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Applications of Carbon Dioxide Emissions Calculations in the Operation of Public Passenger Transport Systems

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Abstract

This paper aims to analyze emissions from public passenger transport systems, metros and buses, compared with private cars, establishing calculating these emissions. The calculations were applied in the city of Rio de Janeiro, Brazil. The results obtained indicate that the electric trains of the system had an average emission of 4.5 g of carbon dioxide (CO_2) per passenger-kilometer, a result 10 times lower than the emission of buses, which in turn emitted three times less than the private cars. The operation of metros and buses systems, thus, provided the city with significant reduction of CO_2 emissions produced by the transport systems.

Keywords: CO_2 emissions, passenger transportation, operation, metro, buses

INTRODUCTION

The transport sector plays a large part in the emission of greenhouse gases (GHG) worldwide, accounting for about 23% of global emissions [1]. Ribeiro et al. [2] state that, over the past decade, GHG emissions from the transport sector have grown at rates higher than in any other sector that uses energy. In Brazil, the transport sector reached 48% of total emissions in the country, being the main responsible for emissions [3]. Carbon dioxide (CO_2) is the main greenhouse gas, being commonly used as a reference in the GHG emission measurements.

A way to avoid the growth of CO_2 emissions by the transport sector is to encourage society to use public transportation systems, of high and medium capacity, as the metros and buses.

The total CO_2 emissions of the means of transportation occur, to a greater or lesser proportion, regardless of their occupancy rate. However, the higher the occupancy rate of the means of transportation, the lower the CO_2 emissions per kilometer traveled by passengers.

For more accurate information, it is important that the measurements of CO_2 emissions be carried out according to the mileage travelled by passengers, using to this end the measure grams of CO_2 per passenger-km (gCO_2 per pkm). Thus, it is possible to establish emission comparisons involving all means of passenger transportation.

The absence or inefficiency of high- or medium-capacity transportation means makes the use of automobiles more and more intense, increasing congestion and, consequently, emissions from the transport sector. The average occupancy rate of cars is low when compared to the metros and buses, causing gCO_2 emissions per pkm in automobiles to be usually larger than the metros and buses. The average occupancy rate of automobiles in Brazil is of 1.5 passengers per trip, while the metros' is of 900

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passengers per trip [4]. Thus, the transportation systems composed of integrated metros and buses occupy a prominent position as a solution of lower impact on CO_2 emissions by the transport sector.

The aim of this work is to present calculations for emissions in gCO_2 per pkm on the operation of metro systems and their integrated buses by applying the calculations proposed in Rio de Janeiro Metro and its buses fleet. The first section is an introduction, with a brief contextualization of the study and the establishment of the goal. The second section defines, in general terms, the issuance in gCO_2 per pkm in the operation of metro and buses systems, showing comparative results of emissions in these two transportation systems. The third section defines and presents the calculations of emissions proposed. The fourth section addresses the application of the calculations of emissions proposed in Rio de Janeiro Metro and in its buses fleet. The final section addresses the conclusions of the work.

CO_2 EMISSIONS IN THE OPERATION OF PUBLIC PASSENGER TRANSPORT SYSTEMS - METRO AND BUSES

The pkm measure is the most suitable in passenger transportation activity, being also commonly used for purposes of comparison of emission results between means of passenger transportation. It is more representative than the value of total emissions of vehicle travel, since it considers CO_2 emissions directly related to the number of passengers transported. The pkm measure is obtained by multiplying the corresponding total passengers transported in a particular preset period (daily, monthly, or yearly) by the average extension of passenger trips based on origin-destination surveys of these trips.

Below you will find details about the emissions, in gCO_2 per pkm, in the operation of metro and buses systems, as well as comparative results on the emissions of these two systems of passenger transportation.

Emissions in gCO_2 per pkm, in Operation of Metros

CO_2 emissions in the operation of metro systems occur mainly in the generation of electric power required for the operation of the metro trains. These emissions, called indirect emissions of CO_2, by electricity, are produced by third parties [5], since that electricity is usually not generated locally by the metro system, but obtained from third parties, from the local electricity supply company.

