Capítulo 80

Optimization in urban transport: an intermodal simulation with emphasis on energy efficiency

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ABSTRACT
In general, it can be said that patterns of energy production and consumption have been based on fossil fuels, which generate emissions of local pollutants; greenhouse gases (GHGs) and jeopardize the energy supply long-term on the planet. Concerning urban transport, Brazilian cities have developed with an emphasis on road transport. Thus, it is relevant to study energy efficiency in transport, to implement good solutions that meet the movements of users, and promote the efficient use of natural resources. This paper aims to estimate, on a network of fictitious transport, energy efficiency displacement of a given passenger demand using different modes of transport to measure the energy efficiency of the network. Specifically, we intend to verify and compare the energy consumption and carbon dioxide emissions in intermodal transport by rail modes - Light Rail (LRT) and bus - bus. The methodology was developed based on documentary and bibliographical research for data collection, and applied operations research techniques to assess the energy efficiency of the simulated network. The review includes the study of transport, its indispensability, and its influence on the environment. Energy efficiency in the transport matrix and the use of operations research as a support tool for optimization models are discussed. Finally, it observed that the modal integration, feeder system - distributor system - is an efficient solution as the energy consumption and GHG emissions. The methodology proved to be satisfactory and relevant and can be used for larger networks and real scenarios. As a continuation of this study is developing a methodological contribution to sustainable planning of urban passenger transport (MPTS - URB), which aims to estimate the monetary cost of energy efficiency from data on emissions and energy consumption by transport modes used in the transport network.

Keywords: Optimization, Intermodal Transportation, Rail Transportation, Energy Efficiency.

1 INTRODUCTION

Transport is essential to modern life. It makes most social and economic activities possible. However, although essential, transport also influences the environment, since it is an activity that demands interference in the natural physical environment, for the implementation of its infrastructure, and consumption of energy and fuel, for its operation (D`AGOSTO, 2015).

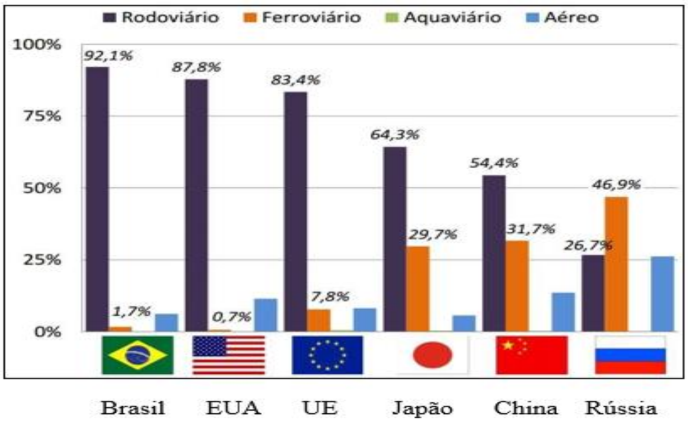
In 2012, Brazil hosted the United Nations Conference on Sustainable Development (RIO +20), the meeting addressed issues on society's awareness of the urgency of treating the environment responsibly, in addition, it brought to the center of debates the Green Economy[1], the most concrete form of economy to progress towards Sustainable Development.[2].

Passenger transport is part of the themes addressed in the Green Economy, in which one of the principles is the change to more environmentally efficient models of transport – collective systems, urban trains, subways, and non-motorized ones. According to the United Nations Environment Program (UNEP) Green Economy report, investing just 0.16% of global GDP in green transport would reduce greenhouse gas (GHG) emissions by up to 70% of global emissions. transport sector by 2050, also resulting in a reduction of one-third in the number of vehicles using road transport and the consumption of petroleum derivatives (UNEP, 2011).

In this context, rail transport can be an important ally both for improving urban mobility and for the environment, mainly because it serves a high transport capacity by emitting fewer GHG gases (EPE, 2012). According to the Balance of the Metrorail Sector 2012/2013, there was an increase in passengers transported on rails in Brazil, but the growth of the network did not follow this increase.

To demonstrate this issue, data published by the Ministry of Mines and Energy, referring to the modal distribution of passenger transport in Brazil, show that the rail mode, between urban trains and subways, represents only 1.7% of the total number of passengers transported in the country. Brazil, as shown in Figure 1.

Fig. 1 – Modal distribution of passenger transport. A comparison between Brazil and other countries (billions of passengers/km). Source: MME – EPE (2012).



