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Pathways to sustainable urban mobility planning: A case study applied in São Luís, Brazil

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A B S T R A C T

The fast territorial growth of developing countries has led to problems of displacement in urban space, such as traffic jams, greenhouse gas (GHG) emissions and traffic accidents. As an alternative to change this scenario, it is proposed in this study to develop sustainability guidelines for urban mobility projects that can be applied in developing countries. Through a case study in a Brazilian city, a method of quantifying GHG emissions for the current scenario of the transport system was developed. From this, it became possible to construct four scenarios that determine sustainable urban mobility guidelines organized by complexity levels from the simplest to the most elaborate, each having different GHGs emission levels. The results indicate that the more comprehensive the mobility system remodeling measures, the lower the GHG emissions. The application of the generated guidelines could lead to a reduction of up to 88.6% of annual GHG emissions in the transport sector for the Brazilian city. Thus, the contributions of this work can guide policymakers and planners to define the levels of complexity to be applied in public policies according to the need to reduce emissions or the resources available to invest in this change.

1. Introduction

In the 19th century, 2% of the world's population were living in urban areas, but after two centuries, more than half of the world's population were living in them (Zhang, 2016). The growth in the size of cities resulted in the necessity to offer basic services as housing, sanitation and transport (Venables, 2018). This scenario in developed countries has resulted in higher levels of quality of life (Antrop, 2004; Glaeser, 2011; ITF, 2019). But in developing countries, it is still important to consider key areas for public policy investment such as the transport and mobility sector (Zhang, 2016).

In non-OECD (Organization for Economic Co-operation and Development) countries, individual vehicles carry out 60% of urban passenger transport. There is also an increase in the demand of urban public transport (PT). This is partly because of the inability of existing road networks to meet the population's travel demand, but also because this system can improve accessibility and reduce CO_2 emissions.

The daily commute in developing countries being based on motorized individual vehicles has generated several problems. For example, car-generated congestion has increased greenhouse gas emissions (GHG) in São Paulo (Vasconcellos, 2018). There are inequalities in access to transport and a lack of infrastructural provisions in non-motorized modes in Bangalore and Mumbai (Rahul and Verma, 2013). And there is a lack of a modern multi-mode transport system and road safety problems at several cities in Pakistan (Tahir Masood et al., 2011).

However, in the last decade, some cities have invested in sustainable urban mobility policies. Nagpur addressed solutions for the safety of pedestrians and cyclists and the development of an accessible, efficient, economical and sustainable transport system. Chihuahua developed proposals for PT and bicycle system improvements. Belo Horizonte proposed improvement in social inclusion through mobility and increasing the PT system attractiveness (GIZ, 2013). Those initiatives were based on the European Sustainable Urban Mobility Plans (SUMP) which aim to improve accessibility, integration, efficiency and quality of transport, and to reduce accidents and GHG emissions (Machado and Piccinini, 2018).

As developing countries, such as Brazil, are still taking their first steps in the preparation of SUMP, the present research aims to assess general guidelines that could help those places to reach them. Thus, we present a case study in the city of São Luís, Brazil, through a diagnosis of mobility conditions, followed by urban mobility guidelines. Such guidelines intend to generate positive sustainable impacts in the transport system to be applied in other cities in developing countries. A method based on the IPCC (2014) will be developed to measure the environmental impacts through four different scenarios.

2. Theory

The transport system based on individual vehicle travel is found in several places that have gone through similar processes of economic

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development and urbanization and are classified as “developing”, “emerging” or “peripheral” countries (Maricato, 2017). These localities also underwent times of colonization, slave rule and later independence. As a result of these, the process of late industrialization and capital accumulation began, under the clear influence of hegemonic economies (Maricato, 2017). These countries have similar historical growth and present similar current economies. This construction causes similar problems. In the transport sector, it occurs when the sector is based on individual transport.

It is important to note that the range of inhabitants of a city and the economic development of the country, in general, also help to determine the use of transport modes in such cities. This system is also used to analyze Brazilian cities (ANTP, 2018).

Due to these similar components, solutions generated for a city with certain characteristics can help other similar cities. These characteristics lead to similar problems in the transport sector (Figueroa et al., 2013; Pojani and Stead, 2015; Sobhani et al., 2019). However, it is important to take into account each cities peculiarities determined by its historical construction, geography and population, during adaptation.

Brazil, for example, has territorial development that happened intensely between 1960 and 1970. The country industrialized, grew economically and invested in the road system. However, this process was quick and caused issues such as poor road infrastructure, urban sprawl and inefficient transport systems (Brito and de Souza, 2005; Fernandes, 2015; Paula, 2010).

Only in 2012, this scenario lead the Brazilian federal government to approve Law number 12.587, called as Política Nacional de Mobilidade Urbana (National Urban Mobility Policy - NUMP). The NUMP is a tool to guide the country to a new model based on accessibility, sustainable urban mobility and integration between different transport modes (Brasil, 2012). Out of 3341 municipalities, plus the Federal District, which must approve the mandatory Urban Mobility Plan (SEMOB and Ministério do Desenvolvimento Regional, 2016), only the city of Rio de Janeiro developed a SUMP.

In order to briefly present the transport issues in Brazil and search for key developments to reach sustainable urban mobility in developing nations, this research will develop a case study in a Brazilian city: São Luís. The city is located in the northeast region of Brazil and is the capital of the state of Maranhão. It occupies 582,974 km^2 and has a population of more than 1 million inhabitants (IBGE, 2010a; Lopes, 2008).

São Luís launched its Urban Mobility Plan (UMP) through Urban Mobility Law, number 6.292 in 2017. On one hand, it reinforces the general principles of the NUMP (São Luís, 2017). But on the other hand, the plan has a theoretical character, through measures widely described and illustrated by generic models of what should be performed. It is lacking systematic implementation of the proposed actions (SISTRAN Engenharia, 2016a, 2016b, 2016c).

3. Material and methods

3.1. Field research and guidelines

The place of study is the city of São Luís, capital of the state of Maranhão in Brazil. At first, responsibilities of governmental bodies, laws and plans related to urban mobility in Brazil were analysed: Política Nacional de Mobilidade Urbana (Federal Law no. 12.587/12) and the Estatuto da Cidade (City Statute Federal Law no. 10.257/01). Also examined in São Luís were: Plano Diretor (Municipal Master Plan Law no. 4.669/06), Lei de Mobilidade Urbana (Urban Mobility Law no. 6.292/17) and Zoneamento, Parcelamento, Uso e Ocupação do Solo (Zoning Law no. 3.253/92).

Other institutions were also consulted to collect statistical and quantitative data subject to modes and systems of transport: The Brazilian Institute of Geography and Statistics (IBGE), the National Traffic Department (DENATRAN), the Municipal Traffic and Transport Secretariat (SMTT), the Maranhão Transit Agency Department (DETRAN-MA) and the State Agency for Urban Mobility and Public Services (MOB). Other data were collected through questionnaires. The interviews were conducted to understand the population's mobility patterns and opinions about the urban mobility conditions of the city of São Luís. The questionnaire was directed to users of public transport, car drivers, motorcyclists and cyclists. The other modes of transport were classified in the category “other”. The respondents initially provided information on which means of transport they used the most, followed by the main reason for using this mode, as well as their stress level due to being in a daily traffic jam and their level of satisfaction with the city's urban mobility.