A large amount of electric power is required to provide the tractive force that moves the trains. As an example, one can cite the London Underground, whose system's electric power consumption reaches almost 3% of the total consumption of the city, using more than 1 TWh of electricity per year [6]. The New York City Metro consumes 3.4 TWh each year [7]. The metro of the city of Porto, in Portugal, consumed 0.52 TWh [8], while the Metro of São Paulo consumed 0.58 TWh [9].

As the tractive force of the trains is responsible for much of the energy consumed in the metros, it is the biggest responsible for CO_2 emissions in the operation of metros. The rest of the electric power consumed by the systems, called auxiliary power, aims to supply lighting and auxiliary equipment of the stations, such as: escalators, pumping, technical rooms, etc., including also other electric power consumptions of the metro company.

The generation of electric power for train traction considers only the emission related to the "fuel" of the metro system trains, which is electric power. For the metros, according to Andrade and Bittencourt [10], the CO_2 emission caused by generation of electric power for train traction is the most suitable for purposes of comparison of results with other means of transportation, when assessing the emission caused only by fuel consumption. The emissions of electric rail modes depend highly on the cleanliness of the electricity generated [11].

The values of CO_2 emissions due to the generation of electric power used in metros show a great variation in results among the metro systems around the world, due to the different energy matrices used in each location. In most countries of Europe, Asia, and Oceania, the thermal sources are predominant, with a mix of coal, oil and gas [12], which are the largest emission source types. Brazil is favored for using predominantly hydroelectric sources, which is considered a "clean" energy source, with low impact on CO_2 emissions. The hydroelectric source in Brazil represented 77% of the internal offer of national electric power [13].

Table 1 shows the results of CO_2 emissions, total and in pkm, due to the generation of electric power in three metros. It is possible to identify major differences in the results, as they depend on the amount of electrical power used by the systems and on factors such as: local energy matrix, energy efficiency, technology used, system's age, system design, load of passengers (occupancy rate), the size of the system, the quantity of trains, intervals practiced and others.

The total CO_2 emissions, by electricity, in the Metros of Lisbon and Bilbao are similar, while the values of emissions in gCO_2 per pkm are quite different. These two metros have the same network extension, with 43 km, but have different demands of passengers a year, with 52 million/year in the Lisbon Metro [14] and 87 million/year in the Bilbao Metro [15], which justifies the better performance of the Bilbao Metro for less emission of CO_2 per pkm, when compared to the Lisbon Metro.

Emissions in gCO_2 per pkm in Operation of Buses

The modal matrix of passenger traffic in large urban centers of Brazil shows 4% on rail systems, involving the metros and railroads, and 60% on buses [4]. This great use of buses in Brazil also occurs in several countries of the world, where, usually, the buses transportation stands out in relation to other systems, as in the countries of Latin America, where 43% of passenger transportation is done by buses [16].

Motor vehicles constitute worldwide the main source of air pollution in large cities, being this problem worsened in recent decades due to the increase in the fleet of road vehicles powered by fossil fuels, mainly gasoline C, used in automobiles, and diesel oil, used in buses, which are great emitters of CO_2. According to the United Nations [17], road transport is responsible for the majority of current emissions and its estimated growth, since the forecast is that the global vehicle fleet is set to multiply three- or fourfold in the next few decades.

The calculation of CO_2 emissions by the buses is done according to the amount of liters of fuel burnt, usually diesel oil, which is multiplied by an average emission factor. Emission values, in gCO_2 per pkm, for buses, depend heavily on passenger load. In Brazil, considering the maximum capacity of the buses, with 80 passengers, the emission average is 16 gCO_2 per pkm [4], while the buses of the city of São Paulo emit 64 gCO_2 per pkm, considering the average load on the buses [9]. Table 2 shows the emission results of buses of some cities in the world, considering their average capacity.