[1] Green Economy is understood as an economy that takes into account the finitude of natural resources and the services provided by nature in the decision-making process of the behavior of economic agents (IPEA, 2012).
[2] Sustainable development is a model that reconciles economic growth, social inclusion, and environmental protection. (IPEA, 2012)

2 THEORETICAL FRAMEWORK

2.1 ENERGY EFFICIENCY IN TRANSPORT

Concerning passenger transport, for Gonçalves et al. (2014) it is known that Brazilian cities had their urban development based on the road mode. In general, it can be said that the quality of life in these cities has been deteriorating, causing diseconomies due to congestion, accidents, and environmental impacts. Especially in metropolitan regions, such problems are currently aggravated, partly due to the lack of planning and intermodal coordination by public managers, and partly due to political-economic competition between road and rail modes in public transport solutions. A proposal for restructuring the current model should incorporate concepts that seek to articulate the different modes in a single transport system, aiming at the efficiency of displacements, the sustainability of energy sources and resources, and user satisfaction.

To prove their point of view, Gonçalves et al. (2014) referred to good international practices of socioeconomic development, both in regions of the developed world, such as Stockholm and in regions in accelerated development, such as Singapore. Regarding urban transport, these cities have in common the efficiency of the system, which invests in intermodal planning and coordination techniques, prioritizing the connection between the most remote regions and suburbs, to their respective workplaces, through a system of integrated transport, with priority given to rail.

According to the National Energy Balance - BEN (2012) report, road transport is responsible for 93% of final energy consumption in the transport sector, which directly influences the amount of carbon dioxide - CO2 emitted, and demonstrates the inefficiency of Brazil's transport matrix, from an environmental point of view. Thus, investing in other modes of transport, such as rail, in the centers of large cities and metropolitan regions brings, among others, gains in energy efficiency, since it consumes less energy, and at the same time, it produces fewer pollutants and GHG in the atmosphere.

Tables 1 and 2 bring, respectively, data referring to local pollutant emissions and CO2 by mode of transport; and energy released per mode, per kilometer, for a person to carry out any displacement.

Table 1 – Emissions of pollutants by mode of transport in municipalities with more than 60,000 inhabitants.

Transport	Emissions (millions of tons/year) in municipalities with more than 60,000 inhabitants.		
	Local pollutants *	CO_2	Total
Collective	0,1	9,5	9,6
Individual Motorized	1,5	16,3	17,8
Total	1,6	25,8	27,4

Source: adapted by the author of Revista BNDES 60 anos – Perspectivas Setoriais (2015).

According to data from IPEA (2012), motorized transport, based on the burning of fossil fuels, is responsible for the emission of various pollutants that are harmful to health and that degrade the urban environment, the so-called local pollutants: carbon monoxide (CO), hydrocarbons (HC), particulate matter, nitrogen oxides (NOx) and sulfur oxides (SOx). Table 3 describes some harmful health effects of the high concentration of these pollutants on health.

Table 2 – Energy released per person per mode (kep/km).

Mode of Transport	The energy required per person per mode in kep (kg oil equivalent)		
	1 km	10 km	100 km
VLT (rails)	0,010	0,10	1,0
Subway (rails)	0,021	0,21	2,1
Bus	0,026	0,26	2,6
Individual Motorized	0,055	0,55	5,5

Source: adapted by the author of Revista BNDES 60 anos – Perspectivas Setoriais (2015).

Table 3 – Harmful effects of the main local vehicle pollutants.

Polluting	Impact
CO	It acts on the blood by reducing its oxygenation and may cause death after a certain period of exposure.
NOx	Formation of nitrogen dioxide and the formation of photochemical[3] smog and acid rain. It is a precursor to ozone.
HC	Unburned or partially burned fuels form smog and carcinogenic compounds. It is a precursor to ozone.
MP	It can penetrate the body's defenses, reach the lung alveoli and cause irritation, asthma, bronchitis, and lung cancer. Dirt and degradation of properties close to transport corridors.
SOx	Precursor of ozone, forming acid rain and degrading vegetation and buildings, in addition to causing a series of health problems.