Based on the population of São Luís, which, according to the IBGE (2010b) latest census, has 1,014,837 inhabitants, we calculated the sample size using the simple random sample method for 90% reliability and 5% of margin of error (Bolfarine et al., 2007). Using the concepts of Bolfarine et al. (2007) and SOLVIS (2019) calculator, 273 questionnaires were obtained. Based on this calculation, and to facilitate the division of questionnaires between online and in-person interviews, 300 interviews were carried out, a number that respects the margin of error and reliability according to the population of the municipality. The 300 questionnaires were divided as:

- 200 questionnaires with mixed questions (closed and open) applied to the population in the city of São Luís, through Google Forms. The choice to use this tool is due to the fact it reaches a large scale of people quickly, and can better cover the study area which extends across the whole territory of the city.
- 100 in-person questionnaires close to the bus terminals (Table 1), as part of the field research. This procedure was performed to reach the population that does not have access to online questionnaires, or has difficulty answering them. This step also included annotations and a photographic survey to list which modes of transport exist in the city, how they relate to each other and what the main problems of urban mobility are.

The questionnaires developed for this research seek to know: the main means of transport used by the population, how much time is spent travelling to their daily destinations, how much time they spent in traffic jams, and what the reasons to choose a specific mode of transport are. Other aspects applicable to the four main types of transport are also covered in the research, in order to gather data on the current situation of urban mobility in the city.

Through the questionnaires, it was possible to understand the population displacement preferences according to the transport system used. Specific questionnaires were developed for the four main types of transport (cars, motorcycles, buses and bicycles) to understand individually how each group perceives the state of urban mobility in São Luís. In addition, common questions were done for all transport users, resulting in collective inferences about the level of satisfaction with public transport and the urban mobility of the municipality. Based on the collected data, sustainable mobility guidelines are proposed in the form of flowing text and illustrated by maps.

3.2. GHG emissions

A model that calculates the total GHG emissions by mode, total GHG emissions associated with the mode per passenger (p) was developed that simulates several established scenarios. It was based on the IPCC (2014) model, by which the total GHG emissions by mode share are calculated

Table 1
Description of application questionnaires.

Application date	Neighborhood	Applied questionnaires
Questionnaires *in loco*		
April 13, 2018	São Cristóvão,	25
	Cohab Anil e Turu	25
April 16, 2018	Praia Grande	25
	COHAMA	25
Online questionnaires (*google forms*)		
April 11 and 12, 2018	–	200

based on: fuel carbon intensity (FCI), energy intensity (EI) and activity. Each element of the equation quantifies the total GHG emissions (Fig. 1). This model produces a variation in the activity factor that was performed to enable the calculation of two indices: the total GHG emissions by mode and the total GHG emissions by passenger in each mode. For the first case, the activity is the total number of kilometres travelled in the year by each mode (Fig. 1a). The second case was calculated with the total kilometres travelled in the year by the total number of passengers travelling in the year by mode (Fig. 1b).

The data search begins from the establishment of the parameters by which the calculations were performed. The transport mode for which the analyses will be performed are: walking, cycling, electric car average, electric car margin, car gasoline, car ethanol, motorcycle gasoline, bus diesel and bus biodiesel (motorized ones are associated with the type of fuel). The electric car was divided into two cases: average and margin. This division occurs due to the Brazilian power supply system.

The Brazilian electric system is mostly composed of hydroelectric plants (65.2%) and thermal plants (17.1%). Thus, it is important to consider the emission factors related to each source, since the values of each are fairly different (MATRIZ ENERGÉTICA, 2019).

Due to non-constant energy demand during the day, thermal plants are operated to satisfy the peak energy demands (margin). Most of the electricity demand is provided by hydroelectric plants (base), however during the peak periods of electricity demand (demand displacement) other sources such as thermal power plants are operated (Empresa de Pesquisa Energética, 2019). The electric car average takes into account that the electric car consumption was realized as the average between the margin and the base. The electric car margin assumes that the consumption happened during the peak consumption period.

3.2.1. Fuel carbon intensity (FCI) and energy intensity (EI)

There are several data points related by mode to carbon fuel intensity and energy intensity calculations. In this way, we will present similar data to each mode that was used in the calculations.

3.2.1.1. Emissions factor (EF). The CO_{2eq} (CO_2 equivalent) emission factors for the electric car margin and the average were obtained according to official data provided by Brazil (MCTIC, 2018a, 2018b). An average was calculated between the EF values during 2016, 2017 and 2018 for two cases, average and margin. The energy transmission and distribution loss in Brazil, which reaches 17.5% (ANEEL, 2019), was also considered.

In the mode types using an internal combustion engine (ICE), the emissions related with each fuel's life cycle type were counted and the vehicle life cycle was considered. The values were obtained by Peterson Solutions (2015) and da Silva and Walter (2008) under Brazilian production conditions (Tables 1 and 2).

Based on the Ma et al. (2012) research, another EF that was considered was the vehicle production life cycle. The emission factor values for vehicles driven in urban conditions are in Table 2.

Lastly, the factors related to cycling and walking were analysed. In the bicycle production and maintenance life cycle, the emission factor is 5 gCO_{2eq}/km. Considering that the fuel is the food consumed by the cyclist, the emission factor is 16 gCO_{2eq}/km (Blondel et al., 2011).

3.2.1.2. Calorific power and autonomy/consumption. The data related to the fuels calorific power (C gasoline, hydrous ethanol, diesel and biodiesel B100) were obtained through the Brazilian National Oil Agency (Agência Nacional do Petróleo, 2019).

The data related to the consumption and autonomy of vehicles are different for each car, so it is necessary to use a model to use as a basis. For the car ICE, the Onix 1.4 at 8 V 2019, which was the bestselling car in Brazil in 2018, and there is a flexible version (which can use both ethanol and gasoline) (Auto Esporte, 2019) was chosen. The consumption was obtained by INMETRO (2018) (Table 2). The consumption of buses and motorcycles was obtained as an average (ANTP, 2018; De Carvalho, 2011).

For the electric car, the model used was the Nissan Leaf 150 CV 2019. The necessary data was obtained by NISSAN (2019).

3.2.1.3. Calculation. From the data properly collected and presented in the previous sections, it is possible to calculate the fuel carbon intensity (FCI) and energy intensity (EI). The previous mode division presents a data and calculation summary. Tables 2 and 3 present the summary and results.

3.2.2. Activity

The activity data can be used to change different indices that culminate in important data (Fig. 1). These data are different for each city or metropolitan region. In this research, the case study was applied in the city of São Luís. Thus, all activity data used were obtained from the São Luís

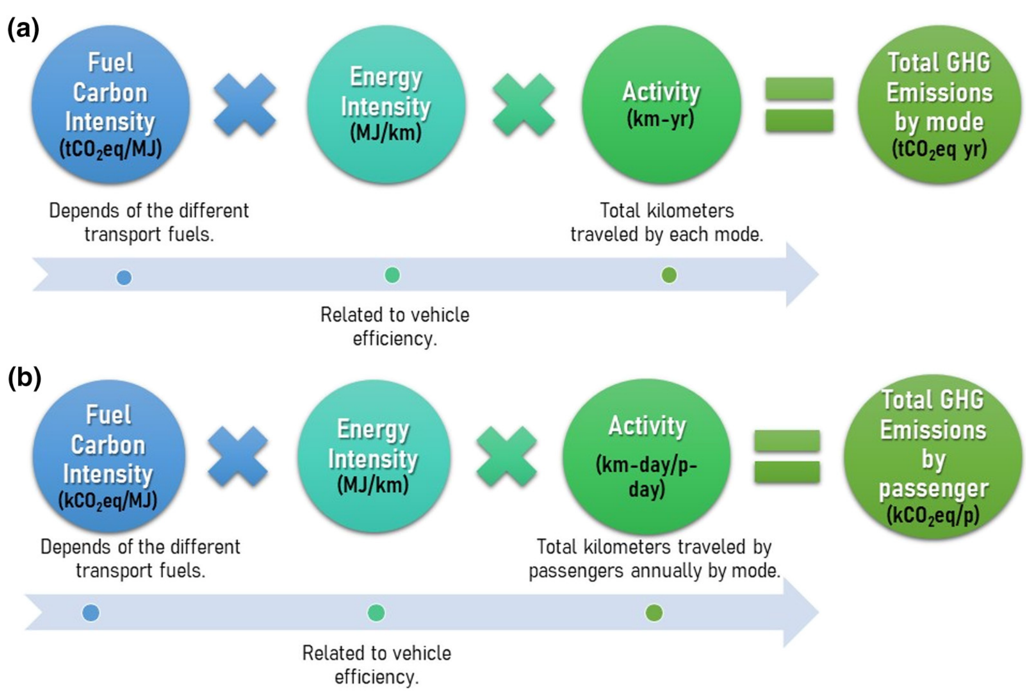

Fig. 1. Decomposition of GHG emissions by transport mode (eq-equivalent).