Table 1. CO_2 Emissions related to electric power generation in the metros of Lisbon, Bilbao, and Sao Paulo.

Metros	Total Emissions in Tons of CO_2	Emissions in gCO_2 per pkm	Sources / References
Lisbon	14,500	49	[14]
Bilbao	16,638	28	[15]
Sao Paulo	44,000	4	[9]

Table2. CO_2 emissions of buses in the cities of Almada, Adelaide, Birmingham, and Washington

Countries	Cities	Emissions in gCO_2 per pkm	Sources / References
Portugal	Almada	85	[18]
Australia	Adelaide	140	[19]
England	Birmingham	186	[20]
USA	Washington	202	[21]

General Comparative Results of Emissions, in gCO_2 per pkm, of the Metros and the Buses

Different research studies indicate that the metro systems that use electric power from less polluting sources take advantage over other means of transportation in a comparison of emission in gCO_2 per pkm. Andrade et al. [22] conducted a study on the contribution to reducing CO_2 emissions by rail systems, concluding that in all the approaches of emissions, these systems show that, in general, worldwide, they are a good alternative for passenger transportation of low CO_2 emission. The transport authority of the city of London conducted a study that shows the emission per pkm of various transportation systems. This comparison proves the better performance of the metros regarding lower CO_2 emissions. While the London Underground emits 50 gCO_2 per pkm, London buses emit 80 gCO_2 per pkm, and automobiles emit 110 gCO_2 per pkm, considering the average passenger capacity [23].

A study was carried out in Europe to identify the average values of emissions, in gCO_2 per pkm, of the various types of passenger transportation in 27 countries in Europe. The emission results, in gCO_2 per pkm, showed a value of 109 for road transport, whereas for metros it was 41 [24]. Another example of comparison between metros and buses from the European continent is a result from the city of Bilbao, Spain, where the buses emit 5 times more (135 gCO_2 per pkm) than the metro system (25 gCO_2 per pkm) [25].

The emission averages, in the United States [18] by the metros and buses are: 62 gCO_2 per pkm for the metros and 180 gCO_2 per pkm for the buses, considering the average capacity of the systems. It is noted that emissions by buses are almost 3 times higher than those by metros. This survey also revealed the average occupancy rates of these two systems across the country, which shows 47% occupancy for metros and 28% for buses. If the maximum passenger loads were considered, the metro would still have the lowest emission values, with 31 gCO_2 per pkm for metros and 51 gCO_2 per pkm for buses [18]. Figure 1 shows examples of results of buses, metro and car emissions in four cities in the United States.

It was noted that, among all American cities, in only one of them, Baltimore, the metro presented an emission value greater than that of the buses. This is because there was a low rate of use in the Baltimore Metro, with only 17 percent of average occupation, justifying the emissions being higher than those of the buses in the city of Baltimore, which have 34% of average occupation rate [18].

In Oceania, the Urban Transport Government of Australia conducted a study on CO_2 emissions in the transportation systems of the city of Melbourne, finding, for the metros and buses, respectively, 145 and 159 gCO_2 per pkm [26].

