Reception: **October 1, 2020**| Acceptance: **February 22, 2021**| Publication: **October 1, 2021**

Analysis of the sustainability of urban mobility alternatives in Tuxtla Gutiérrez, Chiapas

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To quote this article:

Ruiz Sibaja, J. A., Guillén Trujillo, H. A., & Ramos Palacios, W. A. (2021). Análisis de la sostenibilidad de las alternativas de movilidad urbana en Tuxtla Gutiérrez, Chiapas. *Espacio I+D: Innovación más Desarrollo, 10*(28). https://doi.org/10.31644/IMASD.28.2021.a01

— Abstract—

In recent years the demand of the urban mobility sector has become of particular interest. The high dependency on mobility and the excessive use of cars in urban areas are matters of concern because the transportation systems are lead to unsustainable scenarios. This circumstance makes long-term planning highly relevant in trying to reverse this trend. There should be an integrating project that is based on the development of strategies according to indicators that show whether urban mobility is intended to be sustainable, and at the same time its positive effects are maximized and the negative ones are mitigated.

This paper proposes a new method for calculating such indicators and sustainability relationships for long-term decision-making, to analyze urban mobility in Tuxtla Gutiérrez and achieve sustainable urban mobility environments.

A methodical analysis is made of the flows that intervene in the dynamic functioning of urban mobility and its different alternatives, by evaluating all the energy used in this process (all this energy is called eMergy), of the different components to quantify them in identical units. With this evaluation, we attempt to know the emergetic flows and deposits of the different mobility alternatives. The sustainability indexes and other correlations that indicate the degree of dependence on urban mobility were also calculated, the results are shown graphically.

Finally, an analysis of the environmental burden is presented, showing how environmentally friendly the current urban mobility system can be. It was found that the bicycle is the mobility alternative that consumes less eMergy and that the one that consumes the most eMergy is the Conejobús. Regarding the eMergy index per kilometer per person per type of unit, it is shown that the Conejobús is the most efficient modality above bus and bicycles. Concerning the total eMergy index of mobility by type of alternatives, the most efficient was the Conejobús followed by bus and bicycles.

Keywords:

eMergy; sustainability; urban mobility; environmental burden; ecological system.

Starting in the 1970s, the metropolitan area of Tuxtla Gutiérrez, which constitutes the most important population, economic and political center of the capital of Chiapas, had a significant population increase, due to the construction of the Manuel Moreno Torres Hydroelectric Plant (Chicoasén, Chiapas). Many of the foreign workers who participated in the construction of the dam settled in the city permanently. For this reason, in recent decades there has been rapid population growth in the municipality of Tuxtla Gutiérrez and, although to a lesser extent, also in the surrounding municipalities (Silva *et al*., 2015).

According to the SHGEC (2014), the municipality of Tuxtla Gutiérrez, Chiapas, has a total area of 335 km² and, with data from 2014 projected to 2018, it is inhabited by around 600 thousand people. Because it is the capital and the main political, commercial, and service center of the state, many inhabitants of nearby municipalities come by to this place every day (to carry out multiple activities: to work, study, buy, get medical assistance, etc.), some of whom have even moved or have their second place of residence in Tuxtla Gutiérrez.

Similar to other medium-sized cities in Latin America (Henríquez, 2007; Avalos *et al*, 2016), Tuxtla Gutiérrez shows rapid horizontal growth. A constantly growing population demands the expansion of living spaces, communication routes, and other infrastructures. In particular, the city's growth has created the need to travel to carry out all daily activities. In most cases, motorized vehicles are used, which has generated a notorious collapse in urban circulation as a result of the saturation of roads and the inefficiency of public transport services. However, the growing number of motorized vehicles and their greater use, as well as the reduction in their occupancy rate, causes pollutant emissions to increase, which translates into increasing pollution of the atmosphere. This pollution affects climate change, due to greenhouse gases and carbon dioxide (CO_2).

In recent years, strategies to achieve sustainable mobility and transportation have met with limited success. This raises the question of how the sustainability of transport systems and policies can be assessed, and how these measurements can be used to plan transportation (Gudmundsson, 2003; Polea, 2019).

Consequently, in this work, it is proposed to resort to a recent strategy called *Sustainable Mobility*, which has shown its benefits and possibilities in the treatment of urban mobility alternatives. The purpose of such a tool is to reconcile the mobility needs of citizens, with the quality of life and the environment, without limiting the potential development that these activities generate, or restricting the right of people to quality transportation (Ferreyra, 2008; ITDP, 2013). The main objective is to show, through measurements and evaluations, the analysis of the sustainability of urban mobility alternatives in Tuxtla Gutiérrez and to show whether it is really sustainable. This environmental assessment will be based on eMergy, which is a methodology capable of integrating environmental, economic, and social indicators. EMergy is the sum of all energy inputs, directly or indirectly, necessary for a process to provide a specific product or service, these inputs are expressed in the same form or type of energy, usually solar energy. The eMergy analysis is designed to evaluate the energy and material flow of the systems in common units (solar joule, seJ) that allow the analyst to compare the environmental and financial aspects of the systems (Guillén Trujillo, 1998).

EMergy is defined as the amount of solar energy to make a product, its unit is the solar joule (seJ). Although energy is conserved according to the first law of thermodynamics, according to the second law, the ability of energy to do work is exhausted and cannot be reused (Odum, 1996), it is only conserved in a chain of transformations. This series of transformations makes it necessary to resort to the concept of Transformity, which is the amount of direct or indirect energy required to produce one type of energy in another type, but more useful -10,000 seJ/J wood, for example-. In other words, it is the measure of the energy required to transform one type of energy into another. Establishes the ecological hierarchy in energy analysis. Three different energy inputs are recognized: renewable premises, non-renewable premises, and purchased or imported flows. By dividing the community's energy inputs into these terms, it is possible to perform several very illuminating calculations: the population's environmental burden rate, its energy yield rate, and, most importantly, its sustainability index. In the emergetic analysis, environmental, social, and economic variables are included, and indexes are calculated as comparison tools for different systems. (Odum, 1996).

