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Thematic Section - Sustainability in Transportation and Logistics

Comparative analysis between transportation modes for sustainability perspective in one metropolitan region of southern Brazil

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Abstract

Paper aims: The objective is to make a comparative analysis between different transportation modes used in the Metropolitan Region of Porto Alegre and to analyze its performance in relation to time, cost and carbon emissions.

Originality: Investigation of the urban mobility situation on the perspective of sustainability in a Latin American city, including the analysis of Uber pool, implemented in November 2018 in the metropolitan region analyzed.

Research method: A case study was carried out in the metropolitan area of Porto Alegre, as well as the definition of 4 different routes used as unit of analysis for different types of transportation modes.

Main findings: Riding bicycle is a very convenient transportation mode in terms of its environmental perspectives and costs. However, the time of locomotion using bicycle is superior in relation to other modes of transportation. Therefore, riding a private car still stands out in the comparisons between different types of transport, since it is a faster mode of transportation.

Implications for theory and practice: As riding bicycle is a very convenient transportation mode, we highlight the importance of encouraging its use. People can benefit from practicing physical exercise while moving from one place to another and also benefit the environment from lowering carbon emissions.

Keywords

Transportation modes. Sustainability. Metropolitan region. Urban mobility.

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1. Introduction

Public transportation is essential in large urban centers as citizens need to move from one place to another (Bubicz & Sellitto, 2009). In this sense, urban mobility is becoming a problem in most major cities, and it is necessary to understand how these areas are dealing with this issue. In fact, transportation in metropolitan areas is a subject that has been under discussion in several developing countries, mostly due to national concerns about the increasing levels of population growth and the identified unsustainability of urban transport (Cervero, 2013). In Brazil, discussions around the concept of urban mobility are considered quite recent, since developed countries in Europe and north America have already approached the subject and worked towards developing indicators for monitoring and assessment of urban mobility in most of their large cities (Magagnin & Da Silva, 2008). Differently, in the Brazilian scenario, this debate involving metrics is still ongoing and is unclear for much of the population. In fact, as the problem of excess traffic increases, it forces the citizens themselves create alternative solutions. For instance the use of bicycle, a means of transportation mode has been widely used in the Metropolitan Region of Porto Alegre (MRPA henceforward) (Araújo et al., 2009).

As seen, the implementation of intelligent and adaptable public transportation is a major challenge in developing cities and newly industrialized economies, whose growth characteristics contribute and can be impacted by factors such as overcrowding and travel delay (Ram et al., 2016). Although for emerging latin American countries, the increase in the number of private cars is an indicative of social and economic growth (Hidalgo & Huizenga, 2013), its current patterns and trends of growth are not sustainable. In choosing MRPA, it is possible to analyze aspects of urban mobility in a Latin American city with such characteristics. Thus, this article aims to investigate the urban mobility situation in the metropolitan region of the city of Porto Alegre, southern Brazil. Also, our study seeks to analyze the environmental performance of different transportation modes in this region.

The comparison of the different means of transport modes was carried out through the definition of representative routes within the MRPA along with the use of secondary data, which helped us to set up different scenarios. As the results of our study have shown, the use of bicycle represented a very convenient way of transportation, especially in relation to sustainability. However, there is still a major problem related to higher displacement times, which ends up causing an increase in the use of private cars.

The remaining sections of this article are outlined as follows. In Section 2, we introduce a theoretical background about urban mobility and an overview of urban transportation in Brazil. In Section 3, we bring our methodology, with the definition of the transportation modes in Brazil and the main routes that cross the metropolitan region of Porto Alegre, while we present the main results of our analysis in Section 4. Finally, a comprehensive discussion of the results is presented in Section 5, followed by our conclusions, research limitations and possibilities for future research in Section 6.

2. Theoretical background

2.1. Urban mobility

Goldman & Gorham (2006) argue that the world's major cities, including the most efficient in terms of transportation, are facing growing demands for motorization and mobility. Hence, it is firstly necessary to define the whole system of transportation, which includes an integrated participation of different modes: subway, train, bus, tram, motorcycle, bicycle or pedestrian (Wilheim, 2013). However, one of the greatest problems with the demand for transportation its tendency to increase faster than the capacity of these cities to keep up with the development of cleaner technologies that display less pollution to the environment (Goldman & Gorham, 2006).

A great deal in understanding sustainable development is to take into account that it is part of the history of thinking about economic and social development (Duarte et al., 2015), being therefore understood as the ability to meet the demands of the present without compromising the welfare of future generations (World Commission on Environment and Development, 1987). In this sense, sustainable transport refers to the concept of providing mobility with sustainability (Organisation for Economic Co-Operation and Development, 1997). In view of the importance of global sustainability and the use of cleaner energy, the United Nations (UN) has set an agenda containing seventeen Sustainable Development Goals (SDGs) (World Health Organization, 2016) for 2030 and the Brazilian government has ratified these objectives internally (Carmo et al., 2011; Itamaraty, 2016). Among them, we highlight objective 11, whose goal is to achieve sustainable cities and communities, which comprises inclusion, security, resilience and sustainability. Also, one of the dismemberments of this goal is the accessibility to public transport in order to guarantee security, sustainability and affordable prices (Organização das Nações Unidas, 2015).