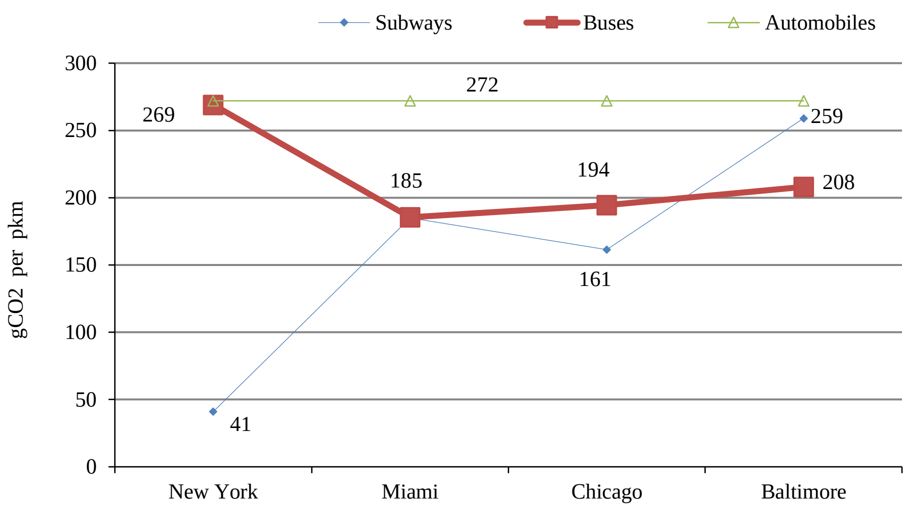

Figure 1. Average emissions, in gCO_2 per pkm, of metros, buses, and cars in the United States [18].

A high value is found, above average, in the emission by Melbourne Metro. This is because Australia has an energy matrix constituted basically of thermal sources, based on coal, which is the thermal source with largest emission [27], making Australia the fifth country in the world in the production of coal and the second country in the world in the export of coal [28]. The generation of electric power in Australia raises the result of CO_2 emission as compared to other countries that have energy matrices with less thermal sources. As a result, the CO_2 emission values of the metro and buses in the city of Melbourne remain so close.

CALCULATIONS OF EMISSIONS, IN GRAMS OF CO_2 PER PKM, IN THE OPERATION OF METROS AND BUSES

Some metro systems possess and administer a buses fleet, either their own fleet or a leased one, to complement part of the itineraries, not supplied by the train network. Often, the use of these buses is covered by a single metro fee. As examples, we can mention the metro systems of five cities: (a) Delhi – it has several own minibuses lines, with capacity for up to 30 people per vehicle. As in the Delhi metro trains, the value of the minibuses fee varies according to the mileage traveled by users [29]; (b) New York – it has free buses lines for its users by using the Metro Card pass, which offers a price per trip lower than the unitary fee of New York Metro [30]; (c) Paris – it has free transfer for its users between zones I to V, during a period of 2 hours by use of the Paris Visit Pass [31]; (d) Rio de Janeiro – it has two buses lines administered by the metro system with no fee [32]; and (e) Santiago – where it is possible to make free integration with up to two consecutive buses lines, during the period of 2 hours by use of the Targeta Bip pass [33].

Calculation of Emissions, in gCO_2 per pkm, in the Operation of Metros

The proposed for calculating the emissions, in gCO_2 per pkm, in the operation of metros should be applied monthly, so as to reach an annual result, and should follow the following steps:

1. Determine the traction power (including energy losses) monthly consumed by the metro, in MWh.
2. Find the monthly average factor of electric power generation, defined by the regulatory agency, in tCO_2/MWh. This factor can be regional or national, depending on the characteristics of the generation and distribution of electric power. This average factor released by the regulatory agency must be used when the goal is to quantify emissions from electric power generated, serving, therefore, to inventories in general, corporate or otherwise [34].
3. Multiply the monthly traction power consumed by the metro system by the monthly average factor of electric power generation established by the regulatory agency, which will result in total emissions, in that month, in tCO_2.
4. Turn the result of the total emissions, in tCO_2, into gCO_2 by multiplying it by 1,000,000.
5. Determine the quantity of monthly pkm of the metro system by using the data from the monthly demand multiplied by the average extension of the passenger trips, based on origin-destination surveys on these trips.
6. Divide the result of total emissions, in gCO_2, by the pkm result for the month assessed. Then, the monthly result of total emissions, in gCO_2 per pkm, is found for the operation of a metro system.
7. The annual emission result, in gCO_2 per pkm, in the metro operation, is obtained by dividing the sum of the total monthly emissions, in gCO_2, by the sum of the monthly results of pkm.