Table 2
Internal combustion engine modes data summary[a].

	Gasoline car	Ethanol car	Gasoline motorcycle	Diesel bus	Biodiesel bus
Fuel LC (gCO_{2eq}/MJ)	87.72	12.35	87.72	83.8	23.78
Vehicle production (gCO_{2eq}/km)	38.1	38.1	38.1	48.4	48.4
Calorific power (MJ/L)	29.34	21	29.34	35.28	33.1
Consumption (km/L)	8.7	7.6	31	2.56	2.56
Fuel carbon intensity-FCI (gCO_{2eq}/MJ)	99.02	26.14	127.98	87.31	27.52
Energy intensity-EI (MJ/km)	3.37	2.76	0.95	13.78	12.93
FCI EI (gCO_{2eq}/km)	**333.93**	**72.23**	**121.12**	**1203.3**	**355.87**

FCI, Fuel carbon intensity; EI, energy intensity. This definition is explained in Section 3.2.1
[a] The value references cited in the tables are shown above in Sections 3.2.1.1 and 3.2.1.2.

UMP diagnosis stage (evaluation of urban infrastructure, road and mobility) (SISTRAN Engenharia, 2016a).

This stage presents several data such as: number of travelers, daily average kilometres travelled for public transport (bus is the only public mode in the city), individual transport (car and motorcycle) and non-motorized mode (walking and cycling).

The SISTRAN plan provided the number of miles travelled per day by the public transport. The equation used to determine the total activity by mode, except for the bus, is:

$$Activity_{km-yr} = \overline{km_{day\ by\ vehicle}} * \frac{N\ ^{\circ}travelers_{day} * N\ ^{\circ}travel_{day}}{N\ ^{\circ}passengers\ in\ the\ vehicle} * 30 * 12 \tag{1}$$

Eq. (1) calculates the activity taking into account the number of average km travelled by the mode, the number of trips made in the day by a vehicle or mode and how many vehicles are active. However, the data of active vehicles are easily obtained for buses, but not for other modes. In this way, it is calculated by taking into account the total number of passengers and how many people are in each vehicle ($\frac{No.travelers_{day}}{No.passengers\ in\ the\ vehicle}$).

Some scenarios were assumed to use the equation. The SISTRAN Engenharia (2016a) report only provides the total value of individual and non-motorized passenger transport. In the case of individual transport, a percentage of cars and motorcycle in the city was used to identify the number of travelers by mode (DETRAN-MA, 2018). The individual transport using ethanol was considered to be 1.68% of car users, because of the total of vehicles powered by ethanol. The flex cars (both ethanol and gasoline) were consider to be using gasoline since the city has the most expensive ethanol price in the region and the state neither subsidizes nor encourages the population to use it (DETRAN-MA, 2018; O IMPARCIAL, 2019).

The non-motorized category considers 70% of the population to be walking and 30% to be cycling, due to only 18 km of cycle path in the city (Jornal Pequeno, 2017). The number of trips per day considered for individual transport and walking is a total of three trips, and cycling a total of two trips. We believe that this number could be higher; however, the UMP does not present information about the topic. Finally, the number of passengers per mode was defined as one for cycling, walking and motorcycle, and 1.3 for car travel (ANTP, 2016).

Table 3
Electric car (average and margin), cycling, and walking data summary[a].

	Electric car average	Electric car margin	Cycling	Walking
EF fuel food (gCO_{2eq}/km)	–	–	16	16
Vehicle production (gCO_{2eq}/km)	54.5	54.5	5	–
EF lossy electrical (gCO_{2eq}/kWh)	97.29	492.33	–	–
Autonomy (km)	329	329	–	–
Battery capacity (kWh)	40	40	–	–
FCI ∗ EI (gCO_{2eq}/km)	**66.33**	**114.36**	**21**	**16**

FCI, Fuel carbon intensity; EI, energy intensity. This definition is explained in Section 3.2.1
[a] The value references cited in the tables are shown above in Sections 3.2.1.1 and 3.2.1.2.

4. Results and discussion

4.1. Diagnosis

The city of São Luís was formed between two bays in the early 17th century. The original location is now called the historic center. The first expansion of historic center was through occupation at the interior of the island and, only in the 20th century, the coast became was occupied. At that time, each new zone was planned for a different segment of the population. The north for the richer, the side close to the port area for the poor and the land in the middle for middle classes (Wall, 2017).

That expansion model was continued over the following decades. The result is a fragmented city, in which residential areas are isolated from each other and do not interact with other areas (Wall, 2017). In addition, the city road network was formed following the urban growth previously presented, which causes large daily displacements of the population. The internal movements within the boundaries of the municipality are mainly performed by primary (Fig. 2a) and secondary (Fig. 2b) roads that stand out for their function of connecting both the city zones, and the city itself with the metropolitan region (SISTRAN Engenharia, 2016a).

With regard to means of transport, the SMMT is responsible for managing the city PT network by buses. The system is interconnected by the Single Ticket which allows bus line exchanges in the same direction and for 90-minute intervals without paying additional value, only inside São Luís (SMTT, 2019). The main infrastructure that serves the collective passenger transport system consists of the five Bus Terminals that allow boarding and disembarking in a closed place through physical, tariff and time integration. In addition, there are 181 city bus lines in the city (SISTRAN Engenharia, 2016a).

The city also presents a shortage of infrastructure for cyclists. The cycling network is the second smallest in the country, with only 18 km of roads. They are disconnected from each other and focused on physical activity and leisure. There is also a lack of signage and no public bicycle parking (SISTRAN Engenharia, 2016a).

The daily commute also presents several problems: public walk aways without sufficient width; ground irregularities; obstacles such as uneven ramps, inspection covers, power poles and others (SISTRAN Engenharia, 2016a). The historic center is the only region with some dedicated pedestrian sidewalks. As it is a commercial and residential area, it has an intense flow of people who face the same accessibility problems presented in the rest of the urban fabric (SISTRAN Engenharia, 2016d).

When it comes to individual transport, the data from the Maranhão Transit Agency Department (DETRAN-MA, 2018) shows the municipality has a fleet of 390,317 vehicles. The majority of the fleet is composed of individual motor vehicles (91.63%). While there is only 1.71% buses, which represents the only PT type in the city. The motorization rate has been increasing since the beginning of the century (DENATRAN and Ministério da Infraestrutura, 2019; IBGE, 2010b).

Between 2015 and 2018, the vehicle fleet in São Luís had an average growth rate of 2.4%, following the pace of national growth of 2.48% (DENATRAN and Ministério da Infraestrutura, 2019). For the same years, automobile growth rate was 1.4%, surpassed by motorcycles, with a growth rate of 3.7%. While the car rate is below the Brazilian national average (2.18%), the motorcycle rate (2.41%) presents a sharp increase (DENATRAN and Ministério da Infraestrutura, 2019). Thus, it is possible to understand the reasons for saturation of the city's main traffic routes, especially at peak hours. This occurs because of the number of individual vehicles in circulation, as well as the limited possibilities for travel by alternative modes.