Urban planners have shown great interest in formulating policies for a more sustainable transport sector (Black et al., 2002). However, while public transport provides multiple benefits to urban systems, it also has several significant environmental, economic, and social impacts (Browne & Ryan, 2011). In fact, the transport sector has a serious impact on the environment due to the emission of polluting gases, such as GHG and NO_x. Furthermore, energy consumption in transport develops a problem of energy dependence, since it mostly relies on the use of fossil fuels (Turcksin et al., 2011).

2.2. Overview of urban transport

According to Yigitcanlar & Teriman (2015), urban environments have promoted substantial impacts on people's lifestyles, behaviors and consumption patterns. Therefore, a development that is sustainable is crucial not only to facilitate the way of living in cities, but also to maintain the existence of urban ecosystems. The incorporation of sustainability in an urban context is centered on the following aspects of the urban life: density, form, design and infrastructure (Yigitcanlar & Teriman, 2015). Table 1 shows the characteristics of the largest metropolitan areas. In the metropolitan area of Porto Alegre, the research site, there is a rate of 31.2 cars for every one hundred habitants, the second largest in Brazil. Equally important to notice from Table 1 is the average time of home-work travel of approximately 27.7 minutes in the metropolitan area of Porto Alegre.

Table 1. Characterization of the Brazilian capitals.

Metropolitan region	Population	Total Area (km²)	Demographic density (km²)	GDP per capita (2008) (R$)	Number of cars/for every hundred habitants	Average work-to-home time (minutes)
São Paulo	19.443.745	7943.8	2447.7	30.349	38.1	42.8
Rio de Janeiro	11.835.708	5643.8	2097.1	19.762	20.8	42.6
Belo Horizonte	4.883.970	14415.9	338.8	19.540	29.6	34.4
Porto Alegre	3.978.470	9800.2	406	23.225	31.2	27.7
Recife	3.870.004	2768.5	1397.9	13.592	15.3	34.9

Source: Adapted from Pereira & Schwanen (2013); Demographic Censuses 2000 and 2010 and PNAD (IBGE, 2001 and 2010 and several years); National Registry of Motor Vehicles (RENAVAN), of the Brazilian National Traffic Department (DENATRAN).

Pereira & Schwanen (2013) argue that the time spent in urban transport is associated with the well-being of citizens and is also directly related to the levels of congestion in cities. Therefore, the amount of time that an average person spends for transportation is a topic of central interest in terms of urban and transportation policies. The home-work travel time is also central to the understanding of the forms of social and economic organization of the urban space (Alonso, 1964), and is considered fundamental for the decision-making of individuals and firms in regards to the location of residence and industrial areas (Gordon et al., 1991; Levinson & Kumar, 1997). Figure 1 highlights the average work-home travel time in the largest Brazilian metropolitan areas, in addition to other countries with high population density.

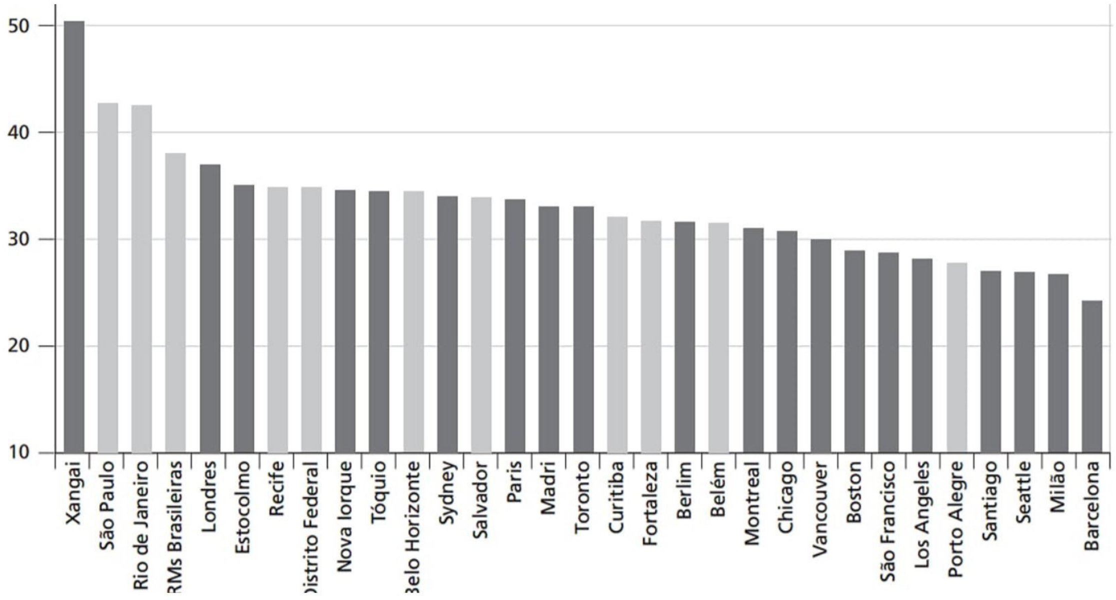

Figure 1. Average work-home travel time in the world's largest metropolitan regions
Source: Pereira & Schwanen (2013).