Source: adapted by the author from (DE CARVALHO, C. H. R., 2011)

In this context, the Environmental Company of the State of São Paulo (CETESB), through a survey carried out in the city of São Paulo in 2007, concluded that the concentration of ozone gas in the atmosphere is more excessive in large urban centers, which are the most affected, in the scope of air pollution. This gas is formed from other gases that are mainly emitted by vehicles, which react when in the presence of sunlight and heat. Despite this, in poorly industrialized cities, the transport sector ends up contributing to almost all emissions of air pollutants, which corroborates the need for policies that promote the reduction of vehicle emissions.

In Santos' opinion, R.T. et al., 2015, public transport should be thought of as a structuring project for urban development, the result of consistent studies, embodied in long-term planning, discussed with society, and endorsed by competent technical bodies. For Marcio de Almeida D`Agosto (2015), there is no substitute for energy, one can even substitute one source for another, but the transport activity without the

[3] Photochemical phenomenon characterized by the formation of a kind of haze composed of pollution, water vapor, and other chemical compounds. (DE CARVALHO, C. H. R., 2011).

consumption of some form of energy does not seem to be possible. Thus, thoughts like these come to persuade the development of methodologies that optimize transport. Like cities, intermodal networks can promote modal substitution, attracting, at least in part, car users to public transport, which promotes the equalization of the transport matrix, and consequently the efficient use of resources.

2.2 OPERATIONAL RESEARCH AS A TOOL FOR OPTIMIZATION MODELS

Operational Research, or simply PO (Operational Research – England; Operations Research – United States; Investigação Operacional – Portugal) emerged during the Second World War (1939-1945) to solve problems of a logistical, tactical, and military strategy nature. The advancement of OR, over the years, has been made with the increase in the processing speed and memory of computers, enabling the solution of increasingly complex problems (FÁVERO & BELFIORE, 2013).

In general terms, it can be said that OP consists of the use of a scientific method - mathematical models, statistics, and computational algorithms - that help in the decision-making process (ARENALES et al., 2007)

Since then, the use of operational research to support decision-making has been widely used in the field of transport. In this article, Operational Research subsidizes the calculation of energy efficiency in different routes (paths, stretches) of a transport network, to contribute to the decision-making of which path is more efficient. The aforementioned species of the Operational Research genre, such as models, for example, may represent a real situation that one intends to evaluate or even a theoretical situation, in the sense of verifying a planned alternative for the future.

According to Lisboa (2009), a model is the simplified representation of a real system, which can be an existing project or a future project. In the first case, the intention is to reproduce the functioning of the real existing system, to increase productivity, while in the second, the objective is to define the ideal structure of the future system.

Lachtermacher (2009) conceptualizes a model as a decision-making process, which provides the decision-maker with the clarity to define his objectives. In addition, this author explains that the correct identification and storage of the different decisions that influence the objectives provides the definition of the main variables involved in the decision-making process and the limitations of the system.

A model is composed of three main elements: the decision variables and parameters, the objective function, and the constraints of the model. The model used here was the Network Programming model, through the Transport Problem with Overflow. Conceptually, this model is classified in Operations Research as a Deterministic Model, in which the variables involved in its formulation are constant and known, thus resulting from a single exact solution, which may or may not be optimal (FÁVERO & BELFIORE, 2013).

Network Programming problems are modeled using a structure called graphs or networks, which consists of several nodes, where each node must be connected to one or more arcs (ARENALES et al., 2007). This concept in the context of passenger or cargo transport can be analogously understood as the set of centralities or facilities (facilities), the nodes, connected by transport corridors (paths, routes) or (corridors), the arcs, which represent a transport network, the graph or network.

In this context, the Transport Problem with Transshipment is a type of network programming modeling, where it is considered, for a given demand (products or passengers), origin nodes, intermediate transshipment nodes (facilities), and destination nodes, connected by transport corridors (corridors), whose objective is to transport that demand at a minimum logistical cost. These models can be solved by linear programmings, like the problem proposed here.

3 METHODOLOGY

The methodology is based on bibliographic references and operational research. The references fed the necessary data for the elaboration of the model, such as data on energy consumption and CO2 emissions, by mode of transport, and by kilometer. They also brought energy efficiency calculation models already studied for different vehicles. The Operational Research subsidized the construction of the model, through the elaboration of the transport network, through a Transport Problem with Transhipment.

For the elaboration of the network, arcs were considered as the displacement corridors and nodes as the points of origin, modal integration (transshipment), and destination. The network layout is theoretical, as this way it was possible to build alternative routes considering the different modes since the objective is to estimate the energy efficiency in this network.

