of the transit network

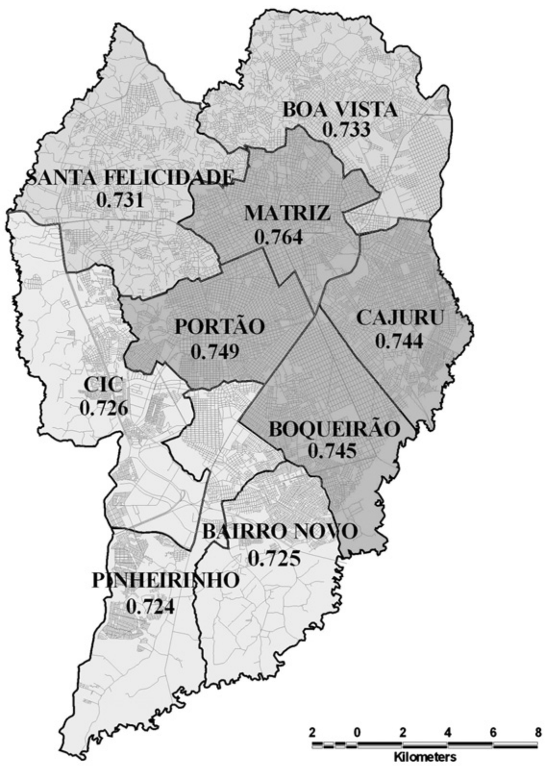

Fig. 1. Local values of I_SUM in the city of Curitiba.

The best performance of the Matriz subdivision (Fig. 1) could be anticipated, since it aggregates the CBD and adjacent neighborhoods where the available transportation infrastructure is very good. The worst performance of the Pinheirinho subdivision was also not a surprise, given it is a sector of the city under development. As a consequence, it still has some illegal settlements occupied by low income segments of the population. In addition, it is the area where the metropolitan landfill, which is a major land use constraint, is located. Another land use constraint in the area is the Iguaçu Environmental Protection Area. High-income subdivisions with large green areas and parks, such as Boa Vista and Santa Felicidade, were penalized in the calculation of the sustainable mobility index. In contrast, popular and high density subdivisions of the city, like Boqueirão, had a good I_SUM score.

The index values range from 0.724 to 0.764, for an overall value of 0.747. Not withstanding the differences in the index values observed in the nine subdivisions, the small variation is noteworthy. It suggests that a balanced distribution of good mobility conditions is provided in the whole city area (and therefore to the entire population), which is quite an achievement for the city.

5. Conclusion

The results obtained in the present study were all based on a comprehensive method developed to assess sustainable mobility conditions in virtually any city. The main output of the method is a value for the Index of Sustainable Urban Mobility, or I_SUM, ranging from zero to one—in which zero is the worst possible value and one is the best situation (Costa, 2008, Rodrigues da Silva et al., 2010). The application of I_SUM in the city of Curitiba produced some interesting outcomes, which are discussed in the sequence.

Curitiba, like any other city, faces many different problems. Therefore, despite being a worldwide successful example of good urban and transportation planning, it may not be a perfect model of sustainable mobility. Considering its structure, the Index of Sustainable Urban Mobility should be able to assess the degree of success of the city regarding sustainable mobility policies. The results, which led to a global value of 0.747, confirmed both the ability of the index to capture the strengths of the city planning strategies and the good results produced with the municipal mobility policies. In addition, when looking at the partial Domain results, the city reputation of good urban and transportation planning is confirmed by the excellent performance in the Domains Infrastructure, Social Aspects and Integrated Planning.

The fact that the index value is not the maximum, however, shows that the city is not perfect in all aspects of sustainable mobility planning. While urban public transportation is an incontestable example of good planning, infrastructure provision and operation, the non-motorized modes (and more specifically, the bicycles) do not seem to enjoy the same status. The reason is quite simple: the planning option of the city was to focus on cycling as essentially a leisure activity. Interestingly, the effectiveness and geographical coverage of the transit system act as a disincentive to the use of the bicycle as a regular transport mode. In contrast, apparently this is not helping to reduce the automobile dependence. The overall high car ownership rate and the low average car occupancy rate may indicate a future need of measures to restrict the car use in the city.

The results have also shown that I_SUM was not able to capture some of the positive aspects of the city. Curitiba is well-known by the successful strategies to implement and to control a long term land use policy, which were not interrupted by government changes. The city was planned in such a way that different parts of the municipal territory were meant to have different population densities. While high densities were stimulated along transport corridors, many other areas were valued by the low density patterns free of tall buildings. As a result, the overall average population density is below the value seen as the ideal value in the index methodology. A critical analysis of the situation suggests that the method recommendation is against a measure that improves the citizens' quality of life. In other words, the method should not focus only on the overall density value, but also on the population distribution in the territory.

Another indicator that was not favorable to the city evaluation is related to the average speed of the urban public transportation system. The value found in the city is below the value seen as satisfactory in the index methodology. The reason for this is the city's reliance on buses to operate the transit services. Even considering their operation in segregated lanes, the buses have more stops than other mass transport systems (e.g., the metro). This increases the accessibility of the system, which is a positive aspect not considered in the index methodology. Once again, the reference values of the method were somehow adverse to the city, given the uniqueness of the city characteristics. Also in this case, what was good for the index was not necessarily good for the city of Curitiba.

We also have to discuss the fact that it was not possible to calculate all indicators. In fact, some of the missing indicators could have been indirectly calculated. This was the case, for example, of CO_2 emissions, which could have been estimated by looking at the fuel consumption. However, the objective of the current application was not to have all the indicators calculated (or estimated), given that I_SUM is flexible enough to give reasonable results even without all indicators values. This is certainly a point that has to be observed when using the index to compare different cities. A common set of indicators has to be considered in this case. Some core indicators could be defined to assure that without those indicators a comparison should not be conducted, but we did not establish it yet.

Alternatively, what we are doing when trying to establish values for comparisons is to work with ranges instead of values. In this case, we calculate all indicators that are available. Next, we arbitrarily set three possible values for the indicators that could not be calculated: zero, one, and our best estimate. We then calculate the Index value three times, one for each set of values. In this way, we may have a reasonable estimate of the minimum and maximum limits and also our estimate within the range. If we adopt the same procedure for the different cities under analysis, the comparison of ranges becomes acceptable.

As a final remark, it is important to highlight the fact that Curitiba is indeed keeping a very good standard of sustainable mobility, particularly considering the city metropolitan insertion. This can be confirmed by the small variation between the overall city index and the intraurban I_SUM values also calculated. The uniformity of the results is an essential characteristic of sustainable mobility. It may suggest that the city provides fair and equitable mobility conditions to all citizens throughout the city.

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