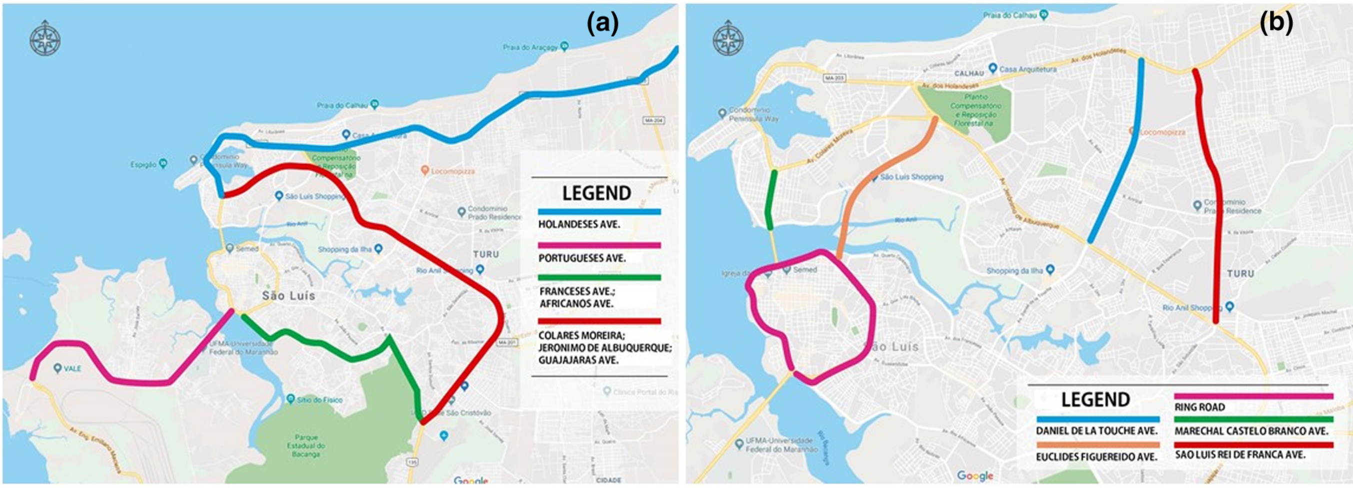

Fig. 2. Main avenues of São Luís; (a) primary avenues (b) secondary avenues.

Lastly, the transport user perceptions regarding urban mobility in the city is an important aspect to understand the transport quality level offered to the population. 300 surveys were applied raising several questions about urban mobility in the city. The largest number of respondents were the public transport users (55%), followed by car drivers (35%), motorcyclists (6%) and cyclists (2%). The numbers referring to "other" portions were disregarded. In terms of use (Fig. 3), the majority of cars and motorcycles drivers, combined with cyclists, use the mode to commute, while 60.24% who use the bus do so to travel to their place of study and only 1% use it for leisure. People who use the car and bicycle, for example, have cited leisure as one of the main purposes of use.

The users stress level related to the city's traffic was also queried, on a scale of "Little Stressed", "Indifferent" and "Very Stressed". Car drivers (42.99%) mostly answered as "Very Stressed", many mentioned daily traffic jams as the main reason, followed by the lack of road infrastructure. A majority of public transport users are also "Very Stressed" (55.42%). Some of them also cited the long traffic jams, as well as the long commute times and lack of comfort on buses. Motorcyclists (45%) and cyclists (50%) are indifferent to the issue. Their given justification is that they have the possibility of deviating from congested places, passing between vehicles and thus spending less time in traffic jams.

How the population evaluated the public transport service of the municipality of São Luís was also questioned (Fig. 4a). 40% of the respondents declared it as regular, although 37% consider it bad and 16%, terrible. The option to classify it as "great" was offered, but none of the respondents selected it. The problems most cited by respondents were the: time-consuming travel; shortage of lines and buses; insecurity and discomfort.

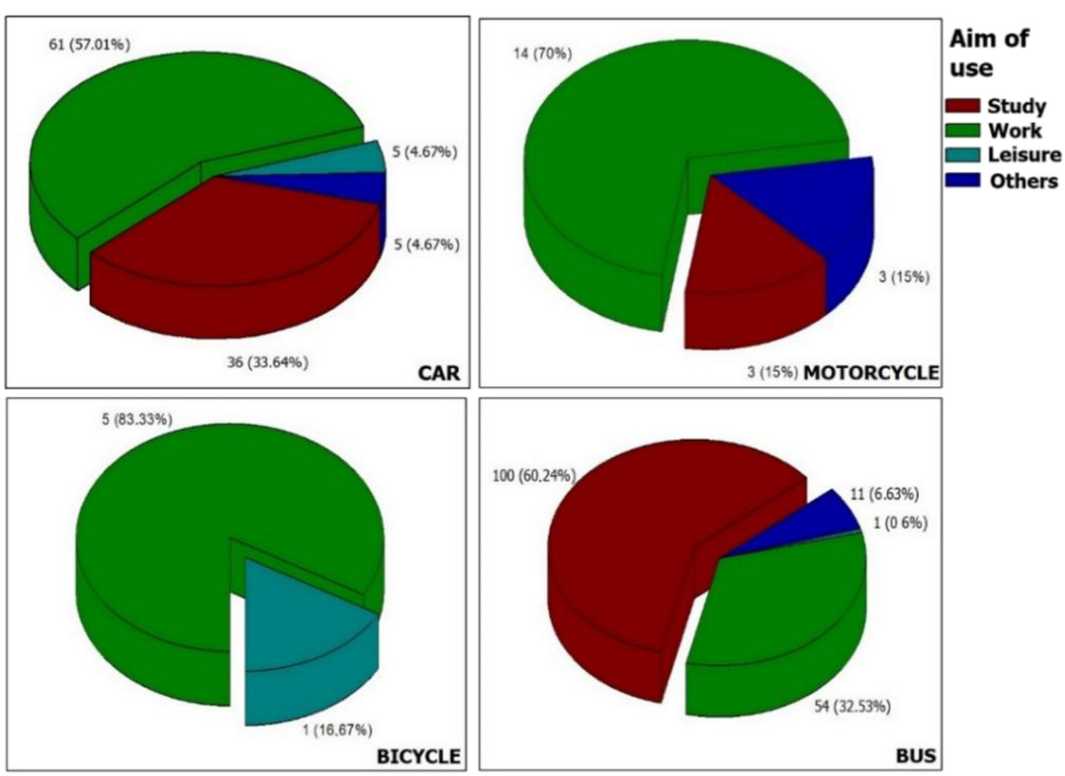

Fig. 3. Aim of use by mode transport for São Luís.

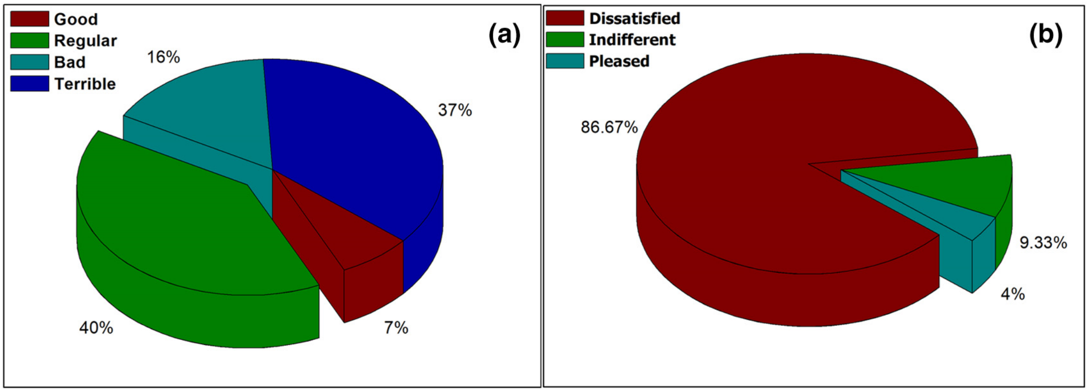

Fig. 4. Level of satisfaction in São Luis; (a) public transport (b) urban mobility.