3.1 PROBLEM DEFINITION

The objective to be achieved here is to estimate the energy efficiency for the displacement – origin and destination – of a certain demand. The problem is inserted in the question: efficiency of the transport of passengers from metropolitan regions to central areas. For this, a transport network model was created that considers different modes such as bus, VLT, and car, for transport demand.

The proposed way to solve this model was:

1) *Create the integrated transport network model through the transshipment transport problem;*
2) *Assign to each node the demand to be met (passengers) and the travel distance (km);*
3) *Calculate for each arc, energy consumption (kj/pass.km) and CO2 emissions (gCO2/pass.km)*
4) *Calculate the number of vehicles to meet the demand according to the transport capacity for each mode.*

The limitations of the model were the lack of real data for an integrated intermodal transport network for Brazilian cities, and consequently the location of transfer points. Thus, it was considered a theoretical network. The center of any city was chosen as the destination, three locations in the metropolitan region of that city as the origin, and hypothetical points as transshipment. Theoretical passenger demand values were also assigned to the origin and transfer nodes.

In order not to induce the results, the transshipment points were arranged in the same place, not generating different distances between the connections, since the objective here is to verify the energy efficiency of each route, arriving at the most efficient one.

3.2 DATA SURVEY

At this stage of model construction, real data were collected (Table 4), regarding energy consumption, CO2 emissions, and transport capacity; and theoretical data (Table 5) in terms of demand and transfer locations.

Figure 2 presents the theoretical intermodal transport network created for the application in this study.

According to D`Agosto (2015), there are several concepts for energy efficiency. This article will consider what is defined by the IEA (2012), as the level of energy consumed to perform a given service. Thus, to be more efficient, one can use less energy for the same service and, or even perform more service while maintaining the same pattern of energy use. Analogously to the transport sector, this concept can be understood as: increasing the amount transported (cargo or passenger) and/or the transport distance, without increasing energy. Or, keeping the same transport work, reducing the energy consumed to carry it out (GUIMARÃES, V. de A.; D`AGOSTO, M. et al., 2014).

Table 4 - Actual data

Mode of Transport	CO2 emissions (gCO2 /pass.km)[4]	Average energy consumed [5] (kj/pass.km)	Carrying Capacity [6] (pass/ vehicle)
Conventional Bus with	16	266	80
MCI* rear diesel	127	2.766	1,3
Compact car with gasoline MCI	2	183	225

* MCI = combustion engine.
Source: adapted by the author through data obtained from DE ANDRADE, C. E. S. (2014); BITTENCOUT, I. A. (2014); BNDES Magazine 60 Years – Sectorial Perspectives (2015); D`AUGUST (2015).

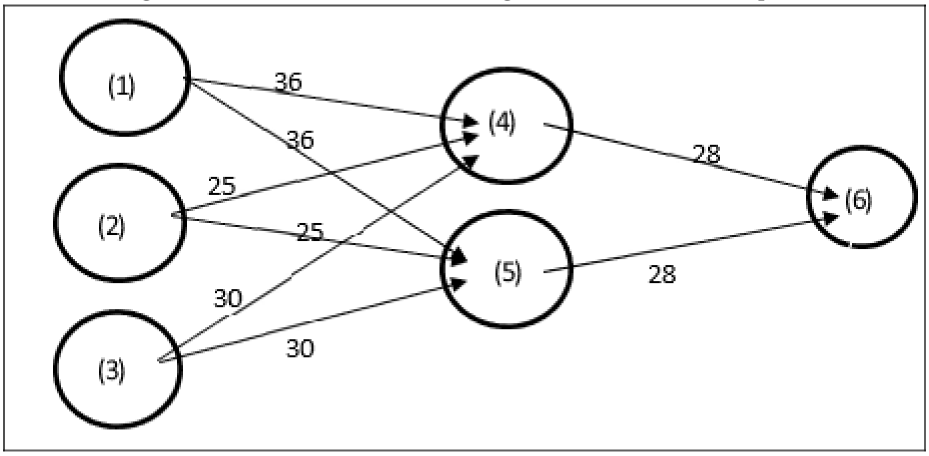
Table 5 - Theoretical data

Points of Origin	Demand (pass)	Distance (km)	Point Transhipment (VLT)	Point Transhipment (Bus)	Distance (km)	Destination Point
(1)	180	36	(4)	(5)	28	(6)
(2)	250	25	(4)	(5)	28	(6)
(3)	200	30	(4)	(5)	28	(6)