In the last 30 years, this technique has shown a great capacity to evaluate the sustainability of different processes in which different forms of energy are consumed. That is, it measures the quality of the different forms of energy that have been used, directly or indirectly, in the transformations necessary to generate a product or service. In this way, by integrating the environmental and financial aspects of the systems considered, eMergy can be used to evaluate urban mobility alternatives in Tuxtla Gutiérrez.

BACKGROUND

The efficient provision of social infrastructure and municipal services is essential to achieve a greater degree of productive specialization in the local economy and, as a result, in the well-being of the population in general. Therefore, investment in the three government levels is important to establish the conditions that allow aspiring to a better quality of life.

Urban development problems and their impact on the environment and quality of life constitute a challenge for those in charge of municipal infrastructure policies. Urban mobility is one of these concerns. This is the capacity and/or possibility of moving within the city. (Velásquez, 2010)

Consequently, urban mobility is a basic need of people that must be respected and satisfied in such a way that the effort and cost of travel necessary to access goods and services are sustainable and do not negatively affect people's quality of life or the possibilities of economic, cultural, and educational development.

Similarly, urban mobility is a fundamental right that must be guaranteed, under equal conditions, to the entire population, without differences derived from purchasing power, physical or mental condition, gender, age, or any other cause. (Velásquez, 2010)

Tuxtla Gutiérrez has experienced disorderly growth in recent decades. Due to this, in 2012 the Instituto Ciudadano de Planeación Municipal para el Desarrollo Sustentable (ICIPLAM) of Tuxtla Gutiérrez was created. The main function of ICIPLAM is to advise the governors for the design, planning, execution, and evaluation of the plans and programs applicable to the city. Thus, ensuring the quality of these and promoting citizen participation, through an approach based on sustainability.

The most important contribution of ICIPLAM, regarding urban mobility, dates from 2012, the year in which the proposal was made to replace the two main bus routes in Tuxtla Gutiérrez -routes 1 and 2-, and that circulated from East to West and from South to North. Such substitution occurred using ecological buses called "*Conejobús*". (Tuxtla 2030, the strategic agenda of our city, 2016).

With this exception, the city does not have a comprehensive mobility study that reports on urban areas that need transportation, how the population moves and what type of mobility is truly sustainable. Nor is there the infrastructure necessary for pedestrian mobility, mainly sidewalks and signs.

A deficiency has been detected in the promotion of mass-use mobility alternatives, at the same time, infrastructure to support the use of non-motorized means of transport is scarce. This aspect is very important since the use of quality mass public transport is directly related to improving the competitiveness and productivity of the city.

METHODS

The environmental accounting method called *eMergy* is used which is a tool to evaluate the sustainability of urban mobility in the City of Tuxtla Gutiérrez. This biophysical method was developed by Odum (1996) and is based on the analysis of energy with memory, to correctly account for the services provided by ecosystems for free. This tool is used to compare nature's work with that of humans on a fair and equitable basis. It can represent, at the same time, the contributions of nature and the economy in a single unit and criterion, providing a diagnosis of comparative evaluation, between the different results of environmental performance over time. (Guarnetti *et al*, 2006; Álvarez, 2020)

The eMergy analysis is designed to evaluate the energy and material flow of the systems in common units, the solar joule (sej), which allows the analyst to compare the environmental and financial aspects of the systems (Guillén, 1998). Three different energy inputs are recognized: renewable premises, non-renewable premises, and purchased or imported flows. By dividing the community's energy inputs into these terms, it is possible to perform several very illuminating calculations: the population's environmental burden rate, its energy yield rate, and, most importantly, its sustainability index. In the emergetical analysis, environmental, social, and economic variables are included, and indexes are calculated as comparison tools for different systems. In this work, emergetic and financial indexes are calculated to determine the sustainability of urban mobility in Tuxtla Gutiérrez. The following characteristic activities of an energy study were carried out (Guillén, 1998):

1. Definition of the space-time limits of the investigated system.
2. Gathering of data in the field, for means of transportation - owned vehicle, taxi, bus, motorcycle, and bike-, to determine the physical quantities of renewable and non-renewable resources, materials, and services that are part of the system studied.
3. Modeling of the system, through matter and energy flow charts, using energy symbology (Odum, 1994; Bravo, *et al*, 2018), of the interaction between the external and internal sources of the system, and the natural productive systems and anthropic, as well as the outflows of the system and its feedback. Figure 1 shows the energy flows that interact with each other in the city of Tuxtla Gutiérrez. This figure is very useful for a better understanding of the laws of thermodynamics since the main flows of energy inputs and outputs in the system can be represented, in this case, the flow for the socio-ecosystem of Tuxtla Gutiérrez, Chiapas. Likewise, all the flows that intervene within the municipality are shown. The rectangle represents the municipality of Tuxtla Gutiérrez, and the elements outside it are flows that are external to the municipality. As they are, renewable resources (sun, rain, nutrients), fuels and minerals (necessary for motorized vehicles), goods (such as vehicles), services, and other goods (federal investment for conservation of roads,

bridges, etc.). Figure 2 summarizes the main energy flows in the municipality of Tuxtla Gutierrez.