Regarding the satisfaction with the urban mobility in the city (Fig. 4b), the great population dissatisfaction is noted, corresponding to 86.67% of respondents. All the problems described above were mentioned by people waiting for solutions that can improve the conditions of displacement in the city.

4.2. Urban mobility management guidelines

Since we understand the population needs and the mobility problems indicated by the diagnosis, it is possible to develop measures applicable to improving the São Luís urban mobility system (Table 4). These options considered both subjective aspects noticed during the field research, such as the stress levels presented by the travelers; their difficulties to access PT and the desire to be able to choose a transport mode to move from one place to another, rather than be dependent on scarce options. Several transport guides developed by the Brazilian government and institutions that deal with the theme of sustainable urban mobility were also considered. Lastly, mobility research and case studies applied to developing countries were examined to develop viable alternatives to the reality of these countries.

4.3. Sustainable impacts

The first calculation made is the total current annual emissions in the city by mode. The calculation process was done according to Fig. 1a. The main contributors to GHG emissions in the city are motorized transport: cars and motorcycles powered by gasoline emit 89% of the annual GHG emissions of the city (Fig. 5). Gasoline-powered cars are responsible for 69.6% of current GHG emissions in the transport sector. Electric cars have no contribution due to the city having only 0.01% of users (DETRAN-MA, 2018). Walking and cycling presented low emission levels in all cases because food consumption has been attributed to both.

Table 4
Mobility measures for the city of São Luís.

Measure	Objectives	Main activities to develop
Clean fuels (individual and PT fleets)	Subsidize the costs of ethanol and biodiesel (as electric vehicles in developing countries have high costs, low autonomy and huge problems with charging infrastructure (Vonbun, 2015) those biofuels are viable technologies to Brazil).	1. Use of biodiesel in PT; 2. Encourage the use of publicly subsidized costs of biofuels for individual motor vehicles;
Collective mobility services	Improve the PT quality and attract part of motorized individual transport users (Hook and Wright, 2017; Ministério das Cidades, 2016; Poku-Boansi and Marsden, 2018).	1. Temporal integration of the metropolitan region through the Single Ticket; 2. Link the dedicated PT lanes; 3. Insert minibuses in difficult areas to reach; 4. Geometrical remodeling of roads: lane duplication on main axes and traffic calming measurements; 5. Integrate the Bus Rapid Transport (BRT) with the existing PT system; 6. Intelligent traffic signaling in the BRT corridors;
Accessibility	Improve accessibility on sidewalks and walkability to access the PT (Jiang et al., 2012; Rahul and Verma, 2014).	1. Define dedicated walkways in areas with high pedestrian flow; 2. Create the Sidewalks Revitalization Plan;
Parking strategy and management	Control parking supply to discourage individual motor vehicle use (Weinberger et al., 2010)	1. Charge progressive fees for parking time; 2. Release the construction of residential parking lots near the bus terminals; 3. Set maximum parking ceilings; 4. Apply toll charges in the Historic Center; 5. Develop parking areas near the city bus terminals;
Increasing bicycle use	Increase bicycle use for short and medium distances (BRASIL, 2007; Litman et al., 2017; Rahul and Verma, 2013).	1. Expand and interconnect existing cycling network; 2. Implement bike racks in new traffic generating centers; 3. Implement bicycle racks and support facilities for cyclists attached to bus terminals and urban equipment; 4. Develop a shared bike system; 5. Improve signaling, shading and lighting on cycle paths; 6. Geometrically remodel roads: insert bicycle lanes;
Carpooling	Offer a carpooling system that increases vehicle occupancy (Vanoutrive et al., 2012)	1. Develop a carpooling system (through private initiative);
Info-mobility tools	Promote technologies that guide the population in the use of PT and help them to choose the best routes (Ministério das Cidades, 2016)	1. Provide user information through city transport maps, while optimizing the existing application.

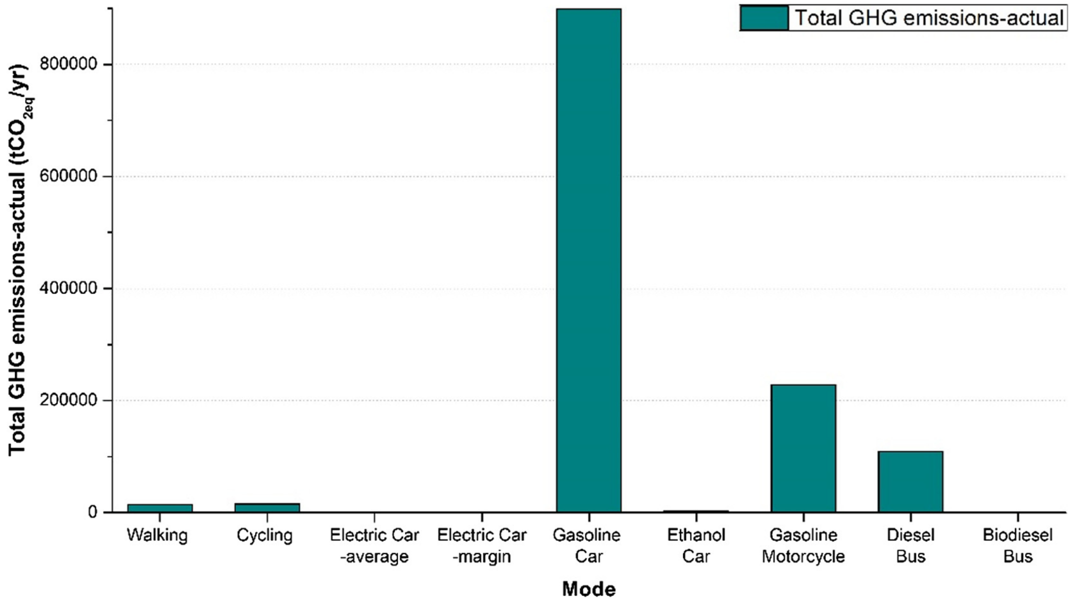

Fig. 5. Total of actual GHG emissions by transport modes in São Luís-MA.

Scenarios for guideline execution were developed regarding the guidelines developed in Section 4.2 and the mapping of the current mode emission factor in the city. Those were created by considering them from the initially easiest, to the hardest implementation by the government.

The criterion for considering what is easier or more difficult to implement was according to a study carried out for Brazil by the world bank (Gouvello, 2010). In this study, the cost of carbon mitigation measures are calculated at a discount rate of 8%. In this case, the measures that have negative costs are easier to implement and those with high positive costs are more difficult to implement. However, it is important to note that implementation depends largely on government investment actions.

The scenarios proceed by increasing or decreasing the number of users in each mode. A percentage in function of current values of the city travelers' number was calculated. In Table 5 the scenarios description,

Table 5
Scenarios created for guideline-based simulations.