In addition, the data has pointed out that there has been a deterioration in urban transportation conditions in the country's main metropolitan areas (RMs) since 1992, as shown on Figure 2, along with a significant increase in home-work travel times (Pereira & Schwanen, 2013). Curitiba and Porto Alegre are the only two exceptions, where travel times have been relatively stable since then. Along with the congestion and the high average time of home-work travel in several metropolitan regions, the great concentration of cars shown in Figure 2 is evident, given the higher levels of demographic density and the higher rate of motorization, as mentioned previously. In the metropolitan region of Porto Alegre, there was an increase of approximately 35% in the rate of private car ownership. There is an average of in more than 30 cars per 100 inhabitants.

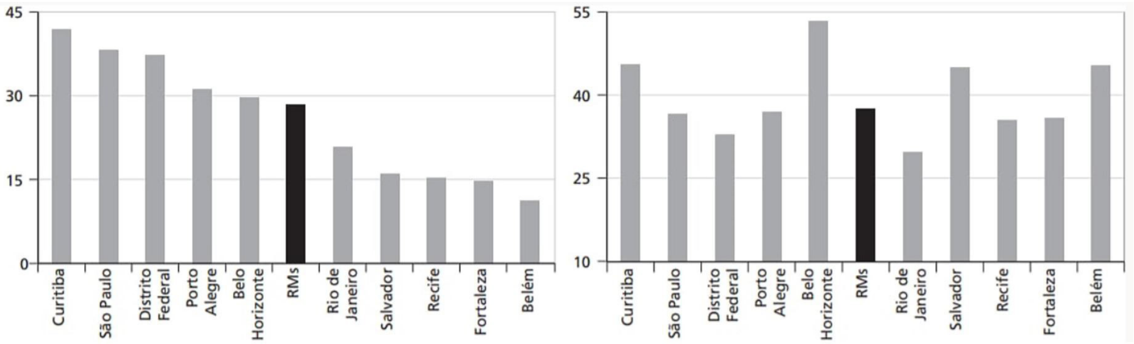

Figure 2. Number of cars per 100 inhabitants and increase of motorization rate from 2000 to 2010 (both in '%')
Source: Adapted from Pereira & Schwanen (2013).

3. Method

3.1. Definition of transportation modes

Pezzuto (2002) argues that the choice of an individual for a mode of transportation (whether collective - bus, train - or individual - car, bicycle) is a complex process that is influenced by several factors, such as: the availability of time and resources, the route that the passenger will be traveling, and the availability of transportation systems. In our study, the transportation modes described in Table 2 were used for performance comparison. Also in Table 2, there is a theoretical rationale for their inclusion.

Table 2. Transportation modes analyzed in the study and the justifications for their inclusion.

Transportation mode	Rationale	References
Car: private, Uber Black and Uber pool	Travel costs have increased substantially, mainly due to excessive traffic and a consequent increase in travel time. However, the car is still the preferred mode of transportation in most situations.	Hensher (2007)
Bicycle: private and rented	The replacement of cars by bicycles is being defended and applied in order to boost their use. This is because it is considered one of the most sustainable transportation modes. In addition, the use of bicycles also promotes increases the health of individuals due to the fact that they are exercising and helps to reduce both transportation and financial problems of urban centers. In 2009 the Cycle Route Master Plan (CRMP) was approved in Porto Alegre and since then improvements in this direction have been designed and implemented.	Teixeira (2017), Meschik (2012), Porto Alegre (2017b)
Train	The systems used by the Brazilian Company of Urban Trains are undergoing a process of renovation. Therefore, it is understood that there is an opportunity to study the consequences of this transportation mode in urban development, as well as promoting this option as a public transportation mode.	Neto & Correia (2011)
Catamaran	This mode of water transportation was implemented as an alternative to improve the mobility of people who used to use buses or other forms public road transportation but were not satisfied. Users agree that their deployment has improved the city's mobility, quality of life, local economy and environmental aspects in the region, but they are unhappy about pricing and the overall mobility time of this transportation mode.	Nunes & Sander (2017)
Bus	Public road transport is still the main alternative of mobility in Porto Alegre. In 2017, nearly 300 million passengers were transported. Therefore, it is a transportation mode of great importance for the region.	Porto Alegre (2017a)

3.2. Route definition

We decided to start studying our routes from the downtown area of Porto Alegre, since it is one of the most populous and well-connected regions of the city under study. Based on this, we have chosen four different destinations that well represent the reality of transportation to different directions of the city. The location of the chosen points with respect to the center is shown in Figure 3.

