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Estimating CO_2 Emissions for Bus Rapid Transit (BRT) Using Life Cycle Assessment: A Case Study in Rio de Janeiro City

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Abstract

The amount of greenhouse gases has been growing dramatically in recent decades, producing global warming and causing climate change that affects the entire planet. To mitigate these emissions, several nations have committed to implementing measures to reduce emissions of these gases, with carbon dioxide being the main one. The transport sector is one of the leading carbon emitters. It needs to be the object of attention from government authorities and private companies so that sustainable solutions are planned and implemented to reduce the fossil fuel consumption. The emerging solutions point to implementing public transport in systems that use large-capacity vehicles, replacing conventional cars and buses. However, such systems require constructing a complex infrastructure, which will also produce emissions. Thus, it is necessary to balance the emissions produced by the new system with the emissions avoided by replacing the old system, for a clear quantification of the carbon reduction. This balance is best accomplished using the system lifecycle assessment approach. This case study presents the life cycle assessment, according to ISO 14040 standards, of the BRT system implemented in Rio de Janeiro, Brazil based on real data collected during the construction of the system. The results show that the system will take 16 years to compensate for the emissions produced, and in the life cycle, the projected reduction is about half a million tons of CO_2. The study indicates a path that can be useful to planners seeking to reduce carbon in the public transport sector.

Keywords
BRT; CO_2; produced emissions; avoided emissions; LCA; infrastructure construction; renewable fuels; biodiesel

1. Introduction

The amount of greenhouse gases released into the atmosphere has been growing yearly, with a sharp increase in the growth curve in recent decades. Among the gases, the biggest concern is CO_2, related to human activity, with an annual increase of 0.85 degrees in the planet's average temperature, between 1880 and 2012 [1]. The IPCC report 2022 warned that the world is set to reach the 1.5°C level within the next two decades and said that only the most drastic cuts in carbon emissions from now would help prevent an environmental disaster [2].

According to OECD [3], the CO_2 emissions related to transport represent 23% of total emissions on the planet, and the largest share of these emissions comes from road transport. IEA [4] estimates transport-related emissions will grow 100% by 2050 based on 2009. The International Transport Forum estimates that global transport activity will more than double by 2050, and traffic emissions will rise by 16% compared to 2015-even if existing commitments to decarbonize transport are fully implemented [5]. In Brazil, the energy consumed by the transportation sector in 2019 represented 32.7% of total energy. The amount of GHG emitted by the Brazilian transport sector reached 200 million tons of CO_2, corresponding to 45.4% of the total emissions associated with the Brazilian energy matrix, being the sector with the greatest share of emissions related to energy use [6].

Due to the established observations and the uncertainties generated by the exploration of the theme, environmental awareness is expanding worldwide, and governments are demonstrating signs of concern in their public policies to reduce greenhouse gas emissions.

Several nations, including Brazil, made GHG reduction commitments in the Paris Agreement and COP26. Brazil confirms its commitment to reduce its GHG in 2025 by 37%, compared with 2005. Additionally, Brazil committed to reducing its emissions in 2030 by 50%, compared with 2005. Brazil´s commitments also include a long-term objective to achieve climate neutrality by 2050 [7].

As the transport sector is responsible for a large share of emissions, planning is needed that leads to more sustainable transport systems, reducing the use of fossil fuels. Public transport must be improved and its use encouraged. Among the solutions that have emerged in public transport are Bus Rapid Transit (BRT) and rail systems (heavy and light rail). BRT is a mass transit system introduced in 1974 in Curitiba, Brazil, and is now active in 173 cities worldwide, mostly in Latin America and Asia [8]. The cost of implementing a BRT system is usually less than that of a rail system [9, 10]. That's why it has become a very popular option in several cities. However, it requires infrastructure construction, with generally exclusive lanes, well-equipped stations, and special vehicles. Commonly the approach used to measure CO_2 emissions in transport systems only considers the emissions from the fossil fuel burned in vehicles operation. This approach can lead to unrealistic results because it does not consider the emissions produced in the construction and maintenance of the infrastructure [11].

A more extensive approach takes into consideration the production of CO_2 emissions throughout the life cycle (LC), considering the operational phases (of vehicles and infrastructure), the infrastructure construction (roadbed, bridges, tunnels, and stations), and the maintenance (infrastructure and fleet) [11]. With this approach, it's possible to measure the environmental impact of the transport system, considering the CO_2 emissions in all phases, from the system implementation, and its operation, to the end of life.

To carry out the assessment of the environmental impacts produced by a transport system during its life cycle, the Life Cycle Assessment (LCA) approach is commonly adopted. ISO 14040 records that the life cycle is the "successive and linked stages of a product system, from the acquisition of the raw material or generation of natural resources to final disposal" and defines the LCA as the "compilation and evaluation of inputs, outputs and potential environmental impacts of a product system throughout its life cycle," which allows the construction of a Life Cycle Inventory (LCI) [12].

The BRT or rail system implementation will produce a certain amount of carbon emission over the system life cycle. However, it will avoid the emission of replaced vehicles (conventional cars and buses). We then have:

Net avoided emission = avoided emission – produced emission

So, the question that arises is:

1. Will a positive net avoided emission result in an effective carbon reduction and quantification of this reduction?
2. How long will it take, within the life cycle, for the emissions produced by the construction of the infrastructure to be offset by the avoided emissions?

Few transport studies using life cycle assessment and generally use estimated data and some simulation software. The contribution of this study is to expand the knowledge we have about carbon reduction in transport systems with the use of life cycle assessment and real data from the construction of these systems. The procedure described can also be applied to system expansions, such as new corridors for this mode of transport, and it is also possible to serve as a guide for adaptation to other modes of transport.

The main objective of this article is to elaborate on a BRT system LCI and investigate the real capacity of these systems to contribute to environmental benefits when analyzing the CO_2 emissions in the atmosphere. The study is based on a BRT system, implanted in Rio de Janeiro city, Brazil, and will allow answering the two questions posed above.

Many life cycle studies in the transport sector are specific to certain system components, such as vehicles, a road, fuels, technologies, etc. Few studies approach the complete system in an integrated way; usually, the construction data are estimated. This study presents a methodology that allows the measurement of carbon emissions throughout the life cycle of a complete transport system, based on real construction data. It enables the quantification of the carbon reduction provided by the system.

1.1 The BRT Corridor

The BRT corridor was deployed in Rio de Janeiro to improve mobility inside the city and is a part of the planning to better adjust passenger demand for the big sports events that took place in 2014 and 2016, respectively FIFA Soccer Cup and the Olympic Games. With a 39 km extension, 6 bridges, 43 stations, and 5 terminals, this corridor, called BRT Transcarioca, connects the international airport to the west side of the city, where it expands.