Scenario	Guidelines applied[a]	Diesel bus	Gasoline car	Ethanol car	Motorcycle gasoline	Walking	Cycling
Scenario 1		The government and competent institutions were unable to implement most of the suggested measures (a).					
	3, 16[c], 17, 23	IMPACTS (%)[b] Percentage calculated over the total number of travelers in the city.					
		↑ 2	↓ − 2	0	↓ − 1	0	↑ 1
Scenario 2		Government and institutions were able to implement some of the guidelines, nonetheless, it had little impact on population behaviour change. No educational actions (b).					
	2[d], 3, 4, 9, 11, 16[c], 17, 18, 19, 23	IMPACTS (%)[b] Percentage calculated over the total number of travelers in the city.					
		↑ 3.15	↓ − 7.4	↑ 4	↓ − 2.05	↑ 0.8	↑ 1.5
Scenario 3		The government and institutions were able to apply almost all of the suggested measures, but there is still a lack of educative actions for population behavioral changes (c).					
	1, 2[d], 3, 4, 5, 9, 10, 11, 12, 13, 16[c], 17, 18, 19, 20, 22, 23	IMPACTS (%) Percentage calculated over the total number of travelers in the city.					
		↑ 7	↓ − 15.1	↑ 10	↓ − 3	↑ 3	↑ 2.2
		Vehicular occupancy rate					
		130.99	2.4	2.4	1.2	–	1
Scenario 4		All suggestion measures were applied and, together, there were educational actions, which generated a great change in population behaviour (c).					
	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23	IMPACTS (%) Percentage calculated over the total number of travelers in the city.					
		↑ 10.5	↓ − 20	↑ 14	↓ − 11	↑ 3.5	↑ 3
		Vehicular occupancy rate					
		130.99	2.4	2.4	1.2	–	1

[a] Guidelines mentioned in this table.
[b] No change in occupancy vehicular rate.
[c] Conserving the current geometry.
[d] Small-scale government incentive to use ethanol.

guidelines and impacts applied according to each mode are presented. The time horizons to achieve the guidelines will follow the same metrics as presented in the Institutional Instruments Proposals - Implantation Strategic Plan from São Luís UMP: short - 2 years; (b) medium - 2 to 5 years; (c) long - 5 to 10 years (SISTRAN Engenharia, 2016a).

The first scenario simulation was related to the total GHG emissions per passenger according to the mode used. This calculation is performed according to the vehicle occupancy rate (Fig. 1b). In the first and second scenarios the vehicle occupancy rate does not change from the current one, so the results are the same for both situations (Fig. 6a). The change in vehicle occupancy rate occurs equally in the 3rd and 4th scenarios (Fig. 6b).

The GHG emissions reduce from 5.85 kCO_{2eq}/p with the gasoline car to only 3.17 kCO_{2eq}/p, with an increase in the number of people in the vehicle. The actual result of GHG emission for the gasoline car is close to the result found by ANTP (2018) considering three trips per day: 4.28 kCO_{2eq}/p. The difference is attributed to this paper considering not just the pollution made by the fuel but also the emissions related to the life cycle of the car.

This measure can be applied to all regions of Brazil since the data for fuels, biofuels and electric consumption is national. This research does not encourage large public sector investment in electric vehicles in Brazil, as mentioned and justified in Section 4.2. According to total GHG emissions simulations by passenger, electric cars and ethanol are close. For the electric cars in the margin this value is higher than ethanol, which reinforces the biofuels advantages.

All scenarios created compared the actual in terms of the annual total GHG emissions for each mode. They are divided by sector to facilitate the discussion of results (Figs. 7–9).

The set of walking and cycling modes were analysed together (Fig. 7) and were attributed to population food-related GHG emissions. The tendency is an increase in the number of people walking and cycling, at least as part of their daily commute, especially for more sustainable scenarios that lead to greater emissions associated with both modes.

The next set of modes analysed are PT (Fig. 8). As the system was based on the bus, BRT and minibus, they were all considered to be buses. For

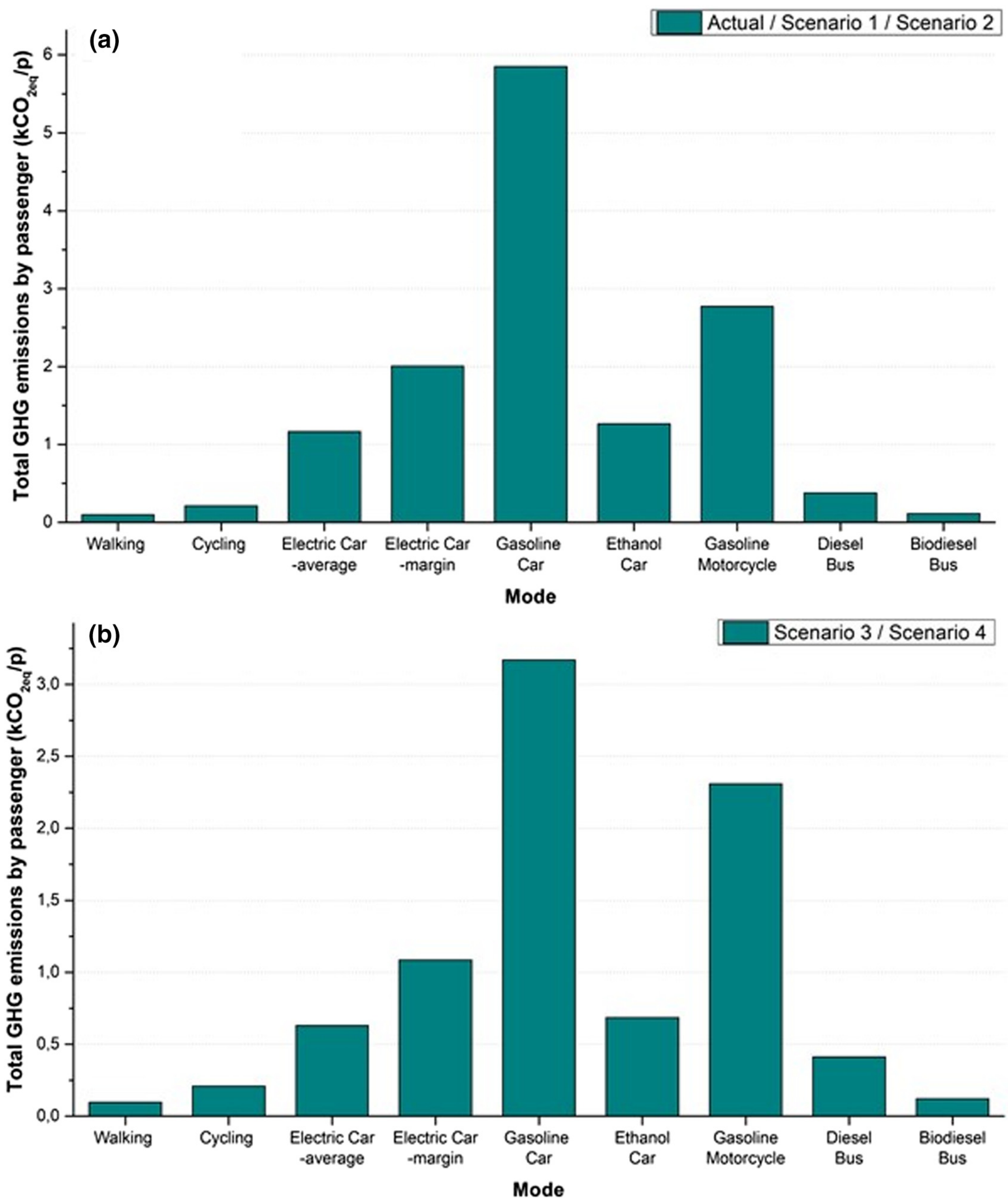

Fig. 6. Total GHG emissions by passenger by transport mode in Brazil.