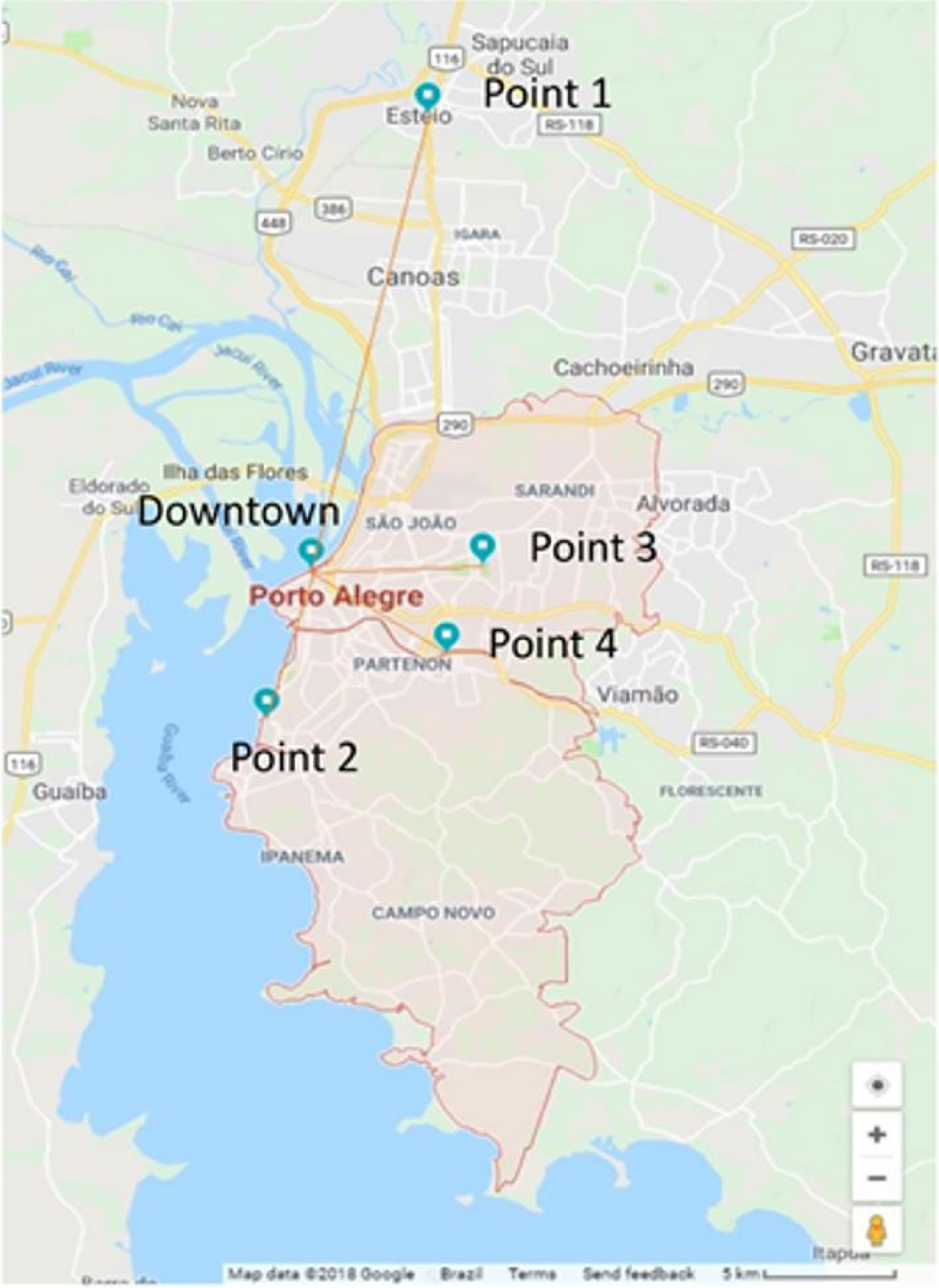

Figure 3. Destination points of the four routes analyzed in the study.

1) Downtown - Point 1 (P1): The distance between the two points is 19.8 kilometers and is the northernmost destination of the analysis. The site was chosen because it represents a route served by the urban train. Also, it is considered an important connection point to all MRPA;
2) Downtown - Point 2 (P2): this depicts the displacement towards the south of the city. The point is located near the banks of the *Guaíba* river, which made possible the analysis of the catamaran. The distance between the two points is 6.6 kilometers
3) Downtown - Point 3 (P3): The point is 6.6 kilometers straight from downtown and represents the route that connects the northeast region of the city. This region has more than 15 hectares and is mostly frequented by residents of various areas of the city.
4) Downtown - Point 4 (P4): Path of great importance in the city due to its connectivity with the state University. The destination is 6.3 kilometers from downtown. Some important places in this area are the university hospital, an event center and a museum.

4. Results

4.1. Travel times

In order to compare the travel time, several sources were used, for instance, Google Maps and the following mobility apps: Moovit and Uber. Based on the information provided by these sources, we could extract valuable information to our investigation: routes, time, and price. Based on the information we have gathered and on our analysis, we found that only for the longest route (from the center to P1), the use of bicycle proved to be a slower transportation mode than bus, as Table 3 shown. In all other cases, the bus had the worst performance in terms of travel time period among all transportation modes analyzed. The average values in Table 3 indicate that the best transportation modes, in terms of the travel time were the catamaran (which only covers one of the routes analyzed), flowed by private car and taxi, respectively.

