A new tool for the assessment of public transportation systems: the METRIX

Uma nova ferramenta para avaliação de sistemas de transporte público: o METRIX

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ABSTRACT
Many transit performance indicators collect excessive data, which are costly, complex, and arduous. An excessive dependence on the availability of various data makes benchmarking difficult and sometimes impossible. However, other methods are simple but too limited to capture a systemic global view. This study presents an efficient tool that acknowledges the current situation of the transit system of a given metropolis and enables comparisons with several national and international references. The Metropolitan Transit Index (METRIX) is the relationship between the number of trips by quality public transit (QPT) modes in a workday and the number of inhabitants in a given metropolitan

region. It was applied to 25 metropolises worldwide for the year 2018, which were then ranked from the highest to lowest to score their transit development. Our results show that Tokyo and Paris are two of the most transit-oriented metropolises globally, while Seattle, Atlanta, and Los Angeles are the most automobile-oriented. Additionally, we found that Asian and European metropolises have a higher METRIX, whereas South American and North American metropolises (especially US cities), except São Paulo, have a lower METRIX. The data indicate a trend towards greater METRIX in cities that chose a greater proportion of rail over bus QPT services.

Keywords: transit performance indicator, transit ridership, mobility.

RESUMO
Muitos indicadores de desempenho de transporte coletam dados excessivos, que são caros, complexos e trabalhosos. Dependendo muito da disponibilidade de vários dados, o *benchmarking* é difícil e às vezes impossível. Por outro lado, outros métodos são simples, mas muito limitados para capturar uma visão sistêmica global. Este estudo apresenta uma ferramenta eficiente que reconhece a situação atual do sistema de transporte de uma determinada metrópole e possibilita comparações com diversas referências nacionais e internacionais. O Índice de Transporte Metropolitano (METRIX) é a relação entre o número de viagens por modais de transporte público de qualidade (TPQ) em um dia útil e o número de habitantes em uma determinada região metropolitana. Ele foi aplicado a 25 metrópoles no mundo inteiro para o ano de 2018, que foram classificadas do mais alto para o mais baixo para pontuar seu desenvolvimento em transporte. Nossos resultados mostram que Tóquio e Paris são duas das metrópoles mais orientadas para o transporte, enquanto Seattle, Atlanta e Los Angeles são as mais orientadas para o automóvel. Além disso, descobrimos que as metrópoles asiáticas e europeias têm um METRIX mais alto, enquanto as metrópoles da América do Sul e da América do Norte (especialmente cidades dos EUA), exceto São Paulo, têm um METRIX mais baixo. Os dados indicam uma tendência de maior METRIX nas cidades que optaram por uma maior proporção de serviços por trilhos em vez de TPQ por ônibus.

Palavras-chave: indicador de desempenho de transporte, transporte de passageiros, mobilidade.

1 INTRODUCTION

A vicious circle can be observed in major metropolitan areas globally. The increase in traffic congestion during peak hours and the poor supply of high-quality public transit services force users to seek alternatives to transit through the city. When migrating to individual transportation modes, such as motorcycles, automobiles, and on-demand transportation applications, public transit demand diminishes. Consequently, a fare rise follows to maintain the economic equilibrium of the system. In metropolises, the growth in private vehicle circulation results in traffic congestion spreading and worsening throughout the day, with this reaching off-peak hours. These changes result from the lack of efficient public transportation (carrying fewer passengers at a higher cost), inhibiting new investments and improvements in the public transportation system, which perpetuates the vicious circle by provoking new passenger migration to private transportation modes (Cervero, 1998; Rode et al, 2017).

It is a considerable challenge for public transportation planners and the public transportation system to break this chain and offer an alternative to private vehicles as a means of transportation (Curtis and Scheurer, 2017). Such a challenge can be summed up as changing the mobility culture in which citizens explore and bring life to the city, that is, bringing together the values, perceptions, and preferences of travelers, as well as the perceptions and preferences of decision-makers within the system of urban mobility; this includes the built environment of cities, transportation networks, and urban design (Kuhnimhof and Wulfhorst, 2013). We need to understand and evaluate the development of transportation systems and travel behavior in metropolitan regions worldwide to address this chronic urban mobility problem and provide a framework to successfully implement appropriate strategies for the future development of urban mobility (Kuhnimhof and Wulfhorst, 2013). Therefore, indicators are the fundamental tools for assessing the underlying driving forces that shape urban mobility within metropolises. This enables the analysis of current conditions, strengths and weaknesses, future mobility opportunities, and a comparison of a metropolis' position relative to its peers (Kuhnimhof and Wulfhorst, 2013; Priester, Kenworthy and Wolfhurst, 2013).