Source: prepared by the author

[4] DE ANDRADE, C. E. S. (2014); BITTENCOUT, I. A. (2014)
[5] The energy required per person per mode in kj. Adapted from BNDES Magazine 60 Years – Sectorial Perspectives (2015).
[6] D`AGOSTO (2015)

Fig. 2 - Theoretical Network of Integrated Intermodal Transport



SOURCE: prepared by the author

3.3 ENERGY EFFICIENCY CALCULATION

This research considers for the calculation of energy efficiency (E) the consumption of CO2 released to carry out certain work in a certain distance (cij in kj/pass. km) and the quantity in gCO2 of emissions that this work generates to the atmosphere (eij in gCO2/pass.km). So you have:

$$\sum_{i=1}^{m}\sum_{j=1}^{n} E_{ij} = c_{ij} + e_{ij} \qquad (1)$$

Due to the difficulty encountered here in equating the respective units of cij and eij, the term u.e. was attributed to Eij. (units of energy).

3.4 DECISION VARIABLES:

The decision variables were defined based on the number of passengers transported for each itinerary. So you have:

xij,k = many passengers transported from origin i to transfer point k. i = 1, 2, 3 and k = 4, 5.
xkj = a number of passengers transported from transfer point k to destination j. k = 4.5 and j = 6.
Thus, one has:

x14 = passengers carried between origin 1 and transfer point 4;
x15 = passengers carried between origin 1 and transfer point 5;
x24 = passengers transported between origin 2 and transfer point 4;
x25 = passengers carried between origin 2 and transfer point 5;
x34 = passengers carried between origin 3 and transfer point 4;
x35 = passengers transported between origin 3 and transfer point 5;
x46 = passengers transported between transfer point 4 and final destination 6;
x56 = passengers carried between transfer point 5 and final destination 6.

3.5 PARAMETERS:

Eij,k = energy efficiency from origin i to destination j passing through transfer point k. With i = 1, 2, 3; j = 6 and k = 4, 5.

cik = energy consumption for transport from origin i to transfer point k. i = 1, 2, 3 and k = 4, 5.

ckj = energy consumption for transport from transfer point k to destination j. k = 4, 5 and j = 6. eik = CO2 emission for transport from origin i to transfer point k. i = 1, 2, 3 and k = 4, 5.

ekj = CO2 emissions for transport from transfer point k to destination j. k = 4, 5 and j = 6.

Cti = carrying capacity of origin i. i = 1, 2, 3.

dj = expected demand at destination j. j = 6.

Lik = displacement in km (kilometers) from origin i to transfer point k. i = 1, 2, 3 and k = 4, 5.

Ljk = displacement in km (kilometers) from transfer point k to final destination j. k = 4.5 and j = 6.

Travel between points of origin 1, 2, and 3 and transfer points 4 and 5 are made by road, a conventional bus with an internal combustion diesel engine and capacity for 80 passengers. As well as transfers between transfer point 5 and final destination 6. Transfers between transfer point 5 and final point 6 are made by light rail vehicles (VLT) with a capacity for 225 passengers.

3.6 PURPOSE FUNCTION:

$$\min Z = \sum_{i=1}^{3}\sum_{k=4}^{5}(c_{i\,k} + e_{i\,k}) + \sum_{k=4}^{5}(c_{k\,6} + e_{k\,6}) \qquad (2)$$

On what:

$$c_{i\,k} = (c_{ik} * x_{ik} * L_{ik}) \; com \; i = 1, 2, 3 \;\; ; k = 4, 5;$$

$$e_{i\,k} = (e_{ik} * x_{ik} * L_{ik}) \; com \; i = 1, 2, 3 \;\; ; k = 4, 5;$$

$$c_{k\,j} = (c_{kj} * x_{kj} * L_{kj}) \; com \; k = 4, 5 \; e \; j = 6;$$

$$e_{k\,j} = (e_{kj} * x_{kj} * L_{kj}) \; com \; k = 4, 5 \; e \; j = 6.$$

3.7 RESTRICTIONS:

1. The transport capacity at the origin must be respected:

$$\sum_{i=1}^{3}(x_{i\,k}) = C_{ti} \qquad com \; k = 4, 5$$

2. All endpoint demands must be met:

$$\sum_{i=1}^{3}(x_{i\,k}) + \sum_{k=4}^{5}(x_{k\,6}) = d_j \qquad com\ k = 4,\ 5\ e\ j = 6.$$