4. Simplification of the models to capture the main inputs and outputs to the system, as well as other flows that explain its internal functioning. For Tuxtla Gutiérrez, the flows of the system that appear in table 1 were considered:
5. Construction of a chart with the main eMergy flows.
6. Calculation of emergetics indexes (table 2).

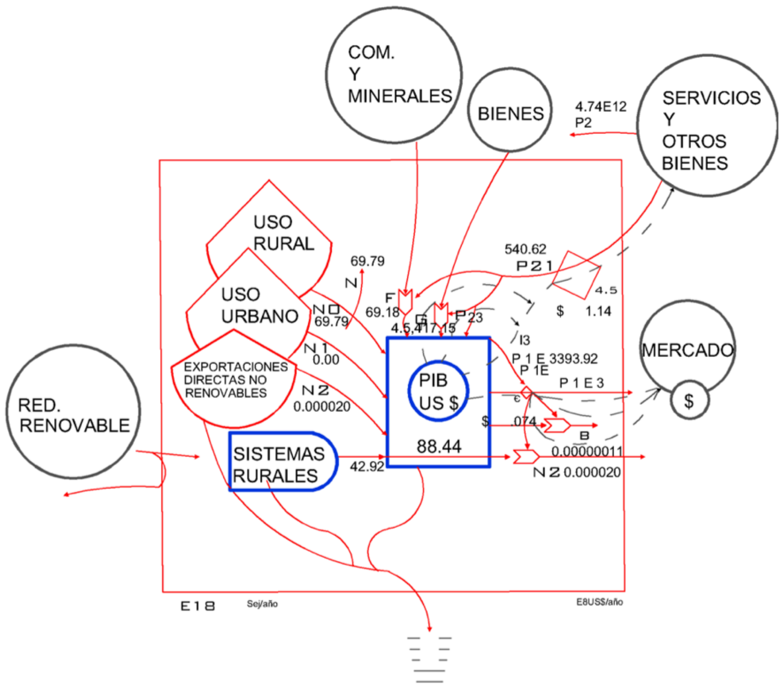


Figure 1. Tuxtla Gutiérrez' energy flows chart. Source: Own elaboration

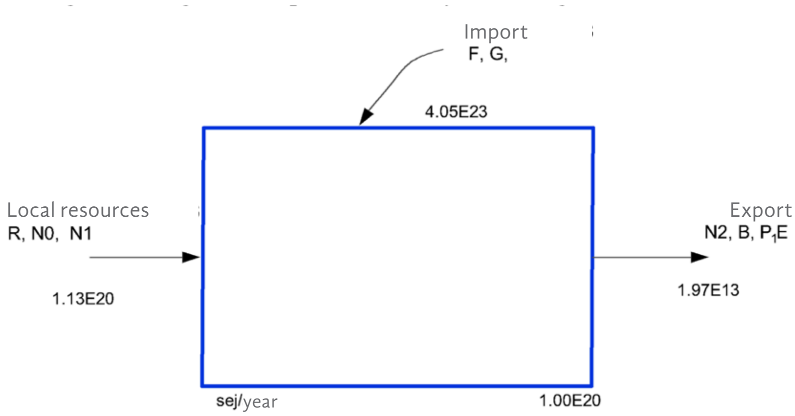


Figure 2. Tuxtla Gutiérrez' energy flows simplified chart. Source: Own elaboration

Table 1
Tuxtla Gutiérrez eMergy flows summary

Symbol	Item	Solar EMergía 1.00E+18 (sej/year)	Dollars 1.00E+18 (US$/year)
R	Renewable resources used (sun, rain, wind, etc.)	42.92	
N	Non-renewable resource flow within Tuxtla Gutiérrez	69.79	
	N0 Dispersed rural resource	69.79	
	N1 Internal consumption	0.00	
	N2 Exported without use	0.000020	
F	Imported fuel and minerals (includes services)	69.18	
G	Imported goods	405417.15	
I	Dollars paid for imports		1.14
P_2I	EMergy value of imported goods and services	540.62	
E	Dollars received from exports		0.74
P_1E	Emergy value of exported goods and services	3393.92	
B	Exported products processed in Tuxtla Gutiérrez	0.0000011	
X	Gross domestic product (GDP) of Tuxtla Gutiérrez		88.44
P_2	Chiapas' eMergy / Chiapas' GDP (used in imports)	4.74E+12	sej/US$
P_1	Tuxtla Gutiérrez' eMergy / Tuxtla Gutiérrez' GDP	4.59E+13	sej/US$

Source: Own elaboration

In table 1, it is observed that, according to its renewable resources, Tuxtla Gutiérrez contributes 42.92E + 18 sej/year, which is the sum of the energy of the sun, rain, wind, and the earth cycle. In the non-renewable resources heading, 69.79E + 18 sej/year were obtained, mostly contributed by the dispersed rural resource. These results indicate that Tuxtla Gutiérrez is a high importer of raw materials, that is, it does not take advantage of its non-renewable resources at all. The transformation (P2) of Tuxtla Gutiérrez (4.74E + 12 sej/US $) also appears in this table, this data was obtained from the total eMergy ratio of Chiapas, between the domestic product of Chiapas and the eMergy P1 (4.59E + 13 sej/US $), which was obtained by dividing the sum of dispersed natural resources (N0), plus domestic consumption of non-renewable resources, plus renewable resources used, plus imported goods, fuels and minerals between the gross domestic product of Tuxtla Gutiérrez, Chiapas. The general methodology of how to obtain these emergetical analyzes is described in detail by Odum in his book Environmental

Accounting (1996), being subsequently reviewed by Brown and Ulgiati (2004). Table 2 shows the emergetical indexes calculated for the municipal system. The heading of renewable eMergy flows contributes 4.29E + 19 sej/year and that the heading of non-renewable resources contributes 6.98E + 19 sej/year, which is much lower than the national contribution (2.21E + 25 sej/year) and the state (2.70E + 25 sej/year) (Ramos, 2016). This is explained because most of the territory is an urban area.

