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# $CO_2$ emissions per passenger-kilometer from subway systems: Application in the Rio de Janeiro Subway

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***Abstract*—The transport sector is responsible for a significant portion of global emissions of carbon dioxide - $CO_2$. The measurement of such emissions, when held in grams of $CO_2$ per passenger-kilometer, enables more significant results, considering the passenger load. This work aims to analyze $CO_2$ emissions per passenger-kilometer from subway systems, comparing those results with buses and private cars, establishing a methodology for calculating these emissions. The methodology was applied to Rio de Janeiro Subway in Brazil.**

***Keywords*—emissions, $CO_2$, subway, passenger-kilometer**

## I. Introduction

The transport sector accounts for around one third of all energy use and one fourth of global carbon dioxide ($CO_2$) emissions [1]. $CO_2$ is the main greenhouse gas (GHG), being commonly used as a reference in the GHG emission measurements. Ribeiro et al. [2] states that, over the last 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].

One of the ways to avoid the growth of $CO_2$ emissions by the transport sector is to encourage the society to use public transport systems of high capacity, as the subways. The total $CO_2$ emissions of the means of transport occur, to a greater or lesser proportion, regardless of their occupancy rate. However, the higher the occupancy rate of the means of transport, the lower the $CO_2$ emissions per kilometer travelled by passengers.

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

The average occupancy rate of cars and buses are low when compared to the subways, causing $gCO_2$ emissions per pkm in automobiles and buses to be usually larger than the subways. The average occupancy rate of automobiles in Brazil is of 1.5 passengers per trip, while the subways' is of 900 passengers per trip [4]. Thus, the subways occupy a prominent position as a solution of lower impact on $CO_2$ emissions.

The aim of this work is to present a methodology for calculating the emission in $gCO_2$ per pkm from subway systems by applying the methodology proposed in Rio de Janeiro Subway. Section 1 is an introduction, with a brief contextualization of the study and the goal setting. Section 2 defines, in general terms, the issuance in $gCO_2$ per pkm from subway systems, showing results of emissions in these transportation systems. Section 3 showing comparative results of emissions in subways with automobiles and buses. Sector 4 defines and presents the methodology proposed and addresses the application of the methodology proposed in Rio de Janeiro Subway. Section 5 addresses the conclusions of the work.

## II. $CO_2$ emissions per pkm from subway systems

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 values 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.

$CO_2$ emissions from subways occur mainly in the generation of electric power required for the operation of the subway 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 subway system, but obtained from third parties, from the local electricity supply company.

The subway systems are large electricity consumers. Large amounts of electricity are needed to provide the traction force that moves the trains and the operation of auxiliary equipment of subway stations such as: lighting, ventilation, escalators,

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elevators, pumping systems, substations and other energy. Table I presents the results of the annual electricity consumption in some subways, showing the high rate of energy consumption.

TABLE I: SUBWAYS ELECTRICITY CONSUMPTION PER YEAR

| Subways | Electricity consumption per year | Sources |
|---|---|---|
| New York | 3,4 TWh | 6 |
| Hong Kong | 1,4 TWh | 7 |
| London | 1,0 TWh | 8 |
| Sao Paulo | 0,6 TWh | 9 |
| Porto | 0,5 TWh | 10 |

As the tractive force of the trains is responsible for much of the consumed energy in the subways, it is the biggest responsible for $CO_2$ emissions in the operation of subways. 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 subway company.

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 subways show a great variation in results among the subway 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. In 2012, the hydroelectric source in Brazil represented 77% of the internal offer of national electric power [13].

Table II shows results of $CO_2$ emissions, total and in pkm, due to the generation of electric power in three subways. 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.

TABLE II. $CO_2$ EMISSIONS RELATED TO ELECTRIC POWER GENERATION IN SUBWAYS

| Subways | Total emissions in $tCO_2$ | Emissions in $gCO_2$ per pkm | Year | Sources |
|---|---|---|---|---|
| Lisbon | 14,500 | 49 | 2012 | 14 |
| Bilbao | 16,638 | 28 | 2011 | 15 |
| Sao Paulo | 44,000 | 4 | 2012 | 9 |

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

# III. Comparative results of emissions in subways with buses and automobiles

Different researches indicate that the subway 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. [16] 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 the best 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 subways 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 [17].

In 2011 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 transportation, whereas for subways it was 41 [18]. Another example of comparison between subways and buses from the European continent is a result from the city of Bilbao, Spain, where the buses emit almost 5 times more (135 $gCO_2$ per pkm) than the subway system (28 $gCO_2$ per pkm) [19].