A series of transit performance metrics have been created and improved over the years (Braga et al, 2019). They have addressed several aspects such as the transportation system's sustainability and its relation to social, economic, and environmental factors (Chakhtoura and Pojani, 2016; Mihyeon, Jeon and Amekudzi, 2005; Rodrigues da Silva et al, 2015), the use of accessibility performance measures (Boisjoly and El-Geneidy, 2017; Curtis and Scheurer, 2017), the reliability of a public transportation system and its impact on travel behavior and system performance assessment (Kathuria, Parida and Sekhar, 2020; Taylor, 2013), the use of both accessibility and reliability to evaluate a network's performance and vulnerability (Kim and Song, 2018), the perceptions of urban travelers in terms of the interactions among accessibility, mobility, and connectivity (Cheng and Chen, 2015), as well as passenger perceptions and transit agency performance measures of transit service quality (Eboli and Mazzulla, 2011), among others. Many of these studies collect excessive data that is expensive, complex, and toilsome. A high dependence on the availability of various data makes benchmarking impossible or challenging. Other methods are simple however they are too limited to capture a systemic global view. Accordingly, to the best of our knowledge, no study has attempted to develop a simpler but more efficient, easy-to-use, and generalizable tool that is broadly applicable to measure public transportation's development within and between metropolises.

We present the Metropolitan Transit Index (METRIX), which is the relationship between the number of trips accomplished by quality public transit (QPT) modes in a workday and the number of inhabitants in a given metropolitan region. This dynamic index captures the demand and supply sides of public transportation and the perceptions and preferences of travelers and decision-makers within the system of urban mobility. The METRIX was envisioned to permit a five-dimensional analysis: (i) monitoring of a metropolis' transit evolution over time, (ii) comparison between different metropolises in the same country or internationally, (iii) definition of an excellence metric through the ranking of the surveyed metropolises, (iv) aiding the impact evaluation of a proposed transit alternative within a network planning context, and (v) the ability to be utilized in conjunction with other indicators to improve a metropolis' transit diagnosis. Consequently, it allows scholars, the press, policymakers, transit planners, and the wider public to participate in the development process of a vision of a sustainable city by fostering the debate on the problems and challenges faced by the process of development of a metropolis' transit system, based on a standardized and comparable model.

The remainder of this study is organized as follows. Section 2 presents the theoretical foundation, in which we discuss the literature background, the definitions of quality and public transportation modes, and the link between land use and transit and its effects on public transportation quality. Section 3 provides a step-by-step guide on the process of developing the METRIX. Section 4 presents the findings of applying the index for 25 metropolises in 2018. Section 5 presents the conclusions and suggestions for further research.

2 THEORETICAL FOUNDATION

For policymakers and practitioners in public transportation to pursue policies and actions to retain current users while attracting new ones, it is necessary to understand, identify, and balance the requirements along the physical dimension (the relationships between urban form, urban structure, transit, and traffic) with the socio-economic dimension (to think of the city as an urban function, analyzing which aspects of public transportation influence users' satisfaction and loyalty) (Van Lierop, Badami and El-

Geneidy, 2017; Zito and Salvo, 2011; Živković, 2018). The interrelationship between all these elements (rather than their particular characteristics) shapes the urban space by creating different configurations of metropolitan areas.

The characteristics of the physical dimension, such as urban design, road and transportation networks, the distribution of densities, and the characteristics of the socio-economic dimension, such as land-use patterns and the level of job centralization, significantly impact demand and supply for urban transportation (Rode et al, 2017). Similarly, aspects such as the accessibility of transportation systems, as well as their degree of connectivity, travel cost, service levels, and travel speeds affect urban function, influencing population density, land-use intensity, urban structure, and urban form (Zhou and Gao, 2020). There are many possible combinations of transportation and urban forms, ranging from sprawling car-oriented cities (Los Angeles) to cities with rail-based public transportation (Tokyo), with each having developed its unique spatial structure and transportation system, providing different levels of access. Diverse types of urban agglomerations at varied levels of development can be found in different parts of the world (Rode et al, 2017).