Table 2

Tuxtla Gutierrez emergetic indexes

Index	Expression	Quantity	Units
Renewable eMergy flow	R	4.29E+19	sej/year
The flow of local non-renewable reserves	N	6.98E+19	sej/year
Imported eMergy flow	F + G	4.05E+23	sej/year
Total eMergy entries	R + N + F + G	4.06E+23	sej/year
Total eMergy used (U)	N0 + N1 + R + F + G	4.06E+23	sej/year
Total eMergy exported	N2 + B	1.97E+13	sej/year
Fraction of eMergy used derived from local resources	(N0 + N1 + R) / U	0.000278	
Imports minus exports	(F + G) - (N2 + B)	4.05E+23	sej/year
Export to import rate	(N2 + B) / (F + G)	0.00000000005	
The ratio of local eMergy to total eMergy	R / U	0.00011	
EMergy acquired to total eMergy rate	(F + G) / U	0.9997	
Free eMergy to total eMergy rate	(R + N0) / U	0.00028	
Processed eMergy to free eMergy rate	(F + G + N1) / (R + N0)	3597.64	
EMergy per unit area (4.12E+08 m²)	U / area	9.84E+14	sej/m²
EMergy per capita	U / population	6.61E+17	sej/person
Total eMergy to GDP rate	P1 = U / PIB	4.59E+13	sej/$
Electricity to total eMergy rate (includes hydroelectric and thermoelectric)	Electricity / U	0.999	sej/year
Fuel use per capita (domestic consumption of natural gas and oil)	Fuel / population	5.98E+13	sej/year

Source: Own elaboration

The total exported eMergy is 1.97E + 13 sej/year, which is lower than the index at the state level, 2.57E + 25 sej/year (Ramos, 2016), which is explained because Tuxtla Gutiérrez exports very few goods and resources. This is confirmed by the index of imports minus exports, 4.05E + 23 sej/year, and the index of exports to imports 0.00000000005 units, close to zero, which indicate that the number of exports is much lower than that of imports. The relationship between local eMergy and total eMergy is an indicator of the use of natural resources, that is, how sustainable society is. In the case of Tuxtla Gutiérrez, this relationship is 0.00011 (0.011%), a very small index, so it is inferred that the city is not very sustainable. The amount of real wealth that circulates through the money reserve is indicated by the total eMergy rate index to GDP (P1), in this case, it was 4.59E + 13 sej/year, which shows the economic strength of Tuxtla Gutierrez. Finally, emergy spending per person was high, 6.61E + 17 sej/year.

CURRENT URBAN MOBILITY IN TUXTLA GUTIÉRREZ

The excessive use of owned cars has had a negative impact on the city since a chaotic circulation is generated, which directly influences the environment, the economy, and society itself, causing health problems due to pollution and environmental noise. This situation is exacerbated due to the poor quality of public transport and the disorderly growth of the urban area.

In 2011, the percentage of the modal distribution of transport was distributed 28% in private cars, 48% in public transport, and 24% in non-motorized active means, while government spending on urban transport was distributed 75% to cars, 11% to public transport and 3% to non-motorized transport (Municipal Government of Tuxtla Gutiérrez, 2014). This shows a clear tendency for governments to privilege the car over mass public transport, which inhibits the use of non-motorized means of transport and raises social and environmental costs in cities. Figure 3 shows the chart for general mobility energy flows of Tuxtla Gutiérrez.

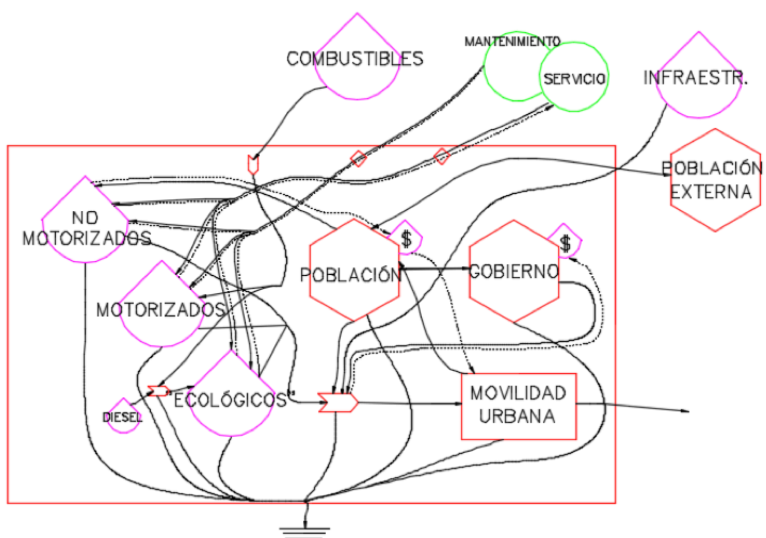


Figure 3. Simplified chart of Tuxtla Gutiérrez' mobility energy flows. Source: Own elaboration

Owned vehicles mobility eMergy analysis

Based on the flowchart in figure 3, we made a flowchart for the case of mobility by owned vehicles, in which the interaction of the flows in it is observed in more detail, from production to delivery operation and maintenance (see figure 4).