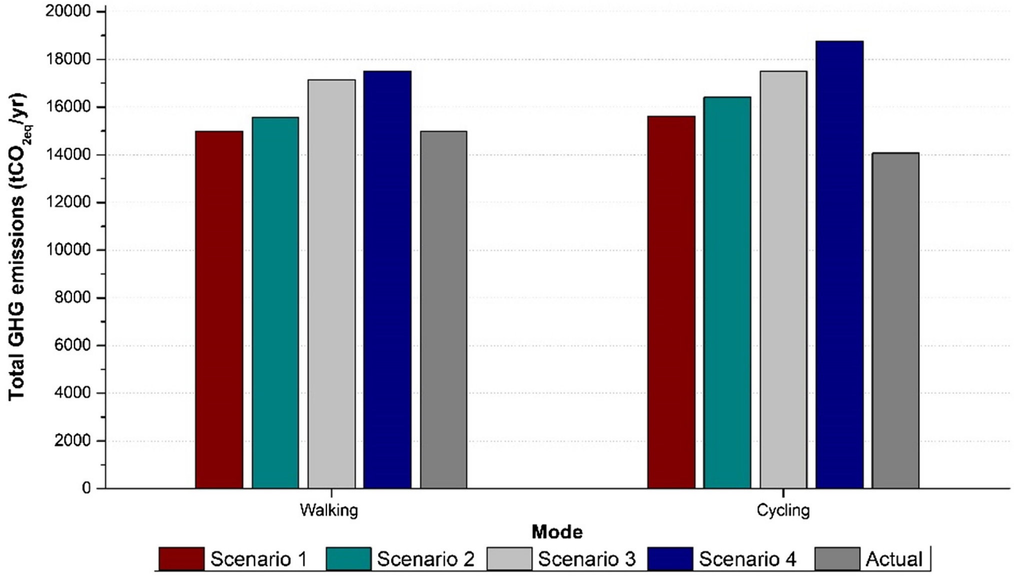

Fig. 7. Total GHG emissions by walking and cycling transport in São Luís-MA (Scenarios).

scenarios that use diesel (1st and 2nd) as the fuel, there is a tendency to increase the amount of emissions in the scenarios. That occurs due to an increase in the mode users' number and it also consider the vehicle fleet to be increasing. For scenarios in which biodiesel use in all vehicles (3rd and 4th) was mandatory, there was a reduction higher than 60% in the GHG emissions.

The individual transport simulated were the major current contributors to GHG emissions (Fig. 9). The gasoline-powered car is the largest actual GHG emitter (Figs. 5 and 9). Therefore, a great sustainable contribution, which can be simple and effective for many cities, is the use of ethanol in vehicles. This solution depends mainly on the government incentive for fuel production at sustainable levels and on the biofuels use. It can be performed for example by applying cost subsidies in gas stations. The reduction from the current scenario to the 4th scenario was higher than 70%.

The expected migration behavior between the scenarios is: the population will be walking and cycling more, using PT more and, those ones that continue to use individual transport (car and motorcycle), will increase their awareness of sustainable practices. This change between the established scenarios is presented in Fig. 10.

Finally, the accounting of the entire actions and measures analysed can be carried out through the process of governmental, population and regional understanding. These measures could induce a reduction of more than 88.69% of the recent current annual GHG emissions of a city such as São Luis (Fig. 11). Comparing the scenarios proposed with the current reality, the reduction in tCO_{2eq} per year is: Scenario 1 × Actual = 7.74%; Scenario 2 × Actual = 24%; Scenario 3 × Actual = 67.44% and Scenario 4 × Actual = 88.69%.

Fig. 5 shows that most of the emissions in the transport sector in the city of São Luis come from individual gasoline transport (cars and motorcycles). This mode is also responsible for other problems such as traffic jams and public health problems, among others (Lockwood, 2015). The mode change within the transport sector is already being adopted as a tool to reduce these problems and GHG emissions (Nelldal and Andersson, 2012). Those facts confirm that it is possible to achieve these scenarios

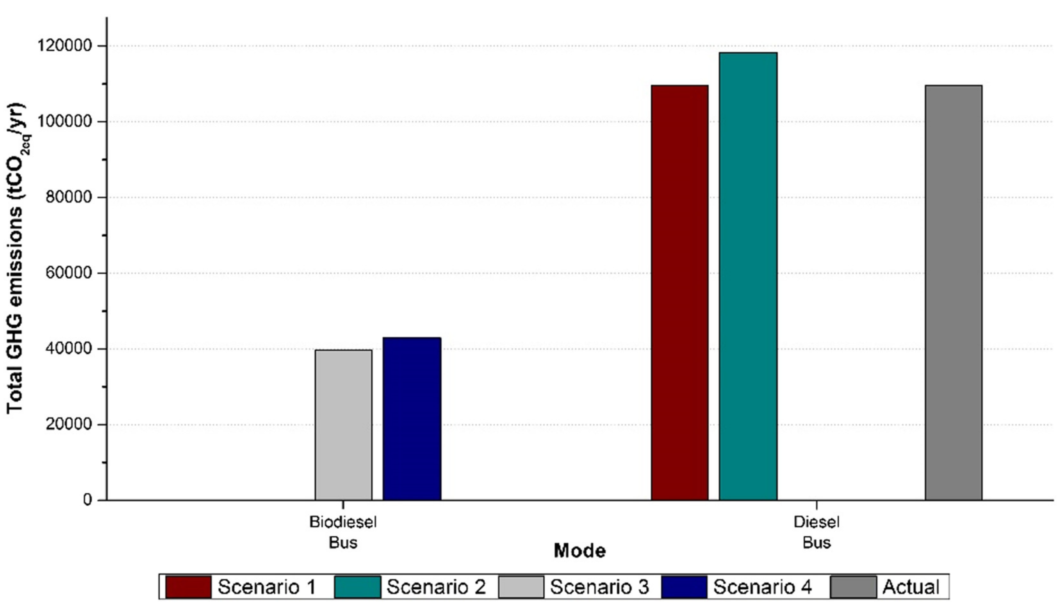

Fig. 8. Total GHG emissions by public transport in São Luís-MA (Scenarios).

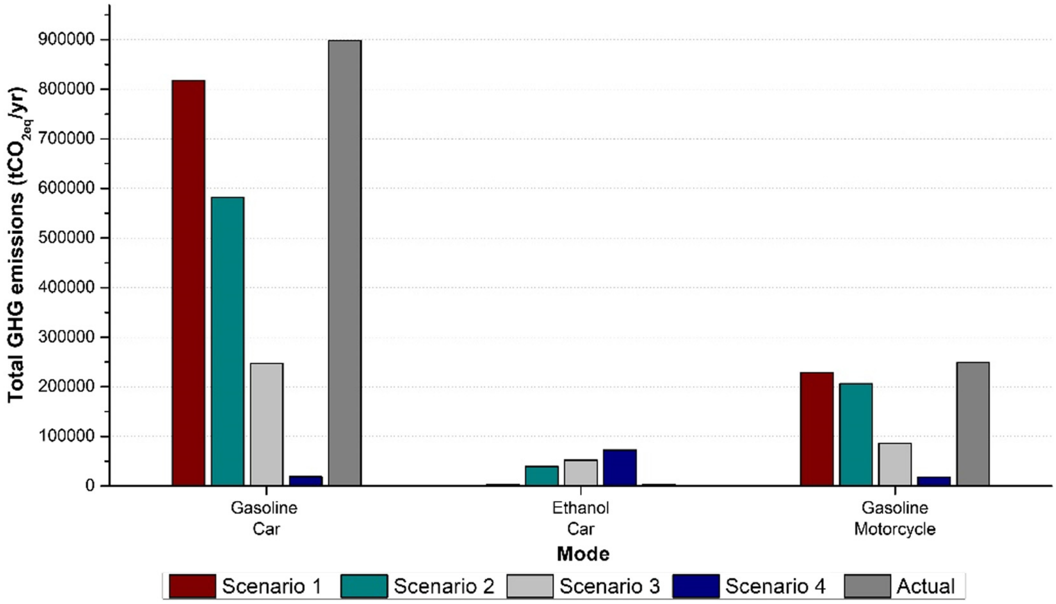

Fig. 9. Total GHG emissions by individual transport in São Luís-MA (Scenarios).

of GHG emissions with mode change such as described in the results obtained in Fig. 11.