A number of studies have analyzed the relationship and interaction of different urban forms and their impact on transportation and travel behavior (Guerra et al, 2018; Hong, Shen and Zhang, 2014; Ingvardson and Nielsen, 2018; McIntosh et al, 2014; Taylor et al, 2009). Various factors, such as transit service provision, urban density, car ownership, provision of road capacity, and land-use diversity contribute to the choice between public and private vehicle travel. Compact and dense urban development creates economies of scale, reducing the need for individual mobility through greater physical proximity (accessibility). Therefore, better public transit supply associated with more diverse land use and less roadway provision is related to lower rates of driving and, consequently, higher ridership (Guerra et al, 2018; McIntosh et al, 2014). However, sprawling cities with low-density urban development and mono-functional land use substitute access by proximity for access by movement, demanding a greater provision of road capacity and rapid modes of transportation to bring down journey times, thus largely depending on cars (McIntosh et al, 2014; Rode et al, 2017).

Metro and heavy rail (MRT) network coverage as well as bus and light rail transit systems (BRTs and LRTs) are mutually co-dependent with urban density. Dense metropolitan areas need mass transit networks to ensure fast, high-capacity, and reliable transport, which can only be sustained through sufficient potential ridership because of their high construction cost (Ingvardson and Nielsen 2017; 2018). Thus, transportation planning and land-use policies, such as transit-oriented development (TOD), can maximize the efficiency of transit services and foster sustainable cities (Cervero and Dai, 2014; Ibraeva et al, 2020). TOD makes sustainable public transportation modes convenient and desirable, building up urban densities around them rather than increasing road capacity. Aspects of the built environment around transport stations, such as land-use diversity, density, and accessibility conditions are key factors in improving ridership (Ding, Cao and Lui, 2019; Ibraeva et al, 2020).

Understanding public transportation aspects that influence passengers' satisfaction and loyalty also contribute to increasing and retaining ridership. Satisfaction can be defined as a passenger's overall experience with the quality of a public transportation service, as compared to their expectations. However, loyalty is best understood as users' intention to continue using the service in the future based on previous experiences and their willingness to recommend it to others (Van Lierop, Badami and El-Geneidy, 2017). The most important factors influencing users' on-board experiences concerning these aspects are (i) comfort (physical aspects, such as vehicle quality and safe and smooth driving), (ii) on-board safety (traffic or crime), and (iii) cleanliness (Van Lierop, Badami and El-Geneidy, 2017). Regarding comfort and safety, on-board crowding significantly influences loyalty, while seating capacity influences satisfaction (Carreira et al, 2014; Van Lierop, Badami and El-Geneidy, 2017). With regard to in-vehicle factors, temperature, physical accessibility, and accurate on-board information also affect satisfaction (Carreira et al, 2014; De Oña et al, 2013; Van Lierop, Badami and El-Geneidy, 2017).

The most important factors influencing users' public transportation service experiences regarding satisfaction are (i) punctuality and frequency of service, (ii) travel time, (iii) network coverage, (iv) quality of transfers, and (v) waiting time (Van Lierop, Badami and El-Geneidy, 2017). The quality of waiting conditions can influence both satisfaction and loyalty (Lai and Chen, 2011; Van Lierop, Badami and El-Geneidy, 2017). Providing real-time information to passengers decreases waiting times, reduces overall travel time due to changes in the path choice, and increases ridership and passengers' security perceptions (Brakewood and Watkins, 2019).

Regarding customer service (passengers' perceptions of the behaviors and attitudes of drivers and personnel), addressing customer complaints is associated with both satisfaction and loyalty (Lai and Chen, 2011; Mouwen, 2015; Van Lierop, Badami and El-Geneidy, 2017). Agencies' abilities and willingness to address customer complaints efficiently can be used as a tool to improve overall customer satisfaction and loyalty, thus improving ridership (Van Lierop, Badami and El-Geneidy, 2017).