It can be seen that the chart in figure 4 emerges from the tank for Motorized Vehicles contained in figure 3, here all the flows that enter the system are shown: fuels -gasoline and oil in the case of owned vehicles-, machinery -which includes the production processes of the vehicle-, labor and services, infrastructure and maintenance -which considers roads, concrete and asphalt, payments, and contributions, which correspond to payments for vehicle ownership and insurance, to the state and federal governments -. All this results in the product of mobility to users. In the chart in Figure 4 there is no external renewable source flow -sun, wind, and rain-, this is because these flows are not required for mobility, since their main source of supply is fossil fuels.

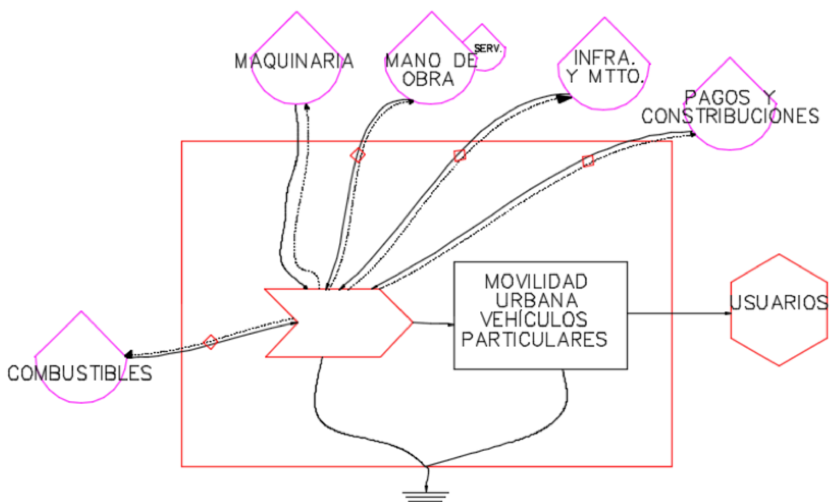


Figure 4. Simplified chart of mobility energy flows of Tuxtla Gutiérrez using owned vehicles. Source: Own elaboration

Taxi emergetic mobility analysis

Urban mobility through taxis involves the consumption of different material and intangible goods. The first consumption is that of space. Mobility demands space when the circulation infrastructure is built and when people use that infrastructure. The second consumption is energy, which in some societies is a scarce good. All motorized vehicles consume energy, from the vehicle production process to operation and maintenance, in addition to other factors that influence mobility such as unit depreciation and annual miles driven estimated by auto dealers. The third consumption is financial resources. This cost affects the government with the costs of road maintenance, signaling, operation, and inspection of traffic.

Figure 5 shows the flowchart in which the inputs of tangible and intangible goods appear, which are correlated with mobility. This diagram shows the interaction of flows, from production to operation and maintenance, and the salaries that the vehicle operator includes. It can be seen that the chart in figure 5 emerges from the tank of Motorized Vehicles contained in figure 3, here all the flows that enter the system are shown: fuels –gasoline and oil in the case of taxi-, machinery –which includes the production processes of the vehicle-, labor and services, infrastructure and maintenance -which considers roads, concrete and asphalt-, payments and contributions, which correspond to payments for vehicle ownership and insurance, to the state and federal governments.

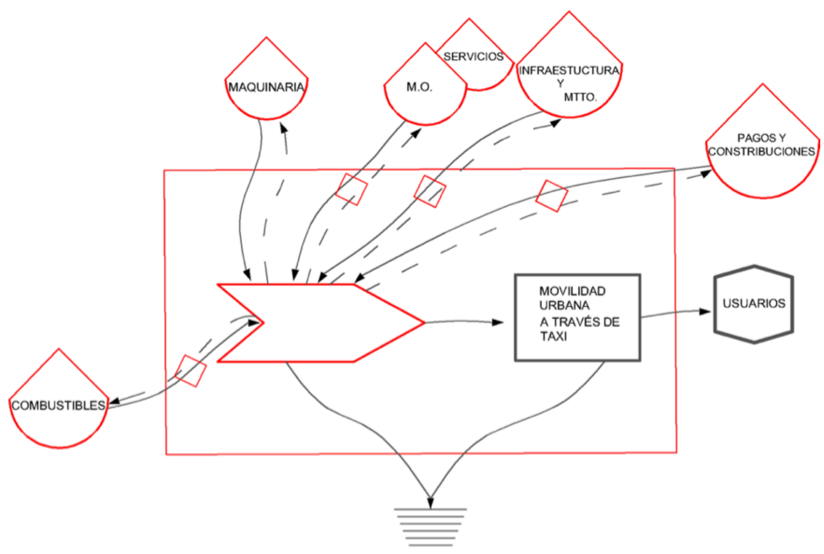


Figure 5. Simplified chart of mobility energy flows of Tuxtla Gutiérrez using taxis. Source: Own elaboration

In the case of taxis, service payments are considered, which include the salary of the unit's driver(s). All this results in the product of mobility to users. It is observed that in the diagram in figure 5 there is no flow from a renewable external source - sun, wind, and rain - since its main source of supply is fossil fuels. This chart is identical to that of figure 4 because private vehicles are acquired for taxi use, and they are adapted for public transport services as a taxi.

Bus mobility emergetic analysis

For this modality the same observations can be made as in the taxi modality, that is, space, energy, and financial resources are consumed. Therefore, the same methodology that was used in the analysis of owned vehicle mobility and taxi mobility was used. Thus, in figure 6 the flowchart for mobility through the bus is presented. This chart shows more precisely the interaction of the flows in it: production, operation, maintenance, and the salary of the unit operator.