3. Conservation of input and output flows:

$$\sum_{i=1}^{3}(x_{i\,k}) = \sum_{k=4}^{5}(x_{k\,6}) \qquad com\ k = 4,\ 5\ e\ j = 6.$$

4. Respect the non-negativity of all decision variables:

$$x_{ik},\ x_{kj} \geq 0,\ i = 1, 2, 3\ ;\ k = 4, 5\ e\ j = 6.$$

4 RESULTS

Using the Solver function of the Exel program (Microsoft, 2014) to solve the problem, and the data provided in Tables 4 and 5, the energy efficiency was calculated for each route, calculating the CO2 emissions (gCO2/pass.km) and energy consumption (kj/pass.km) as shown in Table 6:

Table 6 - Calculation of CO2 emissions and energy consumption for each route

Calculation of Energy Efficiency by section: (calculated using the data in Tables 4 and 5)								
Calculation of CO2 emissions (gCO2/pass.km)					Calculation of energy consumption (kj/pass.km)			
Transhipment	x4	x5	x6		Transhipment	x4	x5	x6
x1	576	576	0		x1	9.576	9.576	0
x2	400	400	0		x2	6.650	6.650	0
x3	480	480	0		x3	7.980	7.980	0
Full stop	x4	x5	x6		Full stop	x4	x5	x6
x4	0	0	56		x4	0	0	5.124
x5	0	0	448		x5	0	0	7.448

Source: Elaborated by the author

The Objective Function (2) was calculated through the EXEL SUMPRODUCT function, in which the matrices of the decision variables were multiplied by the respective matrices of energy consumption and CO2 emissions, respecting the matrix multiplication properties.

The results obtained were: x14 = 180; x15 = 0; x24 = 250; x25 = 0; x34 = 200; x35 = 0; x46 = 630; x56 = 0. All the capacity in the PO (1,2,3) was destined to the PT (4) and from that to the PF (6), resulting in the optimal values of 5,949,300 kJ of energy released and 198,960 gCO2 emitted into the atmosphere, considering the entire demand of 630 passengers, with excellent energy efficiency. The Sensitivity Report showed that for each passenger whose route was changed, the Reduced Cost would be 392 gCO2 and 2,324 kJ, totaling an energy efficiency cost of 2,716 u.e. (unit of energy).

5 FINAL CONSIDERATIONS

In general, it could be concluded that investments in urban rail transport, if properly planned and managed, are favorable to a more sustainable movement of passengers. In terms of energy efficiency, the intermodal network simulated here showed that the integration between road modes, by bus, and rail, by VLT, can be seen as more efficient solutions in terms of energy consumption. The road mode is the feeder of modes with greater capacity, such as the VLT, which can be allocated to make the longest journeys, for example.

Another parameter also presented here, the capacity of the vehicles, and considering, for example, the modal substitution of the individual motorized transport for the VLT, by the data presented here (Tables 2 and 4), in a route of 28 km, it is estimated the reduction of 504 kilograms of oil equivalent (kep) in energy consumption for transport, in addition to the approximate reduction of 307 cars in the same route (considering 1.0 kep for each kilometer (km) traveled, and the modal replacement of the compact car (1.3 passengers per vehicle) for the VLT (400 passengers for the 7 train modules) If this trend is confirmed in another 10 Brazilian capitals, for example, we would multiply the energy savings by ten.

As for the methodology, it is considered satisfactory and relevant for problems such as the one simulated in this research – the calculation of energy efficiency in intermodal transport, which can even be used for larger and real networks.

As for difficulties, it is worth mentioning the fact that no equivalence was found in the units considered for the portions that made up the Energy Efficiency equation, causing the result obtained to be the sum of portions of different units. Thus, the plots were also calculated, using the same Solver model, by separating these plots in the objective function (FO-1 kj + FO-2 gCO2), for individual analysis of the results.

As a continuation of this research, it is intended to deepen the concepts of energy efficiency in transport, indicators, and methodologies developed, and mainly, to find an alternative (method) to convert energy consumption and CO2 emissions, in financial cost (R$), to direct the revenues obtained from these energy savings, in investments for the sector. For this purpose, a methodological contribution to sustainable transport planning applied to an urban passenger transport network (MPTS-URB) is already under development.

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