It is important to emphasize how difficult it is to carry out this type of mode change, as it requires not only investment in infrastructure and urban management, but also public policies to raise awareness of the population.

In this way, two roles are very important to reach these GHG emissions reductions. The main one is the governance role, and the secondary one is the local population behavioral change. We could believe that due to gasoline being the main emitter, the main guideline proposed would be the fuel exchange of cars and motorcycles (currently accounting for 89% of GHG emissions). However, it is necessary to induce people to travel more by PT, which can be more sustainable than individual travel and improves the quality of life of the population.

5. Conclusions

This paper presents a case study that generates sustainable urban mobility guidelines as applied to the city of São Luis, but which can be adopted in other cities in developing countries with any necessary adaptations. A contextualization was performed considering the territorial development of the city and the federal and municipal legislation regarding the transport sector. Cities with similar historical backgrounds and similar transport

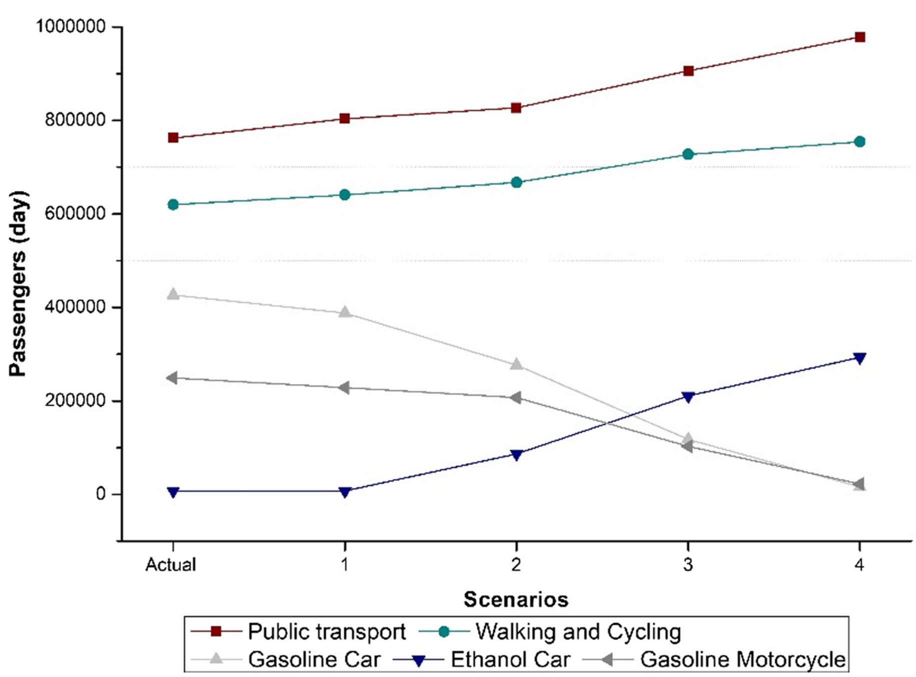

Fig. 10. Number of passengers for scenarios by mode in São Luís-MA.

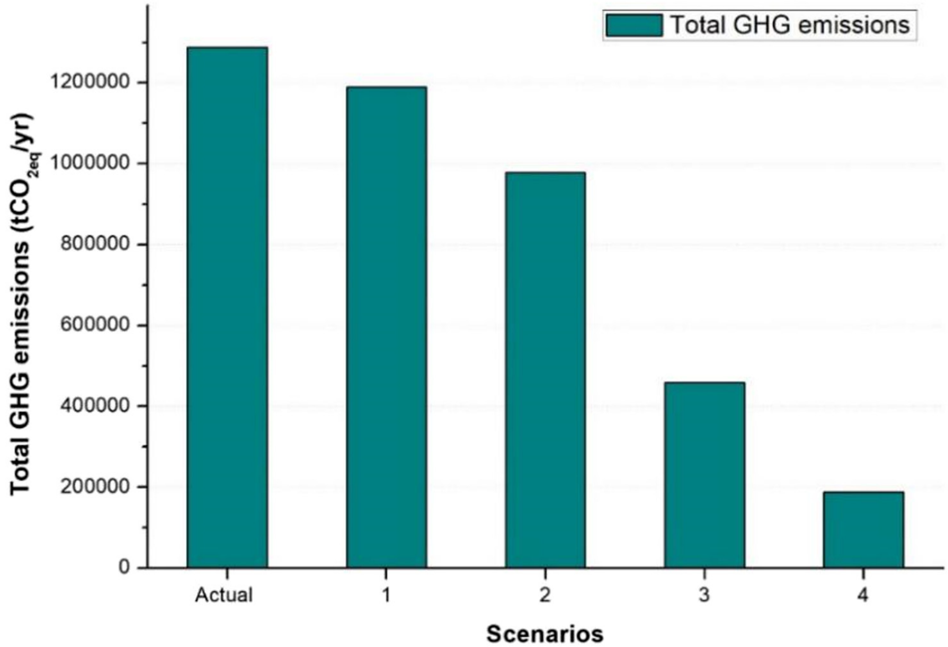

Fig. 11. Total GHG emissions simulated by scenarios in São Luís-MA.

problems were also considered, to expand the extension and applicability of this research.

The data collected from the governmental institutions and the questionnaire applied to the population were used to develop a diagnosis about the city transport system and the population perceptions. Based on the diagnosis, population needs, measures applied around the world and the latent need of the planet for sustainable measures, the urban mobility guidelines were developed (Table 5).

After that, the impact of the guidelines on GHG emissions reductions were assessed. A method based on one presented by IPCC (2014) was elaborated and compiled with data corresponding with the Brazilian reality and with the São Luís activity. Scenarios based on the previously established guidelines were set up to measure the sustainable impacts that could be made depending on the implementation adopted by the government. These scenarios were compared with the current GHG emissions annually produced by the city of São Luís.

The results showed that, currently, the gasoline-powered car is solely responsible for 69.6% of current GHG emissions in the transport sector at São Luís. Gasoline-powered motorcycles and cars are the major emitters, responsible for almost 89% of GHG emissions annually in the city. Another analysis carried out was the GHG emission per passenger per mode, which shows how much CO_{2eq} a passenger emits for each mode per day. This result showed the possibility of decrease the emissions per passenger by increasing vehicle occupancy rate. In addition, it compares the modes and establishes Brazilian ethanol at a better level than the electric car, because its emission rate is almost equal to the average (using hydroelectric and other sources to produce electricity) and it does not need new investment in infrastructure.

The proposed scenarios results are presented on a scale from 1st to 4th, where the guidelines were poorly applied in 1st and fully applied in 4th. The GHG reduction compared with the current reality was: Scenario 1 × Actual = 7.74%; Scenario 2 × Actual = 24%; Scenario 3 × Actual = 67.44% and Scenario 4 × Actual = 88.69%.

These results show the importance of the generated guidelines being centred on the principle of discouraging the use of individual transport and promoting walking, cycling and public transportation. We believe that due to gasoline fuel being the main emitter, the main guideline proposed would be the fuel exchange of cars and motorcycles to another more sustainable fuel (*e.g.* ethanol). However, it is necessary to induce people to a behavioral change in order to use a more sustainable mode of transport by encouraging them to mix the modes. Finally, it is important to provide conditions to make this change, which requires commitment by both the population and, mainly, the government.

CRediT authorship contribution statement

Brenda V.F. Silva: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Project administration, Funding acquisition. **Mavd P.R. Teles:** Conceptualization, Methodology, Software, Validation, Formal analysis, Data curation, Writing - original draft, Writing - review & editing, Project administration, Funding acquisition.

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