1.2 LCA in BRT Systems

CO_2 emissions in BRT systems occur at various stages of their life cycle. The life cycle phases of a transport system, including BRT, can be classified into infrastructure construction, vehicle manufacturing (bus, in the case of BRT), vehicle operation, infrastructure operation, vehicle maintenance, maintenance of infrastructure, and end-of-life [13]. Considering the BRT system's life cycle phase with the highest emissions is the bus (diesel-powered) operation [14]. Emissions from burning fuel occur in various activities related to infrastructure construction, such as transporting materials and people and operating different types of machinery, including heavy machinery, in civil engineering. Emissions from producing intensively used materials, such as steel and concrete, are also considered. These emissions constitute the embodied carbon in the production of each type of material. In the vehicle's manufacture are considered emissions from burning fuels in the production process and the consumption of industrial materials such as steel, fiberglass, copper, aluminum, and rubber. In infrastructure operation, emissions generally occur from using electricity at the stations. The carbon incorporated from spare parts and lubricants is considered in vehicle maintenance. There may also be the burning of fuel and use of electricity in the displacement and execution of tasks by the maintenance team. Similarly, in infrastructure maintenance, the embodied carbon in the materials used, mainly in the reconstruction of the roadbed, the emissions from the burning of fuels, and the use of electricity in typical activities are considered.

2. Materials and Methods

The proposed method establishes and applies two distinct procedures to the BRT Transcarioca corridor to achieve the study's objectives.

The first procedure is oriented toward constructing an LCI according to the standard found in ISO 14040, based on real data of the construction of the BRT system provided by the Rio de Janeiro Municipal Transport Department (SMTR).

The second procedure is oriented toward estimating avoided emissions. A study was carried out with a focus on reducing emissions associated with the migration of car users to the BRT, as well as reducing the mileage of regular buses, resulting from the reorganization of the lines after the insertion of the corridor.

2.1 LCI Objective and Scope

The objective was to quantify the global warming potential of inventory phases, allowing the knowledge of the impact level, by quantifying the CO_2 emissions in each stage and producing the necessary input data for the second procedure.

The LCI scope included building infrastructure, manufacturing buses, operating infrastructure and buses, and maintaining infrastructure and buses. According to the studies [13, 15-19], the end-of-life phase was disregarded due to the small representativeness in the final result and the lack of available data. Input data were processed through acquiring, quantifying, and using raw materials, manufactured goods, electric energy consumption, and fuels used throughout the system life cycle. This study was carried out over 40 years starting with the system's inauguration in the second half of 2014. The construction of the System took place from 2011 to the first half of 2014.

Figure 1 shows the general overview of the procedure with the phase boundaries, processes, inputs, and outputs.

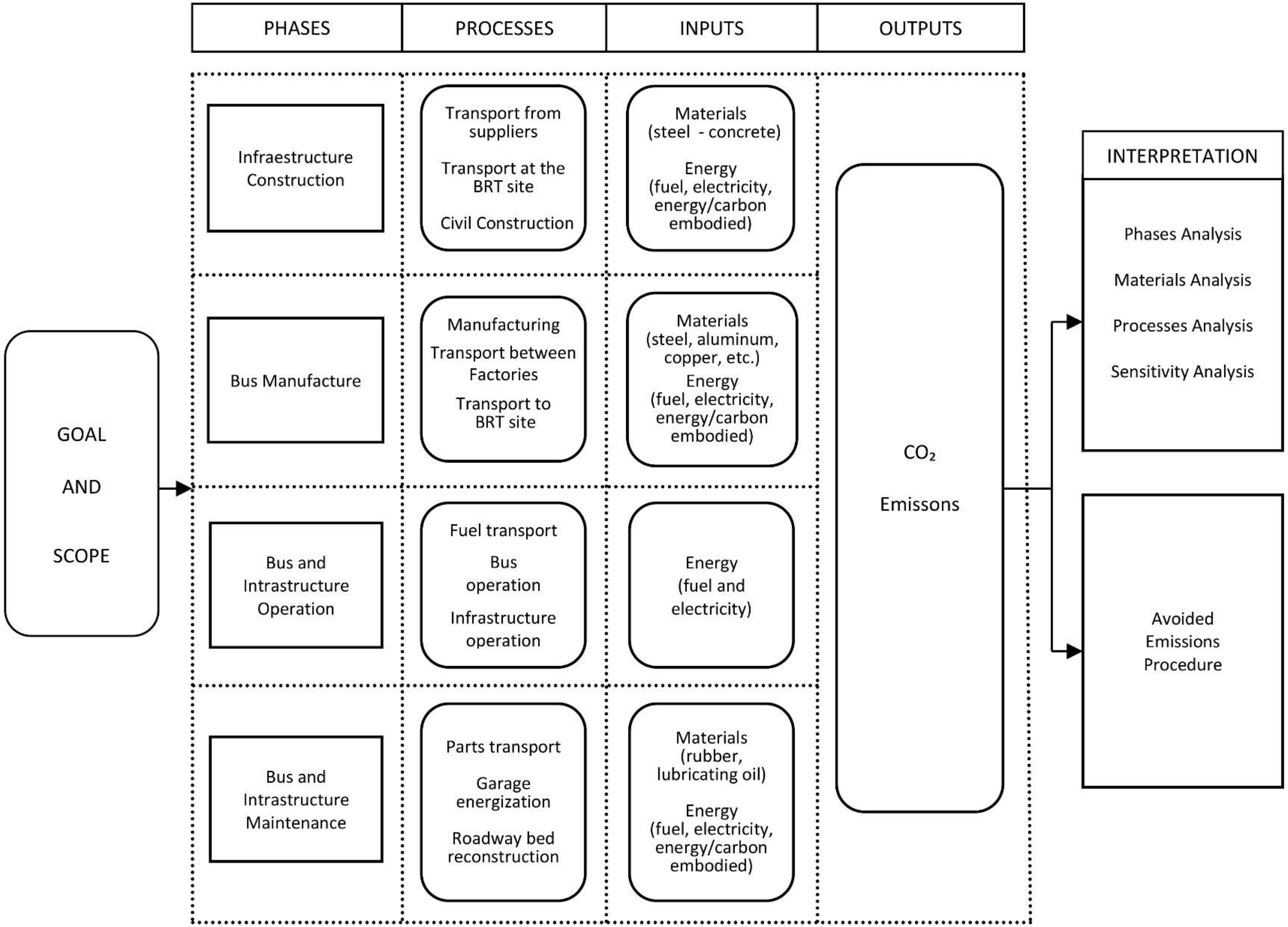

Figure 1 LCI procedure of a BRT system.

2.2 Functional Unit

The functional unit chosen is 1 passenger kilometer traveled (PKT).

2.3 Emission Factors

The IPCC recommends using specific or national emission factors whenever possible [20]. Following this recommendation, Brazilian emission factors were used for fuels and electricity purchased and used in the country. For Brazilian fuels, the emission factors were calculated from data from the IPCC [20] (carbon emission factor and oxidation factor) and the Brazilian National Oil Agency [21] (specific calorific value and density of Brazilian fuels).

In Brazil, anhydrous ethanol and biodiesel are added to gasoline and diesel, respectively, and the government defines the proportion in the mixture as a way of regulating the fuel market. In this study, anhydrous ethanol and biodiesel were removed from the emissions calculation because they have a renewable process in their production, coming from the cultivation of sugarcane for ethanol and soybean for biodiesel. The amounts of gasoline and diesel in the mixture were calculated and considered.

For electrical energy, as the Brazilian electrical system is interconnected, the national factor is used for all locations within the country. These factors are provided by the Brazilian government [22]. T&D losses of 12% were considered.