Users' perception of the cost of using public transportation is an important determinant of customer satisfaction and loyalty (Tyrinopoulos and Antoniou, 2008; Van Lierop, Badami and El-Geneidy, 2017). While ticket-selling networks are related to customers' overall satisfaction, loyalty depends on users' perceptions of value-for-money (the cost-benefit analysis of the amount of money they are spending and the service they are receiving) (Van Lierop, Badami and El-Geneidy, 2017). The image of public transportation also influences user loyalty (Lai and Chen, 2011; Van Lierop, Badami and El-Geneidy, 2017). Hence, transit agencies should highlight the benefits of using public transport to influence users' emotional attachment.

Public transit prioritization plays a key role in ridership (Ingvardson and Nielsen, 2017; Wirasinghe et al, 2013). There are four operational environments divided by their levels of segregation: mixed traffic, semi-exclusive, exclusive, and grade-separated (TCRP, 2013). Public transit modes with a higher segregation from general traffic improve the travel time and reliability of the system, minimize waiting times at stops and interchanges, and prioritize traffic in favor of public transportation (Dadashzadeh and Ergun, 2018). The effects of public transit prioritization on ridership depend on the design of the system and its degree of improvement with respect to prior transportation methods. Conventional bus lines upgraded with a few BRT elements (bus lanes, signal priority, or special vehicles) attract fewer passengers than systems with reserved and efficiently designed transit corridors (completely segregated bus lanes, station-like bus stops with ticketing systems on the platform, and real-time information and signal priority along the entire corridor) (Ingvardson and Nielsen, 2017). When LRTs and BRTs are implemented with dedicated right-of-way and transit preferential treatments, their performance is comparable to that of the metro system (Ingvardson and Nielsen, 2017; Wirasinghe et al, 2013).

The transit quality attributes that are most commonly associated with satisfaction and loyalty are found in public transportation modes with a higher degree of segregation from general traffic. In this study, this is defined as QPT and generally fulfils certain criteria: (i) to be inserted in an integrated transit network; (ii) to operate with minimum general traffic interference; (iii) to fulfill the transit demand by offering an adequate number of vehicle trips; (iv) to operate with punctuality, regularity, and speed; (v) to charge a lower fare, compared with the costs of owning and regularly using a private car or the regular use of transportation apps; and (vi) to provide in all of their vehicles and passenger boarding equipment a safe, clean, and comfortable experience that is universally accessible.

Governance, urban form, infrastructure provision, and travel behaviors are closely linked. Thus, by facilitating different modes of travel, urban planning and public policymaking influence the urban structure and the available transportation system in a metropolis. This establishes a series of incentives for users to engage in travel behaviors while simultaneously discouraging others. MRTs, LRTs, and BRTs, as modes of transit with high service quality, can retain and attract new users, whereas conventional buses cannot (Cao et al, 2016; Engebretsen, Christiansen and Strand, 2017; Ko, Kim and Etezady, 2019). Network connectivity, network coverage, transit system integration, and transferability are also strongly associated with ridership, more so than travel attitudes (Diab et al, 2020; Hong, Shen and Zhang, 2014; Ingvardson and Nielsen, 2018). Hence, public transportation investments can substantially influence commuting patterns as long as they focus on QPT. Facilitating intermodal transfers, increasing schedule reliability, and expanding passengers' mobility and the accessibility of the system will promote the attractiveness of the entire system (Curtis and Scheurer, 2017; Guerra et al, 2018; Ingvardson and Nielsen, 2018).

3 RESEARCH APPROACH

3.1 INDEX PROPOSED

As highlighted by Zito and Salvo (2011), a good indicator must meet five basic requirements:

1. Comprehensive—It should reflect the characteristics of the physical and social-economic dimensions.
2. Data quality—Data collection practices should ensure that information is accurate and consistent.
3. Comparable—Data collection should be standardized, allowing comparison between several cities.
4. Easy to understand—It must be useful to decision-makers and understandable to the general public.
5. Accessible and transparent—Indicator and analysis details should be available to all stakeholders.