For the chart in figure 6, the same observations can be made as for the chart in figure 4, that is, all the flows that enter the system are shown: fuels -gasoline and oil in the case of public transport-, machinery - that includes the production processes of the vehicle-, labor and services, infrastructure, and maintenance -which considers roads, concrete, and asphalt, payments, and contributions, which correspond to payments for vehicle ownership and insurance, to the state and federal governments. In the case of public transportation, payments for services that include the salary of the unit's driver(s) are considered. All this results in the product of mobility to users. It is observed that in the chart in figure 6 there is no flow from a renewable external source -sun, water, and rain-, this is since these flows are not required for mobility, since their main source of supply is fossil fuels.

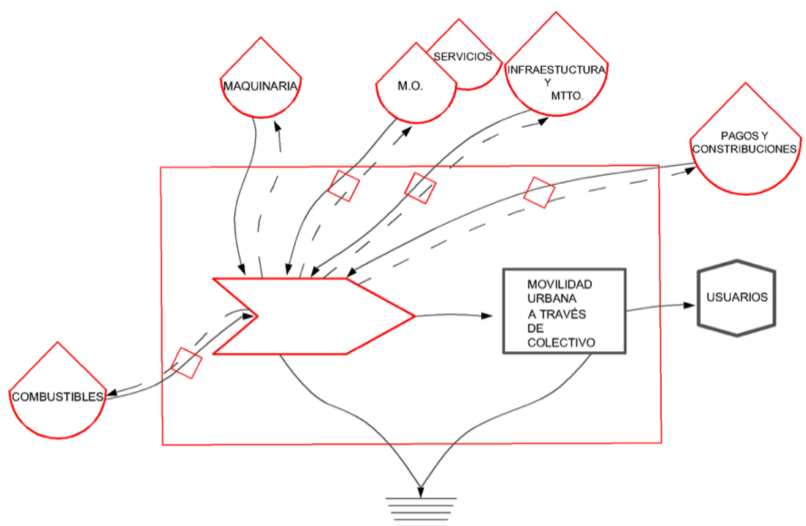


Figure 6. Simplified chart of mobility energy flows of Tuxtla Gutiérrez using public transport.
Source: Own elaboration

Conejobús mobility emergetic analysis

This is one of the most used means of transport in Tuxtla Gutiérrez, it is called *Conejobús* because the inhabitants of this city are known as rabbits (*conejos*). This means of transportation arose when the Chiapas government developed a program to replace 144 *combi*-type units on the main routes of Tuxtla Gutiérrez - routes 1 and 2-. With the *Conejobús*, an attempt was made to establish a more environmentally friendly transport system that would pollute less, stimulate the industry, promote the creation of new jobs and constitute a vision of the future to make cities with sustainable transport.

Urban mobility through the *Conejobús* involves the consumption of different material and intangible goods. The first consumption is that of space. Mobility demands space when there is a construction of circulation infrastructure and when people use said infrastructure. The second consumption is that of energy, which in many cases is a scarce good. Energy is consumed by all motorized vehicles, from the vehicle manufacturing process to operation and maintenance. The third consumption is that of financial resources. On the one hand, this cost affects the government, with road maintenance costs, signaling, operation, and traffic control. Figure 7 shows the flowchart for the *Conejobús* mobility.

This figure shows the interaction of flows, from operation and maintenance to the unit operator's salary. These flows are fuels -diesel and motor oil-, machinery -which includes the unit's production processes, contained in the import item-, labor and services, infrastructure, and maintenance. -this item considers roads, concrete, and asphalt-, and finally, payments and contributions, which correspond to payments for vehicle ownership and insurance, to the State Government and the Federal Government, respectively.

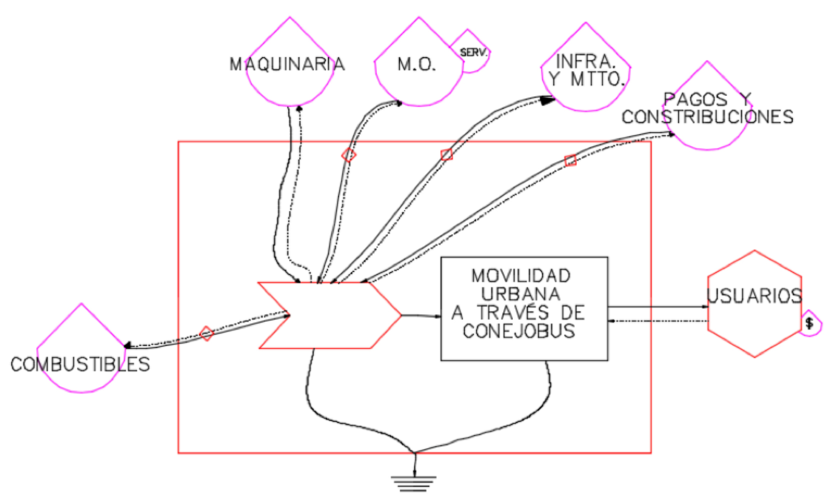


Figure 7. Simplified chart of mobility energy flows of Tuxtla Gutiérrez using *Conejobús*. Source: Own elaboration

It is observed that in this diagram there is no external renewable source flow - sun, wind, rain, etc.-, which is because these flows are not required for mobility, that is, the functionality does not depend on these resources but on fossil fuels.

Bike mobility emergetic analysis

Based on the Tuxtla Gutiérrez mobility flow chart (figure 3), the bike mobility chart is developed (figure 8). This last diagram shows the interaction of the flow, from production to operation and maintenance, as well as the roads used for circulation. In figure 3 the bike mobility alternative is contained within the heading "non-motorized" since the use of the bicycle does not require the use of a motor but rather the rider's strength and physical condition.