For the materials used in the construction of the infrastructure and the buses, the embodied carbon factors of the ICE of the University of Bath were used [23], due to a lack of local data.

2.4 Processes

The processes that make up the LCI are described below, for each phase of the LC. The number of materials, fuels, and electricity used in each process was determined and the corresponding carbon emissions were calculated.

2.4.1 Infrastructure Construction

SMTR, the responsible contractor of the BRT Transcarioca corridor construction, provided all resource consumption, fuels, and materials data. The corridor is a two-lane roadway. The roadbeds were built at 3.60 m wide and 0.25 m thick. Asphalt concrete was used with additives to resist constant vehicle traffic. On average, concrete mixer trucks transported 7 m^3 of concrete, which, when launched, covered 8 linear meters of the route. Modulated steel was used for the stations and terminals, and mixed-use for the six bridges built, part in stainless steel and only with a reinforced concrete structure. We considered:

a) Transport from suppliers-Refers to the emission produced by the transport used to distribute the materials. Deliveries were carried out at a central point or directly at the construction sites. The distances traveled and the diesel burned were considered and calculated from the suppliers to the point of delivery, considering the type of vehicle and its performance. The construction of the six bridges had their materials and pre-molded parts manufactured at the construction sites and using concrete from an external supplier, as it is special concrete. There was also the supply of special steel plates for constructing one of the bridges imported from Portugal. This import involved two 98 km road trips by truck from the Mantifer factory to the

City of Porto in Portugal and an 8,265 km sea trip from the City of Porto to Rio de Janeiro.

b) Transport at the construction site-Refers to the emissions produced by the materials delivery transportation, such as materials transportation inside the construction site, parts and equipment transport, materials from excavations transportation, and people transport. The distances traveled data were processed considering the type of vehicle and the yield according to the fuel used, diesel or gasoline.

c) Civil construction-Stations, bridges and roadbeds-Refers to all emissions associated with diesel consumption by all equipment and heavy machinery used in the construction, such as cranes, excavators, generators, hammers, compressors, etc. The usage data of each piece of equipment in hours was considered. Also refers to the emissions produced by the electrical energy consumption of all equipment used in the construction site operation, such as concrete machining, filling stations, offices, and lighting construction areas. The electricity consumption data of these facilities was processed.

2.4.2 Bus Manufacture

We considered:

a) Bus fleet manufacture-All CO_2 emission coming from the manufacture of 160 articulated buses Volvo model B340M for the initial fleet of the corridor operation, and the 3 fleet renewals every 10 years, was considered. The total fleet in the LC totalizes 640 years, considering that 10 years is the bus lifespan. Volvo is a pioneer in developing vehicles for BRT systems and is the market leader in this segment in Latin America [24]. The manufacturing data was collected from two main companies involved: a chassis manufacturer (Volvo) and a car manufacturer (Neobus).

Measuring 19 meters, and weighing 26 tons, with 3 axles and 10 wheels, the articulated buses can carry up to 145 passengers and are diesel-powered. The most representative material in the manufacturing process is steel with 69.8%. In addition to steel, the consumption of aluminum, copper, fiberglass, and rubber was considered, composing 90% of the mass of the materials that compose the vehicle, global emission factors were also used for the calculus. Fossil fuels used in industrial manufacturing (diesel, gasoline, kerosene, and natural gas) were also considered. The quantity data for the manufacturing of each vehicle were obtained directly from the manufacturers, and local factor emissions were used in the calculation, considering discount indices for renewable energy in diesel, due to the addition of biodiesel, and the anhydrous ethanol added to gasoline. Likewise, the energy use was considered based on the renewable energy share present in its generation, taking into account the predominant hydroelectric matrix in the country. The national emission factor for 2013 was used, the year of the biggest productive vehicle activity.

b) Bus fleet transport between factories - The transport considered at this stage refers to the displacements and diesel consumed by the chassis manufacturers and the car body manufacturers, to combine these parts.

c) Bus fleet transport to BRT site-It was also considered the diesel consumed in the displacement of the finished vehicles from the factory to its operation place in Rio de Janeiro.

2.4.3 Bus Operation

For the operation, all the annual emissions produced directly by the exhausts of 160 vehicles in operation were computed, as well as the emissions produced by tank truck trips that deliver the diesel for storage in the 10 operator's garages. We considered:

a) Fuel transport to garages-The daily demand for diesel for each garage is determined by 2,156 journeys totalizing 36,788 km, which imposes a daily stock of 2,628 liters. Considering the 10 garages containing storage tanks and the capacity of a tank truck to carry 20,000 liters, there is a demand of 959,116 liters per garage in a year. The calculated mileage of this displacement was made by the distance between the supplier in the Rio de Janeiro metropolitan area and one of the ten garages, which has a median 32 km distance about the other nine garages. Therefore, this diesel transportation results in 48 trips, totalizing 1,535 km distance traveled per year. Predicting an average yield of 2.61 km/l, 587.96 liters are consumed.
b) Bus trip operation-The System comprises 160 vehicles, which, in the planned timetable, perform an annual mileage of 13,243,680 km. Tests carried out by the system operator in a real operating situation showed an average yield of 1.4 km/l, a value slightly lower than that indicated by the manufacturer (1.9 km/l), due to the profile of trips, with many stops, and the passenger load of the vehicles. Considering the yield of 1.4 km/l, the annual consumption of diesel is 9,459,771 l, repeated over all the years of the life cycle.

At the system's inauguration in the second half of 2014, the initial forecast was 320,000 passengers per day [25]. However, the actual demand was much lower; for this study, actual data from 2016 were used.

The calculation of the total PKT was based on an O-D survey carried out in 2015 [26] combined with the measurement of the boarding record in 2016, carried out by the operator (SMTR), making it possible to have the total number of passengers transported (60,706,898) and the trip average (10.56 km). Thus, it was possible to determine the PKT of 2016. The same value was considered for 2015 and half of the value for 2014. For the following years, a growth of 5% per year was foreseen for 10 years and, from then on, the value was kept stable, without growth. The final calculation resulted in 35,742,698,503 PKT in the lifecycle.

2.4.4 Infrastructure Operation

For the BRT corridor infrastructure operation, only the electricity consumption for the 43 stations and 5 terminals was considered as well as the associated emissions.

The corridor has stations with a daily operation of 16 h and 24 h. All the terminals work in a 24 h regime. It was considered that consumption varies according to the seasons in consequence of the use of air conditioning; from October to March, spring, and summertime, was noticed to be 34% higher consumption when compared to the other months, due to the greater use of air conditioning systems. The estimation shows that 2,125,390 kWh are consumed yearly.

2.4.5 Bus Maintenance

For the emissions calculation in this item, the substitution of tires and motor lubricants oil was considered, since these are the most frequent substitutions in the maintenance routine. They were divided into two parts, the first one referring to the transportation related to the supply of tires and lubricating oil to the garages, and the second part is associated with the share of electricity consumption for maintenance activities in the 10 garages of the operating companies:

a) Parts transport-Each vehicle travels on average 230 km daily, reaching 83,923 km per year. The life of a tire, as reported by the Municipal Transport Department, is 40,000 km, representing an exchange rate of 2.1 times per year, which results in a consumption of 3,357 tires, considering the 10 tires of each 160 vehicles. According to the Pirelli supplier, the rubber mass of a 295/80 R22 tire weighs 62 kg, which means 208,128 kg of rubber consumption per year. Considering the same mileage described for tire consumption, the lubricating oil consumption occurs every 25,000 km, meaning an annual rate of 3.36 times a year. The sump of each vehicle contains 20 liters of oil, totaling 3,200 liters in the entire fleet and a total consumption of 10,742 liters per year.