Thus, we propose the METRIX considering these five points. The METRIX formula is the relationship between the number of trips by QPT modes in a workday and the number of inhabitants of a given metropolitan region, as shown in Equation (1):

$$METRIX = \frac{\sum(Number of trips — day in QPT mode)}{Metropolitan region population} \quad (1)$$

QPT comprises express bus services in exclusive left lanes, bus services operated (partially or fully) in busways, BRTs, street trams, monorails, LRTs, ferry boats, subways, and suburban or heavy rail. We did not consider express bus services in exclusive right lanes as a QPT mode because such services face interference from converging general traffic from the right lanes, parking, and stop maneuvers; additionally, they do not have the required boarding infrastructure and other BRT aspects for faster and more efficient operations. Thus, express bus services in exclusive right lanes do not have service attributes related to high-quality public transportation.

The number of trips is the data that should be provided by the managing or operating QPT mode transit authority of a given metropolitan region on a typical workday (Tuesday, Wednesday, or Thursday) in a week with no holidays within the school year.

The trips made in QPT mode in a workday comprise two categories: trips with control access registered in turnstiles, and trips without control access. The relevant unregistered trips should be estimated through surveys and explained by the data supplier, such as evasions and transfers through different lines in the same transit mode, made inside a station as occurs in subway stations, from the simpler two-liner to a larger multimodal hub. For this study, we could obtain the number of boardings for each QPT modal or line through public reports, thus calculating the simple index. To calculate the complete index for a given city, the transit operator or manager must detect and report the number of transfers between QPT services.

The metropolitan region population is the number of inhabitants in a given year extracted from demographic reports and analysis published by the country or its administrative region's statistics bureau.

The daily (workday) trips in QPT modes reveal the citizens' adherence to the QPT from a range of trip mode options, individual or collective, motorized or not. Thus, considering only public transit, the value obtained synthesizes the metropolitan region's demand behavior on a workday using the QPT service offering.

As an example, to measure these trips, four home-to-work journey scenarios were established using public transit:

- Journey 1 has four trips: bike, suburban bus, distributor bus line, and walking. No QPT trip is counted.
- Journey 2 has three trips: feeder bus, suburban train, and taxi. One QPT trip is then counted.
- Journey 3 has four trips: car ride as passenger, BRT bus, subway, and walking. Two QPT trips are counted.
- Journey 4 includes two trips: Subways I and II: if a transfer occurs inside the station's paid area, two trips are counted.

As a result of this relationship, a numeric index shows the number of per capita journeys on a workday for a metropolis. This index starts from zero (no trip in QPT mode) and can present values above 1.00. In a comparative study between metropolitan regions, the higher the attributed value of a given region, the more developed and sustainable its transit system is compared to the rest. Metropolises are classified into six brackets based on their METRIX scores as follows: very poor (0–0.199), poor (0.200–0.399), fair (0.400–0.599), good (0.600–0.799), very good (0.800–0.999), and excellent (>1.000).

3.2 DATA COLLECTION

Considering the definitions used to create the index, we must collect data related to:

- Metropolitan region territorial definition.
- 2018 metropolitan population.
- Relationship between operational QPT modes in 2018.
- Registered trips for both paying and non-paying passengers in a typical workday in 2018, and non-registered trips (trips started in or partially made with a same-mode transfer) for each line or service of a given transit mode.

The method was applied to Belo Horizonte's metropolitan region as a reference. This region encompasses 34 municipalities, and the data on population estimates for all municipalities were retrieved from the Brazilian Institute for Geography and Statistics (IBGE) data for 2018. The Belo Horizonte metropolitan region's population comprised

5,292,714 inhabitants. The daily trip data collected pertains to 2018, and only trips with control access were used. Table 1 calculates the METRIX of Belo Horizonte.

Table 1: METRIX of Belo Horizonte

Public Agency	Line or Corridor	Modal	Trips—day (2018)
BHTRANS	MOVE Antônio Carlos	BRT	188,440
BHTRANS	MOVE Cristiano Machado	BRT	65,740
SETOP	MOVE Metropolitano	Metropolitan BRT	109,393
CBTU	Line 01	Heavy Rail	208,000
Total			571,573
Metropolitan Region Population (2018)			5,292,714
METRIX of Belo Horizonte			0.108

Source: BHTRANS, CBTU, IBGE, SETOP.