Table 3. Travel time to destination points.

	TIME (in minutes) from the center to the following points				
	Point 1	Point 2	Point 3	Point 4	Average
Private car (Flex - 16V)	22	12	22	21,5	19.38
Taxi	22.75	17.67	27.5	25.6	23.38
Uber X (1.0 16V)	25.14	20.14	28	27	25.07
Uber Select (1.6 16V)	27.43	22.71	29	28	26.79
Uber Black (2.0 16V)	30.86	25.14	31	30	29.25
Uber pool	-	29	-	41	35.00
Bus	43	41	56	43	45.75
Train	45	-	-	-	45.00
Private Bicycle	69	28	33.5	30.5	40.25
Rented bicycle	-	30	35.5	32.5	32.67
Catamaran	-	15	-	-	15.00

4.2. Costs

We calculated the cost using private car. We considered that a regular citizen travels and average of 1563 km per month, since for Route 1, a person has to travel approximately 52.1 km per day, depending on the route. We consider the cost of R$1.93 per kilometer travelled. Also, we consider other types of costs associated to having a car, such as insurance, maintenance, parking fees, to mention but a few. The information is compiled in Table 4.

To calculate the estimate cost of ride share at Uber, we used the company's own price estimator (UBER, 2018). For the cost associated with renting a bicycle from a particular ride share app, we considered that a person rides 57.4 km per day in a round trip (we used the P1 route for our calculus). Also, we considered the calendar of 360 days/year and 30 days/month and two subscription plans: a monthly plan at a cost of R$20.00/month and an annual plan at a cost of R$160/year (Bike POA, 2019). The cost of a kilometer traveled for the monthly plan was approximately R$0.011/km, while the cost for the annual plan was roughly R$0,007/km.

Table 4. Costs associated with the use of private car.

Cost of having an automobile (monthly)		
Price of the automobile	R$ 60,000.00	
Number of instalments	60	
Price of the instalments	R$ 700.00	
Item	**Monthly cost**	**Annual cost**
IPVA	R$ 166.67	R$ 2,000.00
Insurance	R$ 7.07	R$ 84.87
Licensing fee	R$ 3.19	R$ 38.22
Total insurance cost	R$ 166.67	R$ 2,000.00
Insurance Franchise	R$ 166.67	R$ 2,000.00
Maintenance	R$ 83.33	R$ 1,000.00
Traffic ticket	R$ 80.00	R$ 960.00
Depreciation (10%)	R$ 500.00	R$ 6,000.00
Opportunity cost	R$ 300.00	R$ 3,600.00
Instalments	R$ 700.00	R$ 8,400.00
Parking tickets	R$ 350.00	R$ 4,200.00
Cleaning	R$ 50.00	R$ 600.00
Gas	R$ 400.00	R$ 4,800.00
Others	R$ 50.00	R$ 600.00
TOTAL	R$ 3,023.59	R$ 36,283.09
Total effective cost – until the end of the financing period		R$ 181,415.45

Adapted from de Seabra (2018).

For the private bicycle, in turn, we used a estimation model based on the cost of buying a bicycle (an average price of R$ 600.00) and using it for 5 years, with a monthly depreciation cost of R$ 10.00 (Bike Tribe, 2018; Camelo Urbano, 2018; Bike Pop, 2018; Correio Braziliense, 2018). In addition, we considered a maintenance cost of R$280.00/year (Camelo Urbano, 2018). Using the National Broad Consumer Price Index (IPCA), the monthly maintenance cost of approximately R$24.85 was estimated for 2018. This generated a factor of R$0.017/km, that is, for each kilometer traveled in a private bike, a person spends approximately R$0.017. Finally, the overall costs associated with different transportation modes used to travel from downtown Porto Alegre to each one of the four different destinations selected are presented in Table 5. In addition, we did a series of estimation for Taxi and Uber, usually from between 9 am and at 5 pm, based on the average distance from downtown to one of these routes.

Table 5. Cost values associated with moving to destination points in 2018.

	Cost (R$) of moving from downtown to the following points				
	Point 1	Point 2	Point 3	Point 4	Average
Private car (Flex - 16V)	50.28	18.82	17.85	16.11	25.77
Taxi	62.15	25.90	30.70	27.40	36.54
Uber X (1.0 16V)	38.50	17.50	21.50	18.50	24.00
Uber Select (1.6 16V)	45.00	19.50	24.50	21.00	27.50
Uber Black (2.0 16V)	77.00	33.50	37.00	35.50	45.75
Uber pool	-	10.65	-	10.65	10.65
Bus	5.10	4.30	4.30	4.30	4.50
Train	3.30	-	-	-	3.30
Private bicycle	0.38	0.17	0.16	0.14	0.21
Bicycle Rental - Annual	-	0.08	0.07	0.06	0.07
Bicycle Rental – monthly	-	0.11	0.11	0.10	0.11
Catamaran	-	10.70	-	-	10.70

The calculation of the general average places both bicycle rental subscription plans and the choice of buying and using a private bike as the best options in terms of economic performance. Thus, in relation to cost, the bicycle is the most inexpensive mobility alternative for the routes studied.