The emission averages, in 2010, in the United States [20], in $gCO_2$ per pkm, by the subways and buses are: 62 for the subways and 180 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 subways. This survey also revealed the average occupancy rates of these two systems across the country, which shows 47% occupancy for subways and 28% for buses. If the maximum passenger loads were considered, the subway would still have the lowest emission values, in $gCO_2$ per pkm, with 31 for subways and 51 for buses [20]. Fig. 1 shows examples of results of subways, buses and automobiles emissions in six cities in the United States.

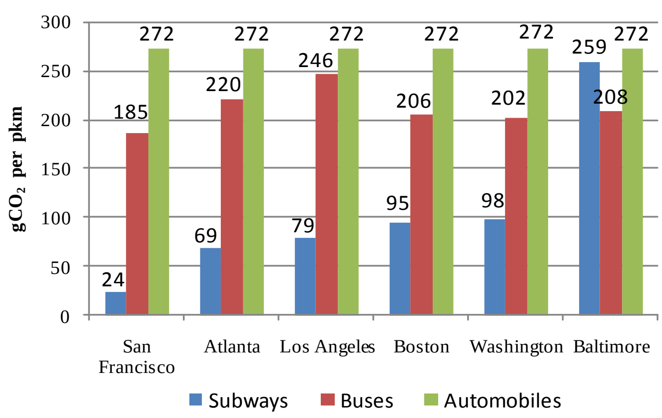


Figure 1. Average emissions, in $gCO_2$ per pkm, of subways, buses and automobiles in the United States - 2010 (*20*)

It was noted that, among all American cities, in only one of them, Baltimore, the subway presented an emission value greater than that of the bus. This is because there is a low rate of use in the Baltimore Subway, with only 17% 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 [20].

In Oceania, the Urban Transport Government of Australia conducted a study in 2009 on $CO_2$ emissions in the transportation systems of the city of Melbourne, finding, for the subways and buses, respectively, 145 and 159 $gCO_2$ per pkm [21].

A high value is found, above average, in the emission by Melbourne Subway. This is because Australia has an energy matrix constituted basically of thermal sources, based on coal, which is the thermal source with largest emission [22], making Australia the 5th country in the world in the production of coal and the 2nd country in the world in the export of coal [23]. 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 subway and buses in the city of Melbourne remain so close.

## IV. Methodology for calculation of emission $gCO_2$ per pkm from subways: Application in Rio de Janeiro Subway

The proposed methodology for calculating the emissions, in $gCO_2$ per pkm, from subways should be applied monthly, so as to reach an annual result, and should follow the following steps:

Step 1: Determine the total power monthly consumed by the subway system, in MWh.

Step 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 [24].

Step 3: Multiply the monthly total power consumed by the subway 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 $tCO_2$.

Step 4: Turn the result of the total emissions, in $tCO_2$, into $gCO_2$.

Step 5: Determine the quantity of monthly pkm of the subway 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.

Step 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 from subway system.

Step 7: The annual emission result, in $gCO_2$ per pkm, in the subway, is obtained by dividing the sum of the total monthly emissions, in $gCO_2$, by the sum of the monthly results of pkm.

In Brazil, Rio de Janeiro Subway has made available the monthly data of passenger-km and total power consumptions in the year 2012. Table III presents the data collected, required for the application of the proposed methodology and the results of emissions.

TABLE III. $CO_2$ EMISSIONS FROM RIO DE JANEIRO SUBWAY – 2012 [24, 25]

| Months | Total Power MWh | Government's Emission Factor $tCO_2$/MWh | Total Power Emissions $tCO_2$ | Passenger-km |
|---|---|---|---|---|
| Jan | 17,223 | 0.0294 | 506.353 | 160,875,859 |
| Feb | 17,372 | 0.0322 | 559.380 | 166,823,976 |
| Mar | 17,747 | 0.0405 | 718.739 | 180,577,528 |
| Apr | 16,426 | 0.0642 | 1,054.566 | 156,885,831 |
| May | 16,528 | 0.0620 | 1,024.729 | 178,363,796 |
| Jun | 15,916 | 0.0522 | 830.790 | 161,865,005 |
| Jul | 16,317 | 0.0394 | 642.890 | 175,907,290 |
| Aug | 16,789 | 0.0460 | 772.278 | 189,090,840 |
| Sep | 15,624 | 0.0783 | 1,223.360 | 168,104,302 |
| Oct | 17,255 | 0.0984 | 1,697.902 | 182,993,862 |
| Nov | 16,313 | 0.1247 | 2,034.293 | 164,354,114 |
| Dec | 18,333 | 0.1168 | 2,141.285 | 170,690,301 |
| Total 2012 | 201,842 | 0.0653 | 9,335.917 | 2,056,532,704 |

Monthly results of total emissions were found to be up to 4.2 times higher from a month to another. By comparing the months of Jan/12 and Nov/12, similar results are observed in total 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 Nov/12, proving the high value of the average emission factor for this month, which was the highest in 2012.