These inputs come through direct deliveries from suppliers to garages. An estimate was elaborated using Municipal Transport Department data, complemented by surveying the distances covered by suppliers. The calculation records 8,392 km distance and 3,215 liters of diesel consumption for tire deliveries from São Paulo state and the consumption of 72.03 liters and 188 km distance for the metropolitan region of Rio de Janeiro suppliers.

b) Garages energization-It was calculated that were was 16,800 kWh of electricity consumption per year in each garage. This information was estimated considering 50% of the total average consumption recorded on the property of the operating company, assuming that this is the portion associated with workshop activities and that this value is replicated in the remaining garages.

2.4.6 Infrastructure Maintenance

The emissions related to the infrastructure maintenance, was considered the complete replacement of the roadbed, disregarding small punctual repairs in the roadbeds as well as in the stations and terminals due to the low intensity and lack of routine of this action.

The service life of concrete pavement is 20 years, the same used by [27]. Rebuilding the pavement requires the same activities as building the original infrastructure, and demolition and removal of demolition debris. Thus, necessary activities such as transport, concrete machining, steel supply, and heavy machinery and equipment were considered, using the same travel distance for suppliers, construction sites, and roadbed construction.

2.5 Avoided Emissions

In order to understand the real impact of emissions from the implementation of the BRT Transcarioca corridor, it is necessary to establish the emissions avoided through the crossing of demand and modal transfer information, to determine the mileage associated with the cars that stopped circulating, as well the mileage associated with bus from data of the Department of Transport on the rearrangement of bus lines caused by the implementation of the BRT. Thus, the avoided emissions come from: a) the shift of car users to the BRT system and b) the restructuring of conventional bus lines with the implementation of the BRT. The restructuring of conventional bus lines did not imply new infrastructure and vehicles for conventional buses.

2.5.1 Avoided by Cars

Field research carried out in 2016 by the Municipal Transport Department with the system already in operation, allowed the construction of the O-D matrix of trips, determining the number of passengers transported, the mileage traveled, the average mileage of each trip, and the percentage of modal transfer of car users. Assuming a load of 1.3 passengers per vehicle, it was possible to determine the avoided car mileage.

The initial car modal transfer rate was 4% and was projected to double every 10 years for the first 20 years of the life cycle, remaining stable with no growth after that.

The cars circulate in the city are fueled by gasoline, hydrous ethanol, and compressed natural gas (CNG). There are also flex-fuel cars, which can mix gasoline and hydrous ethanol in any proportion. To find the avoided mileage of automobiles by type of fuel used, the database of the local traffic control agency was searched [28].

2.5.2 Avoided by Bus

Transcarioca deployment planning required action to reorganize the 51 existing conventional bus lines, avoiding overlapping routes with the BRT corridor layout. The data from the Transportation Department show that only 4 lines could be maintained with minor route changes and no impact on the mileage of the routes; another 12 would be excluded, 35 would have their routes reduced and only 1 line would be created.

To quantify the reduction in mileage of conventional buses obtained by the implementation of the BRT Transcarioca, the Department of Transport measured the mileage of the affected lines in May 2014 (1 month before the inauguration of the BRT) and December 2014 (6 months after the inauguration of the BRT). A decrease of about 41% of the km traveled was found. It was assumed that the decrease obtained would be maintained until the end of the life cycle.

2.6 Sensitivity Analysis

Life Cycle studies of passenger systems have inherent uncertainty. One of the reasons is the long life of their components, requiring estimates for the future. The main factor of uncertainty is the amount of demand. Initially projected based on research and growth forecasts, real demand may not materialize throughout the life cycle. In the case of the BRT Transcarioca, the expected demand comes from the migration of car and bus users, through the restructuring of conventional bus lines.

To address this uncertainty, sensitivity analysis was performed, for the total demand, and, separately, for the migration demand of car users and the demand for restructuring bus lines.

3. Results

The LCI results per functional unit (gCO_2/PKT) are shown in Table 1.

Table 1 CO_2 Emissions per PKT by LC phases of BRT Transcarioca.

CO_2 Emissions (gCO_2/PKT)	Infrastructure		Buses		Maintenance		**Total**
	Construction	Operation	Manufacturing	Operation	Infrastructure	Buses	
	3.48	1.15	3.65	25.97	0.58	0.75	**35.58**

The results for emissions produced, emissions avoided and the balance between them are presented below.

3.1 Produced Emissions

Figure 2 shows the cumulative life cycle carbon emission, grouped by each LC phase. The bus fleet operation stands out as the largest emitter.

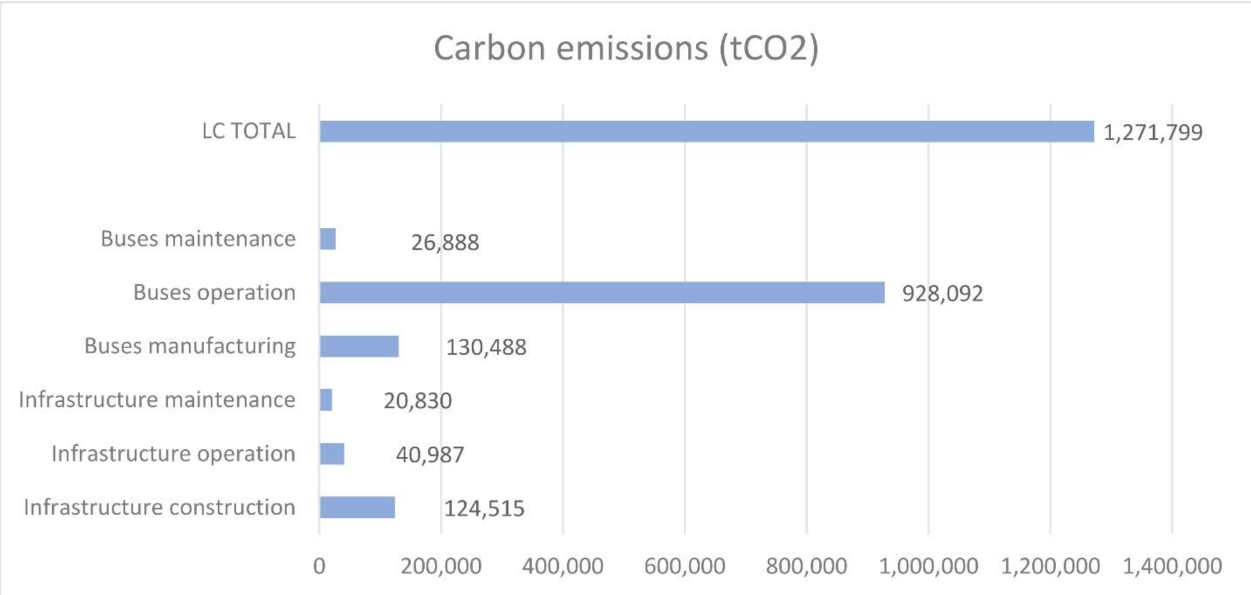

Figure 2 CO_2 emissions in the BRT Transcarioca life cycle.