4.3. Carbon emissions

The calculations for the carbon emissions were made based on some assumptions regarding the different vehicles analyzed in the study. It has been defined that the Uber Black option has 2012 as its average manufacturing year, the Uber Select and the private car option have 2011 as their average manufacturing year of 2011 and, finally, the options Uber X, Uber pool and taxi, 2010 as their average manufacturing, with equivalent levels of carbon emissions. Also, we considered flex model for all cars (Companhia Ambiental do Estado de São Paulo, 2012). All calculations were based on emissions per passenger. Porto Alegre recorded an average occupancy of 1.2 passenger per car (Aeromóvel Brasil, 2013). This was used as a basis for calculations for all cars, with the exception of the Uber pool, which we considered to be an average occupancy of 2 passengers (and 1 driver). The emission factor used for bus fleet considers engines of the diesel cycle in urban buses of 2011 (Companhia Ambiental do Estado de São Paulo, 2012). We used IPK (and index of passenger transported by kilometer) which, in accordance to the Empresa Pública de Transporte Público de Porto Alegre (2018) is of approximately 2.56 for buses. To calculate catamaran index, we followed data from Amante (2010) to find horse-power index, in which we found that in average a catamaran has 500 hp. From this measure, we could classify catamaran as a special technology, and we followed maximum index to calculate carbon emissions (Álvares Junior & Linke, 2001). Finally, for the assessment of carbon emissions eliminated by trains we used the *Iniciativa Verde* methodology (Iniciativa Verde, 2019).

In the route that goes to P1, the following transportation modes were contemplated: private bicycle, train, uber (X, select, black), bus, private car and taxi. In this route, the bicycle rental was not analyzed, because the maximum rental time is 60 minutes and there are no delivery points between the bicycle pickup points at downtown and P1. The lowest carbon emissions verified are from the use of bicycle, train and bus, respectively. In the analysis of the route from downtown Porto Alegre to P2, the following transportation modes were considered: bicycle (private and rental), catamaran, uber (X, select, black and pool), bus, private car and taxi. For this route, we found that bicycle is the best transportation mode from in terms of sustainability (both rental and private), followed by bus and Uber pool.

In the case of the route from downtown Porto Alegre to P3, we included the following transportation modes: bicycle (rental and private), Uber (X, select and black), bus, private car and taxi. Similar to the previous scenario, the best mode of transportation found was the bicycle (both rental and private), followed by bus, taxi and Uber X. Ultimately, for the route from downtown Porto Alegre to P4, the following transportation modes were analyzed: bicycle (rental and private), Uber (X, select, black and pool), bus, private car and taxi. In this case the results also show that the best option is the bicycle (both rental and private), followed by bus and Uber pool. Considering the overall average, the best transportation modes in terms of carbon emissions were bicycle, catamaran, train and bus, respectively. These results presented in Table 6 confirm that the less carbon emission rates come from non-motorized and collective transportation modes.

Table 6. Values of CO2 emissions per passenger.

	Carbon emissions (kg CO_2 per passenger) from downtown				
	Point 1	Point 2	Point 3	Point 4	Average
Private car (Flex - 16V)	3.57	1.50	1.54	1.19	1.95
Taxi	3.55	1.49	1.53	1.18	1.94
Uber X (1.0 16V)	3.55	1.49	1.53	1.18	1.94
Uber Select (1.6 16V)	3.57	1.50	1.54	1.19	1.95
Uber Black (2.0 16V)	3.62	1.52	1.56	1.20	1.97
Uber pool	-	0.89	-	0.71	0.80
Bus	0.43	0.43	0.43	0.43	0.43
Train	0.66	-	-	-	0.66
Bicycle/Bicycle rentals	0	0	0	0	0
Catamaran	-	0.015	-	-	0.015

5. Discussions

5.1. Ranking

The results of the sustainability assessment may be different depending on the weights and priorities attributed to the different factors that represent this variable. These variations in weighting may also occur according to regional aspects (Jeon et al., 2010). In this sense, we made a final ranking. Our ranking was established through an iterative process which we considered QFD (Quality Function Deployment) scales (from 1 to 9) for 3 aspects: cost, emission and time. We followed the criteria lower-is-better and multiplied the QFD scales to achieve the results in Table 7 (e.g., Taxi in Point 3 – cost = 8, emission = 3, time = 2, ranking = 8x3x2 = 48). Based on the results of Table 8, we can conclude which are the best transportation modes for each defined route. According to the ranking, the best means of transport for the P1 are private bike, followed by train and private car.

Table 7. Ranking of different transportation modes in the different routes analyzed.

	Ranking (from downtown to the following points)			
	Point 1	Point 2	Point 3	Point 4
Private car (Flex - 16V)	30	42	20	30
Taxi	56	150	48	72
Uber X (1.0 16V)	48	100	54	84
Uber Select (1.6 16V)	125	240	112	160
Uber Black (2.0 16V)	240	378	225	300
Uber pool	-	120	-	120
Bus	54	84	64	72
Train	28	-	-	-
Private bicycle	8	15	18	18
Bicycle rental - Annual	-	7	7	7
Bicycle rental- monthly	-	14	14	14
Catamaran	-	24	-	-

Table 8. The three best performing means of transport for each of the means of transport on each of the analyzed routes, in descending order.