We chose 25 metropolises to create a cross section between multiple settings, with cities of varying sizes, shapes, and economic and transit profiles. These metropolises best represent their regional or urban peculiarities, or they are of a kind. The two prerequisites were the availability of data and a metropolitan population of more than 2 million inhabitants. The metropolises chosen were Atlanta, Beijing, Belo Horizonte, Berlin, Bogotá, Chicago, Curitiba, Hong Kong, Lisbon, London, Los Angeles, Madrid, Mexico City, New York, Paris, Recife, Rio de Janeiro, Santiago, São Paulo, Seattle, Shanghai, Singapore, Stockholm, Tokyo, and Toronto.

4 RESULTS AND DISCUSSION

For these 25 metropolises, we applied the same index as in Belo Horizonte. We listed the QPT service operators or managers, identified the 2018 annual reports for each, and in case of an absence of conclusive data, contacted the case authorities or companies' representatives, and collected the boarding and passenger data for each service under their respective jurisdictions. In some cases, a factor of 291 days per year was used to determine the average weekday ridership from the annual ridership. It accounts for 252 weekdays per year, plus half of the average weekday ridership for 52 Saturdays (or 26 days) and half of the Saturday ridership for Sundays (or 13 days), for a total of 291 days per year. Table 2 compiles the information collected, from the highest to the lowest METRIX score for each metropolis, with its respective population.

Our findings in Table 2 indicate that metropolises are at different levels of development in different parts of the world, displaying considerable variety in national and regional transportation systems, urban structure, and mobility behavior. For instance, Tokyo, a high-density city with public transportation rail, and Los Angeles, a sprawling car-oriented city, have developed their own unique spatial structure and transportation systems, providing different access levels. In Brazil, São Paulo stands out from other cities in the region and exhibits a much higher METRIX. The same is true for New York when comparing US cities. In addition, similar patterns can be identified in some groups of cities. Asian and European metropolises have a better transit-land use nexus, and governance is expressed through a higher METRIX. South American and North American cities (especially US cities), except São Paulo, have developed less sustainable mobility and have a lower index. Additionally, the data reveal a trend toward greater METRIX in cities that chose more rail over bus QPT services. These findings are consistent with those of McIntosh et al (2014) concerning regions, urban density, and transit.

Table 2: METRIX Comparison between 25 Metropolitan Regions

Metropolitan Region	**Population 2018**	**Boarding QPT/Work Day (2018)**	**METRIX**	**METRIX Performance Evaluation**	**Continent**
Tokyo	37,435,191	44,411,555	1.186	Excellent	Asia
Paris	12,183,893	13,455,908	1.104	Excellent	Europe
Stockholm	2,308,143	1,931,581	0.837	Very good	Europe
Berlin	5,259,363	4,281,787	0.814	Very good	Europe
Hong Kong	7,482,500	5,754,000	0.769	Good	Asia
Singapore	5,638,676	3,501,000	0.621	Good	Asia
London	14,257,962	7,930,467	0.556	Fair	Europe
São Paulo	21,571,281	10,891,696	0.505	Fair	South America
Beijing	21,540,000	10,849,000	0.504	Fair	Asia
Madrid	6,549,520	3,004,467	0.459	Fair	Europe
Lisbon	2,846,332[(1)]	1,243,153[(1)]	0.437	Fair	Europe
Shanghai	24,240,000	10,172,000	0.420	Fair	Asia
Santiago	7,112,808	2,819,961	0.396	Poor	South America
New York	19,979,477	7,066,588	0.354	Poor	North America
Mexico City	20,886,703	7,197,461	0.344	Poor	North America
Bogotá	7,181,469	2,459,437	0.342	Poor	South America
Toronto	6,417,526	1,988,510	0.310	Poor	North America

Curitiba	3,537,894(2)	721,500(2)	0.204	Poor	South America
Rio de Janeiro	13,005,430	2,111,775	0.162	Very poor	South America
Chicago	9,458,539	1,021,539	0.108	Very poor	North America
Belo Horizonte	5,292,714	571,573	0.108	Very poor	South America
Recife	4,054,866	436,302	0.108	Very poor	South America
Seattle	3,979,845	140,553	0.035	Very poor	North America
Atlanta	6,020,364	207,100	0.034	Very poor	North America
Los Angeles	13,291,486	420,425	0.032	Very poor	North America

(1) 2019 data.
(2) 2016 data.
Source: Author's elaboration.