For this reason, a fuel item is not included, since the bike does not require it since it is more ecological mobility. The following flows are involved in mobility by bicycle: machinery supply -which includes the unit's production processes, contained in the import item-, labor and services, infrastructure and maintenance that considers concrete and asphalt roads, it is appreciated that there is no monetary section since anyone can use this mobility without having to pay for it - which makes it more attractive - as in the case of the previous modalities.

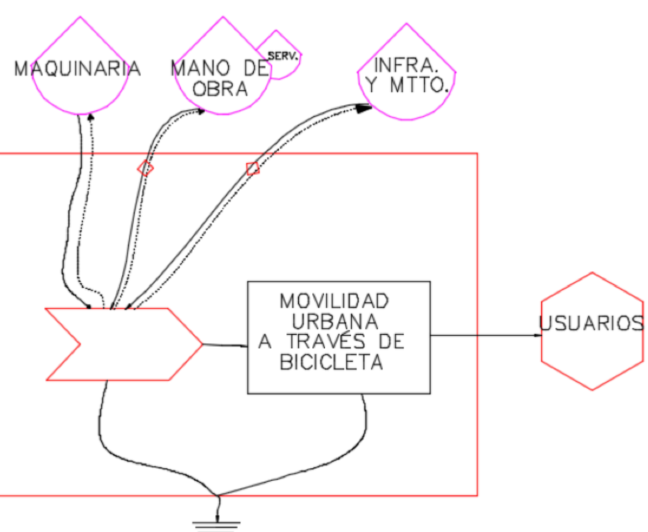


Figure 8. Simplified chart of mobility energy flows of Tuxtla Gutiérrez using bikes. Source: Own elaboration

It is observed that there is no external renewable source flow –sun, wind, rain, etc. -, since this type of ecological mobility does not use any of these resources because its operation is based on the rider's physical condition.

Motorcycle mobility emergetic analysis

Urban mobility by motorcycle involves the consumption of different material and intangible goods. The first consumption that this modality demands is space, this occurs in two situations: when there is a construction of circulation infrastructure and when people use said infrastructure. The second consumption is that of energy consumed by all motorized vehicles, from the vehicle's production process to operation and maintenance, in addition to other aspects such as the depreciation of the unit and the annual kilometers traveled. The third consumption is that of financial resources, which affects the government with the costs of road maintenance, signaling, operation, and traffic control.

The chart in Figure 9 shows the interaction of flows of this modality, from production to operation and maintenance. All the flows in the system are observed: fuels –gas and motor oil-, machinery - which includes the unit's production processes contained in the import item-, labor and services, infrastructure and maintenance –which considers roads, concrete and asphalt-, and payments and contributions –which correspond to payments for vehicle ownership and insurance, to the State and Federal Governments-.

It is appreciated that there is no monetary deposit because anyone can use this mobility without having to give a monetary reward. Neither is there a flow from a renewable external source - sun, wind, rain, etc. -, given that this mobility does not require these flows because it uses fossil fuels for its operation.

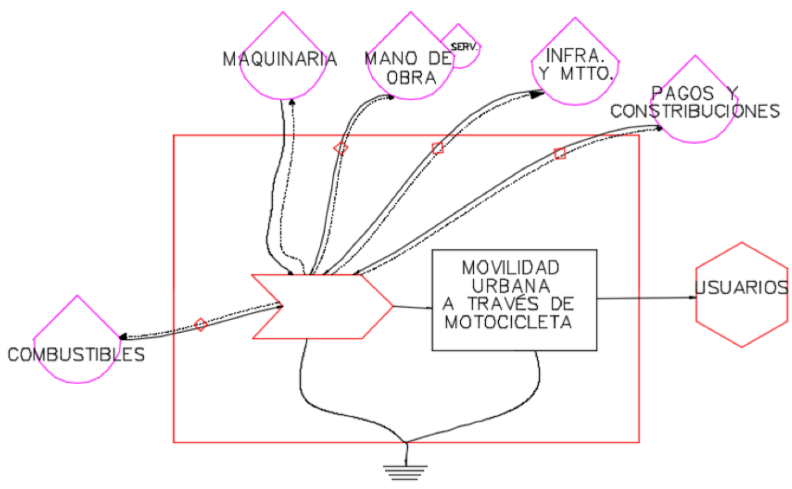


Figure 9. Simplified chart of mobility energy flows of Tuxtla Gutiérrez using motorcycles.
Source: Own elaboration

RESULTS ANALYSIS

Tuxtla Gutiérrez' urban mobility eMergency indexes

Table 3 summarizes the urban mobility indexes, obtained for the urban mobility modalities presented in the previous sections. This methodology, based on eMergy, has a technical and quantitative nature since all the flows involved in mobility are considered and translated into a common unit to be able to add them together. From this, the indexes that allow evaluating the sustainability of the current urban mobility system of Tuxtla Gutiérrez are calculated.

It can be seen in this table that the mobility that consumes the least eMergy is the bike, 22.19E + 16 sej/year, which represents 1.58% of the total eMergy consumed by the system. Followed by the motorcycle that contributes to the system 51.81E + 16 sej/year, 3.68% of the total, the private vehicle with 264.26E + 16 sej/year, 18.77% of the total, the taxi that contributes 290.26E + 16 sej/year, 20.62% of the total, the bus with 317.16E + 16 sej/year, 22.54% of the total and, finally, the Conejobús with 461.76E + 16 sej/year, 32.81% of the total.

The mobility modality that contributes the most eMergy to the system is the Conejobús, which is because much more eMergy is required for the unit's production, as well as more eMergy for its operation and maintenance (see graph 1).