Fig. 2 graphically presents the monthly results of emissions and average emissions over 2012 in $gCO_2$ per pkm, obtained by applying the proposed methodology.

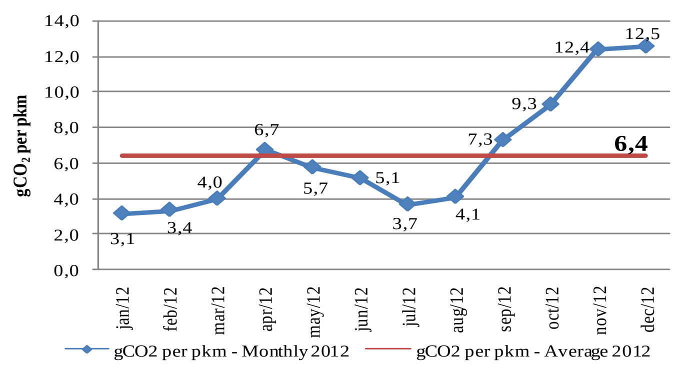


Figure 2. Emissions, in $gCO_2$ per pkm, from Rio de Janeiro Subway - 2012

In 2012, the average emission from Rio de Janeiro Subway was 6.4 $gCO_2$ per pkm. If compared to the results of emissions in other subway systems already presented in this work, it is evidenced that Rio de Janeiro Subway is one of the transportation systems with the lowest emission in the world.

This occurs mainly due to Brazilian energy matrix, composed basically of hydroelectric plants, in addition to the adequate system occupation rate, which, according to Rio de Janeiro Subway [25], was of 50%, representing approximately 910 passengers inside a train in each trip. Differences are noticed in monthly results, ranging from 3.1 to 12.5 $gCO_2$ per pkm. From Sep/12 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 four months of 2012, motivated by greater use of thermal sources during this period. In Brazil, automobiles emit 127 $gCO_2$ per pkm [4] and the buses emit 65 $gCO_2$ per pkm [9], which demonstrates the good performance regarding $CO_2$ emission by Rio de Janeiro Subway, of 6.4 $gCO_2$ per pkm.

# V. Final considerations

The comparative analysis showed that the subway 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 subways 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 bus may also have an emission higher than the emission of automobiles. This occurs when the subway or bus 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 subway system, as in Australia, where the results of emission of subways, buses and cars are similar. So the transportation planning toward the environment should take into account local characteristics of electric power generation. When this generation can be made largely in a *clean* way, rail electric transportation solutions, such as subways, must be considered.

The application of the methodology proposed to Rio de Janeiro Subway throughout the year 2012 revealed that, inside this system, the subway has an emission about 20 times lower than the Brazilian cars and 10 times lower than the Brazilian buses. The proper occupancy rate of Rio de Janeiro Subway, coupled with little use of thermal sources in the energy matrix of generation of electricity powering, enabled these results.

For next studies we will explore 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 period off-peak, 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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## References

[1] UN ESCAP – United Nations Economic and Social Commission for Asia and the Pacific. *Sustainable and inclusive Transport.* http://www.internationaltransportforum.org/Pub/pdf/10GHGTrends.pdf. Accessed July 5, 2014.

[2] Ribeiro, S. K.; Metz, B; Davidson, O. R.; Bosch, P. R.; Dave, R.; Meyer, L. A. *Transport and its infrastructure*. Chapter 5. Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007. Cambridge e New York , Cambridge University Press.

[3] EPE - Empresa de Pesquisa Energética Brasileira. *Balanço energético nacional de 2011*, 2012. https://ben.epe.gov.br/downloads/Resultados_Pre_BEN_2012.pdf. Accessed July 5, 2014.

[4] IPEA - Instituto de Pesquisa Econômica Aplicada. *Emissões Relativas de* 23 *Poluentes do Transporte Motorizado de Passageiros nos Grandes Centros Urbanos Brasileiro* , 2011.

[5] WRI - World Resources Institute. *GHG Protocol*, 2013. www.ghgprotocol.org. Accessed July 15, 2014.

[6] MTA - Metropolitan Transport Authority. *Renewable energy task report*, 2008. http://web.mta.info/sustainability/pdf/MTA%20Renewable%20 Energy %20Report %2010%2029%2008.pdf. Accessed July 15, 2014.