Routes'	Costs	Time	Emissions	Ranking
Point 1	Private bicycle, train and Bus	Private car - Flex - 16 (16V) Taxi Uber - Flex - 1.0 (16V) - UberX	Private bicycle, Train, Bus	Private bicycle, Train, Private car
Point 2	Bicycles (private, monthly and annual rental)	Private car - Flex - 16 (16V) Catamaran Taxi	Bicycles (private, monthly and annual rental)	Bicycles (private, monthly and annual rental)
Point 3	Bicycles (private, monthly and annual rental)	Private car, taxi, UberX	Bicycles (private, monthly and annual rental)	Bicycles (private, monthly and annual rental)
Point 4	Bicycles (private, monthly and annual rental)	Private car, taxi, UberX	Bicycles (private, monthly and annual rental)	Bicycles (private, monthly and annual rental)

The use of cars has many individual advantages over other urban transportation modes, such as practicality and speed of mobility. Considering individual interests alone, it seems that public transportation modes can hardly compete with cars (Linda, 2003). Particularly, energy savings and emissions can be made from policy measures regarding the use of private cars, but only when the level of activity of the car is controlled or new technologies and decarbonized fuels are continuously introduced (Daly & Gallachóir, 2012).

For route P2, the best transportation modes are the three types of bicycle: rented bicycles (considering both the annual and monthly subscription plans) and private bicycles. Therefore, it is possible to perceive that the bicycle shared rentals in the annual plan is the most prominent transportation mode that can be used to accomplish this displacement. Bicycle sharing is a relatively new concept in Brazil, especially when compared to developed countries, such as Holland, the pioneer country of this system in 1965 (Bachand-Marleau et al., 2012). This means that there is room for improvement in Brazil, particularly in terms of the number of docking stations available in residential neighborhoods (Bachand-Marleau et al., 2012).

For P2, the catamaran is also an alternative, but it is more expensive. The catamaran is the most used transportation mode from Porto Alegre to the city of Guaíba (which is not along the path of P2). In addition, although the population is satisfied with the implementation of this transportation mode (both in economic and sustainable perspectives), there are some points to be improved: scheduling and tariffs (Nunes & Sander, 2017). Because of these problems, the catamaran is majorly used in the metropolitan area of Porto Alegre for tourism purposes, not being generally considered for regular urban mobility.

For P3, the best transportation modes are annual or monthly bicycle rentals and private bicycle. The value of the private car is higher than the private bicycle, which makes bicycle a better alternative in terms of cost. Most bicycle sharing models have been introduced in cities that have established sustainable transportation policies

(Midgley, 2011), because bicycle sharing systems play an important role in increasing sustainable transportation options in cities and the understanding of their potential use and impact in various types of cities and users is becoming increasingly important (O'Brien et al., 2014). However, although bicycle sharing is seen as an element of sustainable urban mobility, cycling infrastructure is still needed in most cities (Midgley, 2011).

Finally, for the route from downtown Porto Alegre to P4, the best transportation modes are also bicycle rentals, both annual and monthly, and private bicycles. The urban mobility service is constantly evolving (Goldman & Gorham, 2006). Thus, it aims to integrate traditional offers with bicycle rental and even minimize the inconvenience of waiting (Goldman & Gorham, 2006).

5.2. Opportunities for improvement in public transportation in Porto Alegre for upcoming years

It is necessary to increase the use of urban public transport. However, service improvements must be designed in order to accommodate the levels of service demanded by customers, with the objective of attracting more potential users (Beirão & Cabral, 2007). In 2018, in Porto Alegre, the revitalized border of the Guaíba river was inaugurated, where there are more accessible places to the population with totems of shared bicycles nearby. Also, on Sundays and major holidays, the state government established a street closing policy, encouraging the use of bicycles to promote the sustainability in the city (Melchiors & Wagner, 2016).

Torres-Freire et al. (2018) highlight some individual and social aspects regarding the use of bicycles. One aspect is the exchange of pollutants from locomotion (e.g. cars and buses) to sustainable modes (e.g. bicycles), thus reducing the total amount of GHG emitted in cities. In addition, the authors emphasized that the use of bicycles for physical health is essential, since the lack of physical activity is a risk factor for health. In this sense, the use of bicycles can promote better health and generate financial savings in the health sector.

The bicycles were present in 62.5% of the rankings, presented on Table 8. Private bicycles appear in 12 of the 16 rankings because it was reviewed on all trips. In all routes, the private bicycles are in three different rankings. The shared bike rental was available for 12 of the rankings, since for P1 it was not possible to perform the shared bicycle rental and it has also been divided into two subscription plans: monthly and annual, as there is a variation in cost. For P4 and P3, for example, the private bicycle and the annual bicycle rental were present in the cost, emissions and ranking analyzes. Hence, the results prove that the use of bicycle is an important transportation mode, as they appear on 62.5% of the rankings analyzed. In addition, there are many opportunities for improvement over the bicycle sharing-system (BSS) in MRPA. For instance, in the whole metropolitan area of Porto Alegre, there are only 41 bicycle pickup stations, compared to 260 stations available in Rio de Janeiro and São Paulo, 80 stations in Recife, and 50 stations in Salvador. In relation to the number of sharing bicycles available, Porto Alegre has only 410 of them, while there are 2600 in both São Paulo and Rio de Janeiro, 800 in Recife, and 400 in Salvador (Itaú, 2018).