Figure 3 presents a more detailed overview of the infrastructure construction, revealing that civil construction is the largest emitter of CO_2. Despite the long sea journey to transport part of the imported steel, this was not relevant, in terms of impact on carbon emissions, in the final result.

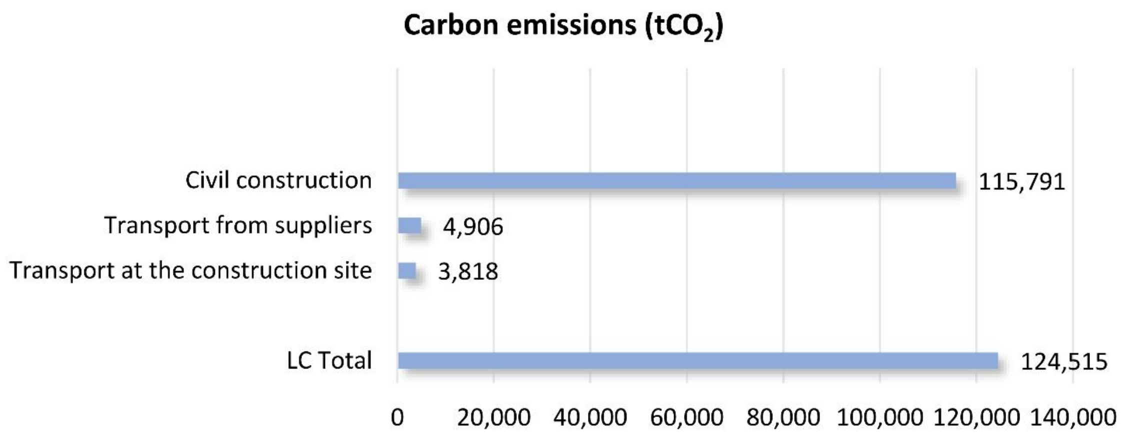

Figure 3 CO_2 emissions in Infrastructure construction.

Figure 4 shows the leadership of using materials (steel and concrete) in the BRT Transcarioca civil construction in the LCI.

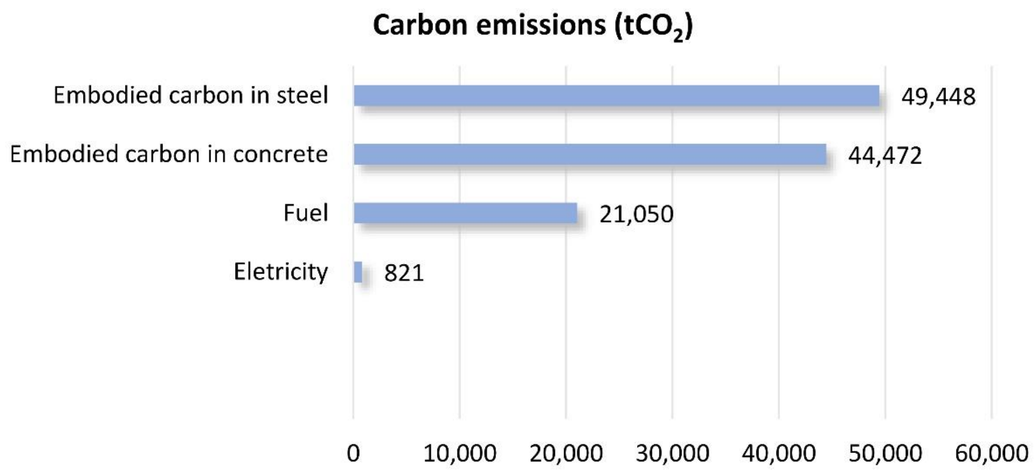

Figure 4 CO_2 emissions in civil infrastructure construction.

For vehicle manufacturing, considering the 40 years of the life cycle and the 640 vehicles production, it has been recorded that electric energy production has the largest share of emissions linked to these vehicles' production process, followed by the embodied carbon in materials. Figure 5 shows the values calculated in LCI.

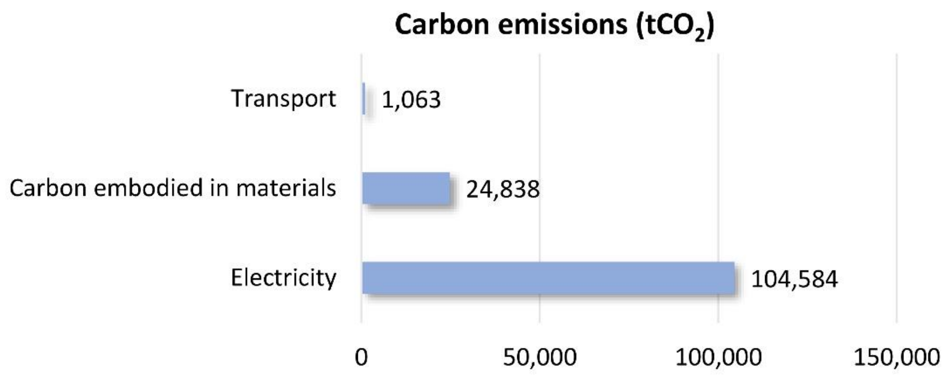

Figure 5 CO_2 emissions in vehicle manufacturing.

For vehicle maintenance, the result of the calculations records the carbon embodied in the tires as the biggest emitter of CO_2. Figure 6 shows the data resulting from these calculations.

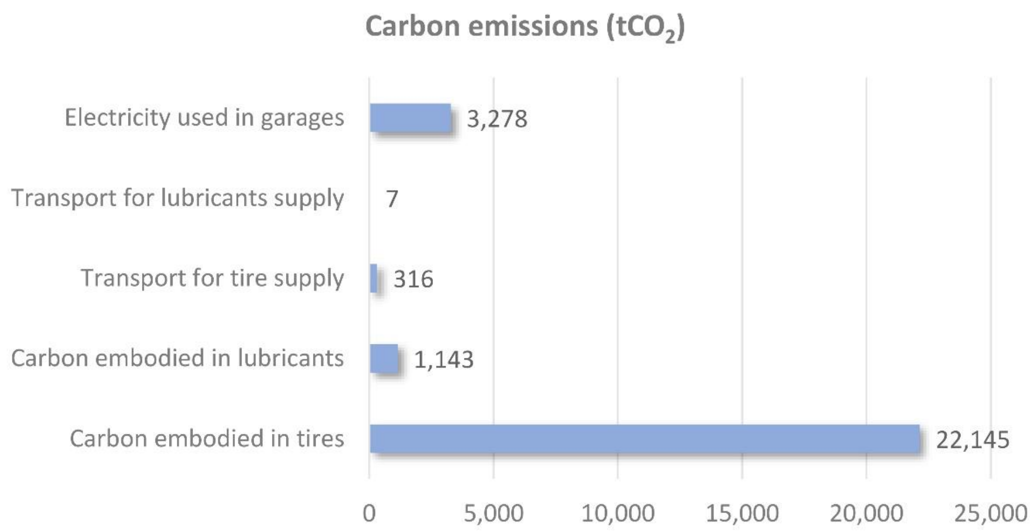

Figure 6 CO_2 emissions in BRT Transcarioca vehicles maintenance.