[7] MTR - Mass Transit Railway System. *Sustainability report 2012*, 2013. http://web.mta.info/sustainability. Accessed July 15, 2014.

[8] LU - London Underground. *London underground carbon footprint*, 2009. http://www.tfl.gov.uk/cdn/static/cms/documents/london underground- carbon-footprint-2008.pdf. Accessed July 15, 2014.

[9] Metro São Paulo. *Relatório de Sustentabilidade de 2013*, 2014. www.metro.sp.gov.br/relatoriodesustentabilidade-2013. Accessed July 15, 2014.

[10] Metro Porto. *Relatório de Sustentabilidade de 2011-2012*, 2013. www.metrodoporto.pt/PageGen.aspx?WMCM_PaginaId=17246. Accessed July 15, 2014.

[11] Messa, C. A. Comparison of Emissions from Light Rail Transit, Electric Commuter Rail, and Diesel Multiple Units. *Transportation Research Record: Journal of the Transportation Research Board*, No. 26, *Transportation Research Board of the National Academies*, Washington, D.C., 2006, pp. 26–33.

[12] CoMet - Community of Metros. *Energy Costs, Renewables and $CO_2$ Emissions Nova Phase 10 Case Study*, 2008.

[13] EPE - Empresa de Pesquisa Energética Brasileira. *Balanço energético nacional de 2012*, 2013. https://ben.epe.gov.br/downloads/Relatorio_Final_BEN_2013.pdf. Accessed July 5, 2014

[14] Metro Lisboa. *Relatório de Sustentabilidade de 2012*, 2013. www.metrolisboa.pt/wp-content/uploads/Relat%C3%B3rio-de-sustentabilidade-2012.pdf. Accessed July 15, 2014.

[15] Metro Bilbao, 2014. www.metrobilbao.net/conocenos/metro-en-cifras-viajeros-y-calidad/demanda. Accessed July 15, 2014.

[16] Andrade, C. E. S.; I. A. Bittencourt; M. A. D'Agosto, I. C. Leal Júnior. *O transporte de passageiros sobre trilhos e sua contribuição para a redução das emissões de gases do efeito estufa*. CBTU – Companhia Brasileira de trens urbanos, 2013. http://www.cbtu.gov.br/monografia/2013/monografias/monografia_01.pdf. Accessed July 5, 2014.

[17] TFL - Transport for London. *Surface Advisory Panel*, 2006. www.tfl.gov.uk/assets/downloads/Agenda-and-Papers-SAP-31-05-06.pdf. Accessed July 15, 2014.

[18] EEA - European Environment Agency. *Specific CO2 emissions per passenger-km and per mode of transport in Europe 1995-2011*, 2011. www.eea.europa.eu/data-and-maps/figures/specific-co2-emissions-per-passenger-3. Accessed July 15, 2014.

[19] Metro Bilbao. *Informe de Gases Efecto Invernadero 2011*, 2012. www.metrobilbao.net/assets/system/attachments/510698fafc7a7b6532000002/original/Informe%20GEIS%202011_verificado.pdf?2013-01-28T15:27:54+00:00. Accessed July 15, 2014.

[20] FTA - Federal Transit Administration. *Public Transportation's Role in Responding to Climate Change*, 2010. http://www.fta.dot.gov/documents/PublicTransportationsRoleInRespondingToClimateChange2010.pdf. Accessed July 15, 2014.

[21] GAMUT - Australasian Centre for the Governance and Management of Urban Transport. *Carbon Emissions Trading and Australia's Urban Transport*, 2009. http://cw.routledge.com/textbooks/9780415529037/data/4-1-Paper.pdf. Accessed July 15, 2014.

[22] Brasil Gov - Brazilian Government. *Carvão mineral*, 2013. www.brasil.gov.br/sobre/economia/energia/matriz-energetica/carvao-mineral-e-derivados. Accessed July 15, 2014.

[23] IEA - International Energy Agency. *Key world energy statistics*, 2013. www.iea.org/publications/freepublications/publication/KeyWorld2013.pdf. Accessed July 15, 2014.

[24] MCT - Ministério da Ciência e Tecnologia do Brasil, 2014. www.mct.gov.br/index.php/content/view/321144.html#ancora. Accessed July 15, 2014.

[25] Metrô do Rio de Janeiro. *Inventário de Emissões de Gases do Efeito Estufa de 2012*, 2013**.**

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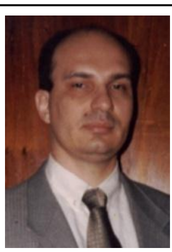

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