Calculation of Emissions, in gCO_2 per pkm, in the Operation of the Fleet of Buses of the Metro Systems

The proposed calculation for the emissions, in gCO_2 per pkm, in the operation of buses fleet of metro systems should be applied monthly, so as to reach an annual result, and should follow the following steps:

1. Find the total monthly mileage traveled by the entire buses fleet of the metro system.
2. Determine the total monthly fuel consumption of the buses fleet of the metro system, based on the information of the total monthly mileage rates. For this purpose, the average efficiency of the fuel used by the buses, in liter per km, must be found.

3. With the total fuel consumption, in liters, of the buses fleet of the metro system, this result must be multiplied by the average emission factor, in $kgCO_2$ per liter, of the fuel used in the buses. That leads to the result of the total emissions, in $kgCO_2$, of the buses fleet of the metro system.
4. Turn the general result of the total emissions, in $kgCO_2$, into gCO_2 by multiplying it by 1,000.
5. Determine the result of monthly pkm of the buses fleet in the metro system by using the data from the monthly demand of the buses fleet multiplied by the average extension of passenger trips based on origin-destination surveys on these trips.
6. Divide the monthly result of total emissions, in gCO_2, by the monthly pkm result of the buses fleet. Then, the monthly result of emissions, in gCO_2 per pkm, is found for the operation of the buses fleet of the metro system.
7. The annual emission result, in gCO_2 per pkm, in the operation of buses fleet of the metro system, is obtained by dividing the sum of the total monthly emissions, in gCO_2, by the sum of the monthly results of pkm.

APPLICATION OF THE CALCULATIONS OF EMISSIONS FOR RIO DE JANEIRO METRO AND ITS FLEET OF BUSES

The metro network of Rio de Janeiro – MetrôRio – is 54.4 km long, with three lines and 41 stations, with an annual demand of about 258 million users. In addition to this network, which is serviced by the metro trains, there is an extension of the network done by MetrôRio's exclusive buses, reaching important neighborhoods of the city, which are not served by the trains of the system. Thus, the users can complete their trip without paying anything extra for this service, because it is free, already included in the system's standard fee [32]. The fleet of the Metro has 32 buses, distributed in two lines.

Application of the Calculation of Emissions in the Operation of Rio De Janeiro Metro Trains

MetrôRio has made available the monthly data of passenger-km and traction power consumptions (including energy losses) of the trains. Table 3 presents the data collected, required for the application of the proposed calculation and the results of emissions.

Monthly results of total emissions were found to be up to 4.4 times higher from one month to another. By comparing the months of Jan and Nov, similar results are observed in traction power consumption and pkm, but with a big difference in the values of total emissions, this being due to an increased use of thermal sources in power generation in November, proving the high value of the average emission factor for this month, which was the highest in this year.

The average emission in the operation of MetrôRio's trains was 4.5 gCO_2 per pkm. If compared to the results of emissions in other metro systems already presented in this work, it is evidenced that MetrôRio has low emission.

This occurs mainly due to Brazilian energy matrix, composed basically of hydroelectric plants, in addition to the adequate system occupation rate, which, according to MetrôRio [32], was of 50% in this year, representing approximately 865 passengers inside a train in each trip. Differences are noticed in monthly results, ranging from 2.1 to 9.0 gCO_2 per pkm. From September to the end of the year, the monthly results in gCO_2 per pkm remained above the annual average, mainly due to the increase in the emission factors released by the Brazilian Government in the last 4 months, motivated by greater use of thermal sources during this period. Automobiles in Brazil emit 127 gCO_2 per pkm [4], which demonstrates the good performance regarding CO_2 emission by MetrôRio.

Application of the Calculation of Emissions in the Operation of the Buses of Rio De Janeiro Metro

The application of the calculation of emissions proposed in this work is shown in Table 4, which displays the result of the total emissions of CO_2, in addition to emission in gCO_2 per pkm, in the operation of the MetrôRio's buses.

It is verified that the average emission in the operation of the two MetrôRio's buses lines was 46 gCO_2 per pkm. According to MetrôRio the average occupancy rate of these buses was 47% [32].

Table 3. CO_2 emissions in the operation of MetrôRio trains.