The vehicle operation phase, which is the more representative of the life cycle, can be detailed by individualizing the contribution of emissions among the studied LCI processes. Figure 7 shows that the contribution of fuel transport to the garages is negligible, with the operation of buses for the transport of passengers being responsible for the emissions.

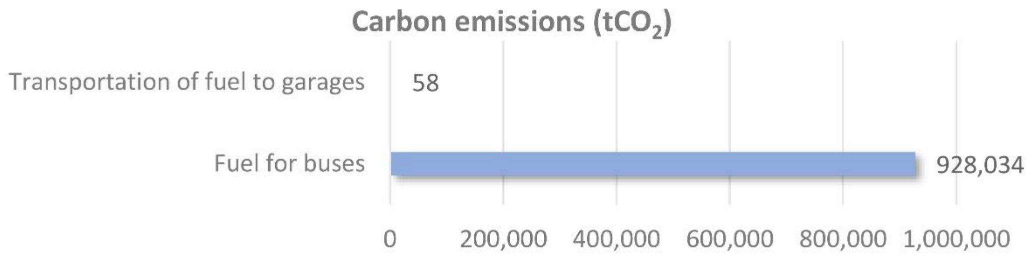

Figure 7 CO_2 emissions in BRT Transcarioca vehicle operation segment.

3.2 Avoided Emissions

The migration of car users to the BRT system resulted in lower burning of gasoline, hydrous ethanol, and CNG by private cars. The reorganization of the bus lines resulted in less diesel burning.

Line reorganization led to a 40.79% reduction in mileage traveled by pre-existing bus lines before the corridor.

Table 2 shows the avoided mileage, fuels, and emissions in the life cycle of BRT Transcarioca.

Table 2 Avoided emissions in BRT Transcarioca life cycle.

Fuels	Avoided mileage (km)	Performance	Avoided fuel consumption	Avoided emissions (tCO_2)
Gasoline	2,539,016,728	9.74 km/l	260,679,336 (l)	422,457
Hydrous ethanol	411,732,442	6.9 km/l	59,671,368 (l)	90,700
CNG	660,938,921	14.08 km/m³	46,941,684 (m³)	96.670
Diesel	1,207,457,784	2.57 km/l	469,827,932 (l)	1,152,291
Total				**1,762,148**

3.3 Produced Emissions x Avoided Emissions

Table 3 and Figure 8 shows the balance between produced and avoided emissions and the recuperation time point, that occurs in 2029, in other words, in the 16th year after the BRT Transcarioca corridor started operation.

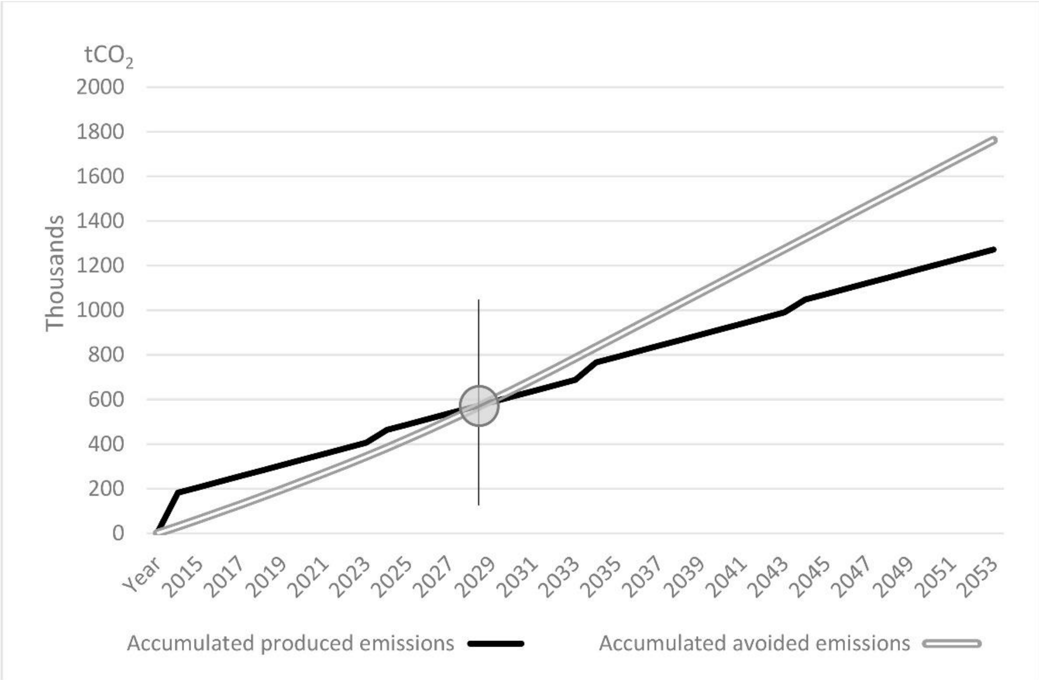

Figure 8 Emission recuperation time in BRT Transcarioca BRT life cycle.

Table 3 Net avoided emissions in BRT Transcarioca life cycle.

Produced emissions	Avoided emissions	Net Avoided emissions
1,271,799 tCO_2	1,762,148 tCO_2	**490,349 tCO_2**

3.4 Sensitivity Analysis

The expected demand for the Transcarioca corridor throughout its life cycle is 3,384,409,564 passengers, as shown in Table 4. For a lower demand, a volume of passengers was assumed without considering the growth applied to the research calculation, resulting in 2,397,922,471 passengers, i.e., -29%. For a higher demand, the SMTR forecast made during the planning and construction phase of the corridor was considered, which indicated that the Transcarioca would carry 320,000 passengers per day [25], which would give 4,672,000,000 passengers over the life cycle, which represents + 38% of the reference value. This initial forecast was adjusted in 2016, as measured by actual data for that year. As shown in Table 4, the result is a 36% loss in avoided emissions in the worst situation (no growth in demand) but avoided emissions remain positive.

Table 4 Sensitivity analysis by demand.

Passenger demand		Net avoided tCO_2	Variation
Base value	3,384,409,564	490,349	Gain (+) Loss (-)
Lower value	2,397,922,471	312,602	- 36%
Highest value	4,672,000,000	722,420	+ 47%

The average modal transfer of cars for the life cycle adopted in the Transcarioca study, resulting from a methodology that attributes growth over the first 20 years, was 13.14%. To compose a more unfavorable scenario, a modal transfer with no increase over time was imagined, remaining at 4% in the 40 years of the corridor. A modal shift of 39% was adopted for a more favorable scenario, imagining a growth of approximately 3 times the reference value. In this simulation, variations are more expressive than in total demand but avoided emissions remain positive in the worst situation.

For the simulation of the demand for restructuring the bus lines, the km avoided by the lesser use of conventional buses was used. The smallest data in this field was adopted as zero, imagining that there was no reorganization of existing lines in the region where the corridor was implemented and no migration of users of these buses. As expected, the BRT system would not be justified in this case, evidenced by the negative value of avoided emissions. For the highest data, in a more favorable scenario, a value 50% higher than the reference value of the avoided km found in the study was adopted, increasing the avoided emission by 117%. Table 5 shows these results.