With a METRIX of 1.186 and 1.104, Tokyo and Paris, two of the most public transport-oriented metropolises in the world, were classified as excellent. As discussed by Cervero (1998), Chorus (2009), Sorensen (2001), and Zhou and Gao (2020), Tokyo is a railway-oriented city with several private radial lines running from the suburbs to the city center. Greater Tokyo's rail transit network was developed through high-density mixed-use sub-centers, showing impressive ridership performance. Thus, Tokyo is considered one of the most efficient and sustainable mega-regions in the world. Corroborating the findings of Chakhtoura and Pojani (2016) and Halpern and Le Galès (2016), Paris' METRIX reflects the transformation of its urban transportation in recent decades. Since the 2000s, the city center and inner suburbs have seen profound changes in transportation, enhancing public transportation services and infrastructure, and reducing car use through urban planning.

Stockholm and Berlin were classified as very good, with a METRIX of 0.837 and 0.814, respectively, while Hong Kong and Singapore, with a METRIX of 0.769 and 0.621, respectively, were classified as good. M metropolises with a METRIX above 0.600, together with Tokyo and Paris, are prime examples of transit-oriented metropolises that embody some of the best practices in integrating land-use planning and transportation efficiency. These findings are supported by Bastian and Börjesson (2018), Cats (2017), and Cervero (1998) in the case of Stockholm; Heinickel (2013) for Berlin; Loo and Chow (2008) and Tang and Lo (2008) for Hong Kong; and Barter (2013), Han (2010), May (2004), and Yang and Lew (2009) for Singapore. With appropriate metropolitan governance, where rational urban planning embraced diversity, density, design, and attractive networks, these six transit metropolises developed a polycentric urban system that prioritized public transportation and achieved substantial success in building a sustainable city. They have a broad and dense rail QPT network, reaching several suburbs and metropolitan cities. Moreover, the primary reason behind the success of these transit metropolises concerns the intelligent linkage of the co-development of land use and transit services with complementary policies, such as the high cost of car travel compared to transit (parking, congestion charging) and highly effective controls for car ownership and use (Börjesson et al, 2012; Cervero, 1998).

Metropolitan regions with a METRIX ranging from 0.200 to 0.599 can be described as hybrid cities. London (0.556), São Paulo (0.505), Beijing (0.504), Madrid (0.459), Lisbon (0.437), and Shanghai (0.420) were classified as fair, whereas Santiago (0.396), New York (0.354), Mexico City (0.344), Bogotá (0.342), Toronto (0.310), and Curitiba (0.204) were ranked as poor. Priester, Kenworthy and Wolfhurst (2013) explained that cities in this cluster present a dichotomy. On the one hand, they have a dense urban core, extending to the inner suburban areas, with good infrastructure and significant public transportation usage. On the other hand, these urban centers are surrounded by a vast and sprawling low-density suburban area that, without sufficient quality public transit services, have become automobile-oriented. This greater dependence on automobiles in the metropolitan region results from a failure to integrate urban activity patterns, transit, and land use. This duality is expressed in public transit and traffic infrastructure development, unraveling a “push and push” phenomenon that can be depicted as the construction of road infrastructure almost at the same level and intensity as the implementation of public transportation networks.

Some of the hybrid cities are rail-based, while others are multimodal (rail and BRT). The only two exceptions are Bogotá and Curitiba, which have evolved through a high-performance BRT system. The results of the indexes of hybrid cities are corroborated by Headicar (2013), Rode (2011), and Wengraf (2013) for London; Costa (2013) and Kezič and Durango-Cohen (2012) for São Paulo; Gao et al. (2018) and Song (2013) for Beijing; Calvo, de Oña and Arán (2013) and García-Palomares (2010) for Madrid; Cabral et al (2007) for Lisbon; Gao et al (2018) for Shanghai; Gainza and Livert (2013) for Santiago; Priester, Kenworthy and Wolfhurst (2013) for New York; Cervero (1998) and Dewey (2016) for Mexico City; Ferro (2011) and Suzuki, Cervero and Luchi (2013) for Bogotá; Cervero (1998) and Sorensen (2011) for Toronto; and Martínez et al (2016) and Mercier et al (2019) for Curitiba.