In relation to social aspects, it is fundamental to analyze the negative aspects of the displacement related to the stress and the irritation, because of traffic jams. In general, in São Paulo, 36% of the population acknowledges thesuffering from stress during home-work travel, while only 14% of cyclists suffer from this type of stress. Already, in relation to delays, 35% of the population of São Paulo have fears about the delays associated with the displacement. On the other hand, only 15% of the cyclists have such a fear. In this case, 51% of cyclists rarely or never have this fear. Insecurity is also an important factor for the population in general: where 60% of the population and 48% of cyclists feel insecure in São Paulo (Torres-Freire et al., 2018). Regarding the positive social aspects of the trip, 45% of cyclists always or almost always enjoy the journey, while only 18% of the population that uses other transportation modes consider the journey pleasant (Torres-Freire et al., 2018).

Regarding the travel time, private car and the taxi are high-ranked in all routes. As for the cost, the private bicycle appears on 3 of the 4 routes. In the ranking of emissions, the private bicycle is highlighted on all routes. Therefore, there is an opportunity for improvement in relation to these modes, since it is possible to migrate from fossil fuels to cleaner alternatives in order to reduce the impact of carbon emissions. It is important to use both cleaner fuels and also to promote the migration to electric cars, whose use is more widespread in developed countries. The alternative of the electric vehicles would change the analyzed scenario, because, although the emissions of these vehicles depend mainly on the form of generation of the electric energy used, the emissions referring to the loading of electric vehicles are smaller than the emissions of combustion cars or hybrids (Von Vliet et al., 2011).

Furthermore, it would be possible to integrate the use of shared cars, both through applications and through withdrawals at specific points. The car sharing concept separates the notion of car usage from car ownership, by providing individuals with convenient access to a shared fleet of vehicles at different locations instead of a single private property (Katzev, 2003).

6. Conclusion

The choice of transportation modes used for different routes depends very much on the individual profile analyzed and can be affected by both personal preferences and financial situation. Therefore, the inherent barriers of each transportation mode have different weights for each individual. Fitness and taste for physical exercise or technology, mobility, access to public transportation options, overall lifestyle, environmental awareness, costs and other factors may influence the choice of transportation mode. Thus, the analysis of the performance of the different modes in terms of time, cost and carbon emissions offers theoretical data for comparison but does not necessarily indicate the best mode of transportation.

It has been found that cycling is a very convenient transportation mode in terms of cost and the most interesting from an environmental perspective. Despite this, displacement times are often higher. Hence, the choice of using bicycle will depend on how convenient the traffic or the route is in relation to the use of a bicycle, in addition to the relief and lifestyle of the potential cyclist. Bicycle rental proved to be an advantageous means of transportation, but its use depends on the coverage and availability of the service. In addition, it can be seen that the performance of the bus is not good in many respects, since it represents a high journey time (in 75% of travels studied) when compared to other transport modes and, depending on the distance, it may not represent an advantage for its users.

6.1. Research limitations

The study considered only some variables, such as travel times, cost and carbon emissions, without evaluating more subjective aspects such as road quality, bicycle rental points, distances traveled to the different transportation modes, quality and stocking of public transportation, climate, relief, among others. In addition, the research could be complemented with data on other transportation modes used and the profiles of users in the Porto Alegre metropolitan region.

6.2. Future research

The concept of Smart Cities is very broad. It encompasses the technological development of cities in order to provide a large number of information in real time, and it is therefore possible to deal with a large amount of data (Big Data), cloud computing and internet of things. Therefore, the development of smart cities seeks to make urban activities more efficient and sustainable, transforming the city into a more pleasant place to live (Lemos, 2013). It is possible to use the association of information to help traffic, control environmental pollution (with the presence of CO2 sensors at strategic points in the city that communicate with mobile applications) targeting the more efficient uses of electricity and monitoring of vehicles (Lemos, 2013). Smart cities are considered the apex of the urban organization, joining the technological capacity of data network in storing information to physical mechanisms of the city's infrastructure. This information is aimed at the benefit of citizens (road infrastructure, energy and communication systems). In addition, a special emphasis is given to the road system, since it is capable of influencing the layout and spatialization of other structural elements of the city (Prado & Santos, 2014). Lastly, as bicycles have stood out among other transportation modes, there are other types of bicycle rentals, known as a bike sharing dockless system, in which bicycles are free through the city with a lock attached to the wheel that is unlocked through a mobile app. The metropolitan area of Porto Alegre already has this type of service. However, we could not accommodate the analysis of this last transportation mode due to insufficient data, i.e. the technology is still in its developmental stages at Porto Alegre.

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