Months	Traction Power (in MWh)	Government's Emission Factor (in tCO_2/MWh)	pkm	Emissions in gCO_2/pkm
Jan	11,626	0.0294	160,875,859	2.1
Feb	11,668	0.0322	166,823,976	2.3
Mar	11,813	0.0405	180,577,528	2.6
Apr	10,943	0.0642	156,885,831	4.5
May	11,866	0.0620	178,363,796	4.1
Jun	11,454	0.0522	161,865,005	3.7
Jul	11,925	0.0394	175,907,290	2.7
Aug	12,294	0.0460	189,090,840	3.0
Sep	11,224	0.0783	168,104,302	5.2
Oct	12,033	0.0984	182,993,862	6.5
Nov	11,837	0.1247	164,354,114	9.0
Dec	13,095	0.1168	170,690,301	9.0
Year	141,778	0.0653	2,056,532,704	4.5

Source: References [32, 34].

Table 4. CO_2 emissions in the operation of the fleet of buses.

Months	Mileage Traveled	Total Emissions from the Fleet of Buses (in $kgCO_2$)	pkm	Emissions in gCO_2/pkm
Jan	121,348	140,922	2,686,318	52
Feb	106,402	123,565	2,638,953	47
Mar	111,676	129,689	3,260,833	40
Apr	102,326	118,831	2,727,308	44
May	109,397	127,043	3,085,043	41
Jun	104,383	121,220	2,740,898	44
Jul	125,095	145,273	2,802,873	52
Aug	120,193	139,580	3,100,684	45
Sep	108,189	125,641	2,655,767	47
Oct	118,949	138,136	2,996,457	46
Nov	110,045	127,796	2,645,088	48
Dec	114,519	132,992	2,536,125	52
Year	1,352,521	1,570,688	33,876,346	46

Buses fuel = diesel; efficiency of the buses = 2.30 km/l;
Buses emission factor = 2.671 $kgCO_2$/L
Source: References [32, 35].

CONCLUSIONS

The objective of this study was achieved through the comparative analysis of general results of CO_2 emissions from metros, buses, and cars and through the proposition and application of a calculating the emission of a metro system and its buses fleet. The comparative analysis showed that the metro mode, in general, is a transportation solution with lower CO_2 emissions per passenger-km than other means of transportation like buses and cars. The buses usually emit less than the cars. However, it is possible for the metros to emit amounts of CO_2 that are close to or higher than those of buses, as in the case of the Baltimore Metro. The buses may also have an emission higher than the emission of automobiles. This occurs when the metro or buses system does not present a proper occupancy rate, causing emissions, in gCO_2 per pkm, to become high. Another reason is the use of an energy matrix based on thermal sources for generation of energy to be used by the metro system, as in Australia, where the results of emission of metros, buses, and cars are similar.

The application of the calculation of emissions proposed to Rio de Janeiro Metro and its buses fleet throughout this year revealed that, inside this system, the metro has an emission (4.5 gCO_2/pkm) about 10 times lower than that of the buses (46 gCO_2/pkm), with similar occupancy rate (50% to metro and 47% to buses). Buses, in turn, emit almost three times less than the Brazilian automobiles (127 gCO_2/pkm). The proper occupancy rate of MetrôRio and its buses fleet, coupled with little use of thermal sources in the energy matrix of generation of electricity powering the trains, enabled these results.

A limiting factor in the study developed here lies in the influence of passenger load and traffic congestion on the fuel consumption of the buses. Since average values of efficiency are used, the actual emission values at rush hours are actually larger than those calculated. However, data on engine operating modes in situations of great load and congestion are scarce in Brazil and in the world.

As an idea for new studies we suggest that a study be carried out to learn about the differences in results in CO_2 emissions in the operation of trains and buses, for a 2-hour period during rush hour and for a 2-hour off-peak period, in order to quantify the differences in the results of emissions according to the time of the day, investigating the influence of occupancy rate throughout the times of operation.

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