Table 5 Sensitivity analysis by car mode shift and bus lines restructuring.

Car mode shift		Net avoided tCO_2	Variation
Base value	13.14%	490,349	Gain (+) Loss (-)
Lower value	4%	66,170	- 86%
Highest value	39%	1,691,082	+ 245%
Km avoided by bus lines restructuring		Net avoided tCO_2	Variation
Base value	1,207,457,784	490,349	Gain (+) Loss (-)
Lower value	0	-661,911	- 235%
Highest value	1,811,186,676	1,066,525	+ 117%

4. Discussion

Grouping phases by operational and non-operational phases, as shown in Table 6, it can be concluded that the operational phase (bus and infrastructure operation) is the one with the highest emission (76.19%), with the non-operational phases (infrastructure construction and maintenance, bus manufacture and maintenance) accounting for 23.81% of emissions.

The largest share (72.97%) comes from vehicles operation over 40 years, followed by 10.26% from vehicle manufacturing, and 9.79% referring to infrastructure construction issuance. Infrastructure operation, Vehicle maintenance, and Infrastructure maintenance have small contributions to emissions.

Table 6 Emissions in operational and non-operational phases.

Phases group	Phases	Emissions in tCO_2	Participation in the total	
Operational	Buses operation	928,091.53	72.97%	76.20%
	Infrastructure operation	40,986.91	3.22%	
Non-operational	Infrastructure construction	124,514.62	9.79%	23.80%
	Buses manufacture	130,487.75	10.26%	
	Bus maintenance	26,888.32	2.11%	
	Infrastructure maintenance	20,830.11	1.64%	

Infrastructure construction will always represent an increase in emissions for any transport system. The more complex the construction, for example involving the construction of tunnels and bridges, the greater the impact on emissions. This impact is generally less in BRT systems than in metro-railway systems, whose construction often has underground sections. In the construction of a subway line in the same city of this study, Rio de Janeiro, with 15 km and a life cycle of 60 years, the construction of the infrastructure accounted for 49.84% of emissions [29], while the construction of the BRT Transcarioca accounted for 9.79%.

It can be seen that carbon emissions come from: a) the use of materials, b) the burning of fossil fuel by equipment, c) the burning of fossil fuel by transport and d) the use of electricity from the grid. To get an insight into participation, at each stage of the lifecycle and throughout the lifecycle of these elements, the graph in Figure 9 is helpful.

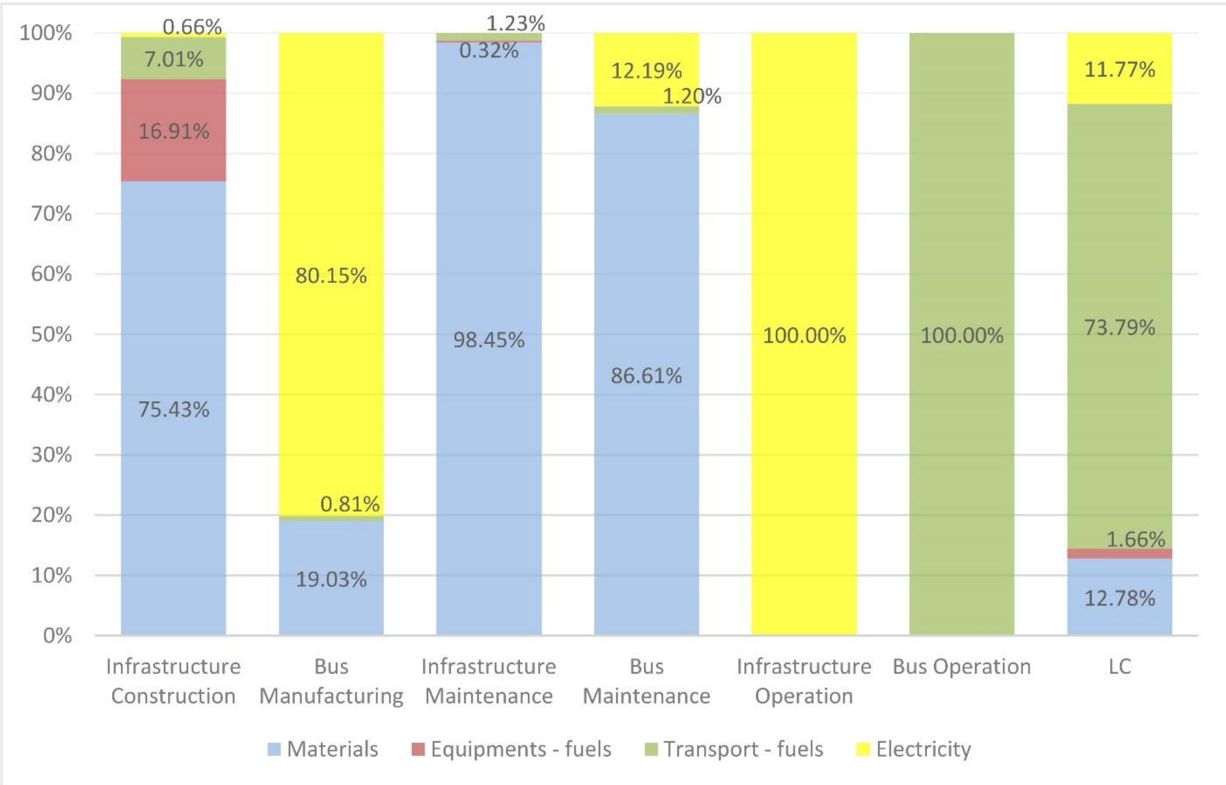

Figure 9 BRT Transcarioca CO_2 emissions: Contribution analysis by resources.

It can be seen that the materials dominate the phases of Infrastructure Construction and Maintenance of Infrastructure and Buses. Electricity dominates the Bus Manufacturing and Infrastructure Operation phases. The burning of fossil fuels for transport dominates Bus Operations.

Considering the entire life cycle, burning fossil fuel by transport has the largest share (73.79%), and burning fossil fuel by equipment has the smallest share (1.66%). The use of materials and electricity have a share, respectively, of 12.78% and 11.77%.

There are two ways to reduce emissions from fuel consumption in transport: increasing the number of renewable fuels, in this case, biodiesel, or using electric or hybrid buses. In the case of biodiesel, the CO_2 exhaust emission intensity is considered to be zero as this carbon is considered to have been sequestered in the production phase (the agricultural planting) [30]. Currently, in Brazil, the diesel sold at stations contains 10% biodiesel, but buses can run on 100% biodiesel (B100). The

BRT system in Curitiba, Brazil, already operates with 30 hybrid buses, powered by electricity and B100 biodiesel. A project foresees the total use of electric/hybrid buses on one of the lines from 2025 onwards [31]. In the case of electric or hybrid buses, emissions will be reduced, which may not be completely zero. In the study [32] it was estimated that, in the city of Amman, Jordan, in the life cycle of a diesel BRT system, the emission would be 2.34 $kgCO_{2e}$/km, against 1.80 $kgCO_{2e}$/km for a BRT Hybrid. In electric BRT, the direct emission would be zero. However, the upstream emissions from the batteries or the electricity grid would remain, which would cause total emissions in the life cycle approach to decrease but not be completely zero. Due to different types of electric vehicle technology, with the need for battery recharges from the electrical grid, quantification of the carbon footprint requires a more accurate calculation. In any case, the recommended policies for reducing carbon emissions from transport systems should be greater use of renewable fuels, such as biodiesel and electric or hybrid vehicles, and increasing renewable sources in the electrical matrix.