With a METRIX ranging between 0 and 0.199 and with their metropolitan transit system development being classified as very poor, Rio de Janeiro (0.162), Chicago (0.108), Belo Horizonte (0.108), Recife (0.108), Seattle (0.035), Atlanta (0.034), and Los Angeles (0.032) are automobile-oriented metropolises. These cities have paradoxical characteristics. While public transportation suffers from a lack of investment and low-quality transit services, private transportation modes are abundantly funded, creating an extensive and well-connected highway network with the best accessibility in the region. With easy access to freeways, low driving costs (poor management of parking supply and pricing), and the lack of a regional public transportation network, people's perception of the public transportation system worsens. Hence, transit patronage diminishes, resulting in a predominance and dependence on personal automobiles as a means of transport. Moreover, a failure to use the dense pattern of functional and spatial interdependencies of land-use or transportation planning in urban outskirts and suburbs also contributes significantly to car use. Even those who live close to public transportation routes may hesitate to use this mode of transportation because they are not attractive. These findings are consistent with Ferranti et al (2020) for Rio de Janeiro; Kezič and Durango-Cohen (2012) for Chicago; Cardoso (2007) for Belo Horizonte; Oliveira Filho (2018) for Recife; Mercier et al (2019) for Seattle; Paget-Seekins (2013) for Atlanta; and Cuff (2011) and He (2013) for Los Angeles.

5 CONCLUSIONS

In this study, we presented the METRIX, an effective tool for comparing and analyzing metropolitan transit system development. The index was created to allow scholars, the press, policymakers, transit planners, and the wider public to participate in the development process of a vision of a sustainable city by fostering the debate surrounding the problems and challenges faced in the development process of a metropolis' transit system within a standardized and comparable model. It was also envisioned to permit a five-dimensional analysis: (i) monitoring the metropolis' transit evolution through time; (ii) comparing different metropolises in the same country or internationally; (iii) defining an excellence metric through the ranking of the surveyed metropolises, (iv) aiding the impact evaluation of a proposed transit alternative within a network planning context; and (v) the ability to be used in conjunction with other indicators to improve a metropolis' transit diagnosis.

Using a sample of 25 global metropolises and analyzing data for the year 2018, our results suggest that metropolises are at different levels of development worldwide, displaying considerable variety with regard to national and regional transportation systems, urban structure, and mobility behavior. These megacities can be classified into three types based on their METRIX scores. The first type, automobile-oriented, comprise cities whose metropolitan transit systems are classified as very poor (Los Angeles, Atlanta, Seattle, Recife, Belo Horizonte, Chicago, and Rio de Janeiro). In these cities, priority was given to private transportation modes, with public transportation suffering from a lack of investment and low-quality transit services.

The second type, hybrid cities, comprise metropolises whose metropolitan transit systems are classified as poor (Curitiba, Toronto, Bogota, Mexico City, New York, and Santiago) or fair (Shanghai, Lisbon, Madrid, Beijing, Sao Paulo, and London). They are characterized by high public transportation patronage in the urban core and high car use in the urban outskirts and suburbs. The third type, transit-oriented, comprise metropolises whose transit systems are classified as good (Singapore and Hong Kong), very good (Berlin and Stockholm) and excellent (Paris and Tokyo). Urban planning embraced diversity, density, design, and attractive networks in these metropolises, prioritizing public transportation, and achieving substantial success in building a sustainable city.

Our findings also show that Asian and European metropolises, which have a better transit-land use nexus and governance, have a higher METRIX. South American and North American cities (especially US cities), except São Paulo, have developed less sustainable mobility and have a lower index. Additionally, the data show a trend towards greater METRIX in cities that chose more rail than bus QPT services.

As many factors explain each city transit development, an in-depth analysis should be conducted together with other existing indicators to assess the underlying driving forces shaping urban mobility within metropolises. This enables the analysis of current conditions, strengths, weaknesses, and future mobility opportunities. We recommend this methodology be applied to more world metropolises, to analyze city size, income, density, and region; to evaluate the metropolises’ transit evolution through time; to calculate the complete QPT modes (the trips with control access, registered in turnstiles, and trips without control access); and to calculate the index at the city level and compare this with the whole metropolitan region.

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