The cumulative emissions for the infrastructure construction are 124,514 tCO_2, which results in 3,692 tCO_2/km. A study by Stripple [18], which analyzed the emissions associated with a highway in Sweden using the same 40 years lifecycle, obtained 2,700 tCO_2/km when paved with concrete, the same pavement used in BRT Transcarioca. This difference, the biggest in BRT, is related to the construction of stations and terminals. Such facilities are not found in the infrastructure mentioned in Swedish work.

A discussion about the bridge-related emissions volume construction can be found in Chang and Kendall's research about the analysis of the new-railroad construction, in California, United States [18]. The result pointed to representative emissions participation when these structures are constructed. About 60% of the emissions came from bridges and tunnel infrastructure construction, representing only 15% of the railroad roadbed. In the BRT Transcarioca corridor, 3.28 km of the total 39 km, 8.5% of the entire course, had to be fulfilled by 6 bridges. Analyzing the data on the construction of the infrastructure separately and considering the amounts of steel, concrete, and use of machinery and transport in the 6 bridges executed, we have that 44% of what was emitted CO_2 for the construction of the infrastructure had origin in the six works of art. Relating the American research values with that obtained in BRT Transcarioca data it's possible to confirm the representativeness of the magnitude of the emissions coming from these infrastructure constructions, revealing the need to consider them in studies when it's an LCA approach.

Based on the system operation-associated emissions, the BRT Transcarioca can be compared to the one existing in Xiamen, China, which was a study case [13]. The Chinese BRT, with a 50 years life cycle, had 62.33% of its emissions associated with the system use, compared to 72.97% in BRT Transcarioca, which had defined its life cycle in 40 years.

The calculated value for BRT Transcarioca reveals the similarity with the Ghate and Qamar [33] study, which has also analyzed the corridor life cycle in Delhi city, India. The Asian survey found 42 gCO_2/PKT in the BRT system, which has a life cycle stipulated in 30 years. The BRT Transcarioca corridor presented 35.58 gCO_2/PKT over its 40 years.

The BRT Transcarioca was built using central lanes of existing roads, but in some places, there was a need to build bridges, totaling 3.28 km, representing about 8.5% of the system's length. However, emissions from bridge construction accounted for 44% of total infrastructure construction emissions, which shows the great influence of the construction of elevated parts on carbon emissions. In BRT projects, it may be more convenient for the system to be totally or partially suspended, which would greatly increase emissions.

Other mass passenger transport solutions are both heavy rail systems (usually called metro, subway, etc.) and light rail systems (usually called LRT). Rail systems usually use grid electricity. Several factors can influence the choice of the best option for a given region, such as demand, cost, environmental impact, land use, etc. The BRT system proves to be a good choice, especially when it is intended to induce the development of a region, as was the case with the BRT in Curitiba. In Rio de Janeiro, planning for the 2014 and 2016 sporting events resulted in new BRT, heavy rail lines, and VLT projects. The subway was the solution for a densely populated region, where the best solution would be an underground route, and the VLT was used to connect points around the city center. The estimated carbon footprint of Line 4 of the Rio de Janeiro subway [29] was 2.5 times lower than that of the BRT. This was due to two main factors: the Brazilian electrical matrix being predominantly hydraulic, with a low emission factor compared to fossil fuel factors, and the construction of infrastructure for subway line 4, which is more complex because it is underground. While the largest share of carbon emissions on subway Line 4 came from infrastructure construction [29], at BRT Transcarioca the largest share came from bus operations, as shown in Table 1. This comparison is possible because the methodology followed is similar in the two studies.

In the future, technological evolution may provide, on a large scale, the use of new energy sources for transport systems. The carbon emission measurement methodology will probably need to be improved to reveal with greater accuracy all emissions produced indirectly using new technologies.

5. Conclusions

The concern with global warming motivates countries, companies, and society to implement measures to reduce emissions. As a significant emitter, the transport sector must play a relevant role in this process. With the growth of cities, mass public transport is the solution to reduce the use of cars and conventional buses, both with low transport capacity, producing traffic congestion and high carbon emissions. In public passenger transport, government authorities are usually responsible for planning, defining, and analyzing possible alternatives. Decision makers, then, need tools to help them.

The construction of a Life Cycle Inventory of a transport system, considering all its components, is a tool that allows decision-makers to estimate the effective contribution that this system will make to carbon reduction efforts. As the international community is more committed to reducing CO_2 emissions, transport systems lifecycle studies may become relevant since they allow a larger view of the subject.

Life cycle studies allow decision-makers to estimate the reduction of gas emissions among the alternatives of possible transport solutions, involving alternative routes, construction technologies, and modes of transport, and compare them with each other and with other parameters that must to be considered.

This study used real data collected during system construction and is comprehensive, including all components of passenger transport. Most life cycle studies published on passenger transport systems are based on fully estimated data based on some assumptions and using specific software. Real data obtained in the first two years of operation were considered, reducing the uncertainty inherent in future forecasts.

In this study, the BRT Transcarioca System proved capable of reducing emissions after the recovery time of additional emissions caused by the construction of the system, estimated at 16 years. The study can be adapted to other transport systems.

The data processed to analyze the emissions avoided show great relevance for reorganizing the existing conventional bus lines and for the percentage of modal transfer from car users. Suppose the reorganization action is not carried out, or the migration rate to the system is unimpressive. In that case, neutralizing the emissions produced in the non-operational phases may never happen.

Several factors influence the emission recoveries time, such as the fuel used and the system load. The ability to attract users of higher emission vehicles, as well as the expected load of a new transport system, must be evaluated with the greatest possible precision, for the correct dimensioning of the system. The new system's fuel must have the lowest carbon emission possible. Thus, using electricity and renewable fuels could reduce the recovery time and should be the subject of further research.

BRT as a mass transport solution is a solution that also meets cost criteria, when compared to other alternative modes of transport, making this solution attractive in budget-restricted regions. Even using fossil fuels, can help reduce emissions, as shown in this study.

The materials have a share in emissions and energy consumption. In BRT systems implemented in streets, without many bridges or viaducts, as is the case of the BRT Transcarioca, the emission of materials has a smaller participation than the emission of the operation. In BRT systems with large suspended parts, the emission may be higher than the operation, perhaps not leading to a reduction in emissions.

The mitigation of these materials' emissions involves, among others, efforts to improve the manufacturing process, greater use of renewable sources for electricity generation, greater use of replacements that emit less and greater use of recycling (during steel making). Future projects can explore and assess these areas.

However, one limiting factor of this stud, was the impossibility of including the fuels' LC in the BRT Transcarioca because the fuels' LC involves many locations, and data are not available for all situations.

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Christiano Lima Machado – data collecting/processing, draft writing. Carlos Eduardo Sanches de Andrade – revising, final writing.

Competing Interests

The authors have declared that no competing interests exist.

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