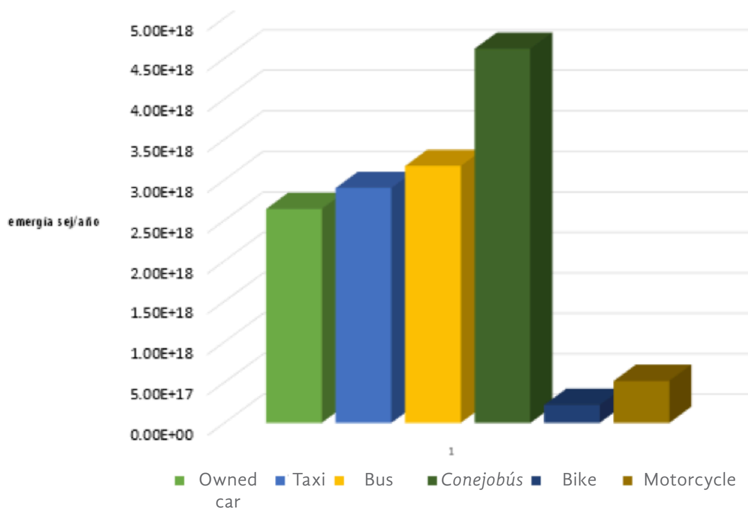
One of the most important indexes in table 3 is the eMergy index per kilometer per person per type of unit. This index makes it possible to directly compare the different alternatives, that is, the eMergy that each alternative contributes to the system, per person who occupies it, and per kilometer traveled by the units. According to the results obtained, it is observed that although the Conejobús contributes more eMergy to the system, it is the most efficient modality given that its eMergy index per kilometer per person is 1.46E + 12 sej/km/person, 0.6% of all the eMergy per kilometer per person of all the alternatives.

Table 3
Tuxtla Gutiérrez' urban mobility eMergy indexes comparative summary

Indexes		Unit	Owned car	Public transport in the modality of: Taxis	Bus	*Conejobús*	Bike	Motor-cycle
EMergy use by unit type	1.00E+16	sej/year	264.23	290.26	317.16	461.76	22.19	51.81
The economic component of eMergy acquired (M+S) by type of mobility (unit)	1.00E+15	sej/year	294.90	555.15	824.21	1850.47	6.41	17.80
EMergy economic component acquired (M+S) by all units	1.00E+18	sej/year	35752.00	2127.32	1695.39	146.19	8.27	26.70
Free eMergy ecological component (R+N) by type of mobility (unit)	1.00E+16	sej/year	234.74	234.74	234.74	276.71	21.55	50.03
Free ecological eMergy component (R+N) by all units	1.00E+18	sej/year	284589.39	8995.39	4828.68	218.60	278.25	750.44
Investment rate (econ/ecol) (M+S)/(R+N) by type of mobility (unit)			0.126	0.236	0.351	0.669	0.0297	0.0356
Investment rate (econ/ecol) (M+S)/(R+N) for all units			15230.21	906.23	722.23	52.83	38.38	53.36
ICA (Environmental Load Index) ((N+M+S)/R			Undefined	Undefined	Undefined	Undefined	Undefined	Undefined
Energy per kilometer per person per unit type per year	1.00E+12	sej/km/per	117.44	11.36	1.58	1.46	45.99	51.81
Energy per type of alternative per year	1.00E+12	sej/km	176.16	39.76	25.26	87.85	45.99	51.81
Total mobility eMergy by type of alternatives	1.00E+20	sej/year	3203.41	111.23	65.24	3.65	2.87	7.77
Total mobility eMergy through the different alternatives per person	1.00E+15	sej/year/per	802.58	942.06	48.05	7.42	221.94	518.09

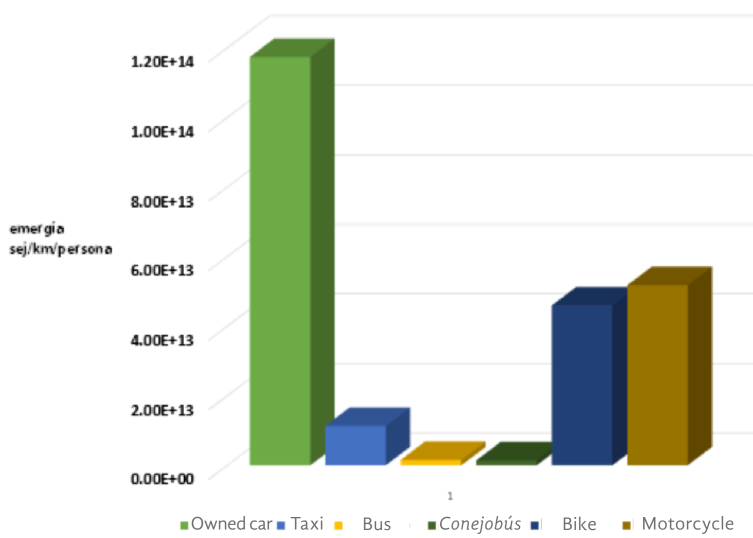
Source: Own elaboration

Similarly, the alternative that contributed very little eMergy was the bus (combi) with 1.58E + 12 sej/km/person (see table 3 and graph 2). This is because the occupancy rate and routes are high, that is, this type of urban mobility works approximately 16 hours a day, and with a capacity of 14 seats, which is why it is a more efficient mobility option. We must keep in mind that many factors do not allow this alternative to be fully exploited, among them the lack of maintenance of the units, drivers who drive without caution, and poor planning of the routes.



	Owned car	Taxi	Bus	*Conejobús*	Bike	Motorcycle
EMergy use U	**2.642E+18**	**2.903E+18**	**3.172E+18**	**4.618E+18**	**2.219E+17**	**5.181E+17**

Graph 1. Use of eMergy U in Tuxtla Gutiérrez' urban mobility. Source: Own elaboration

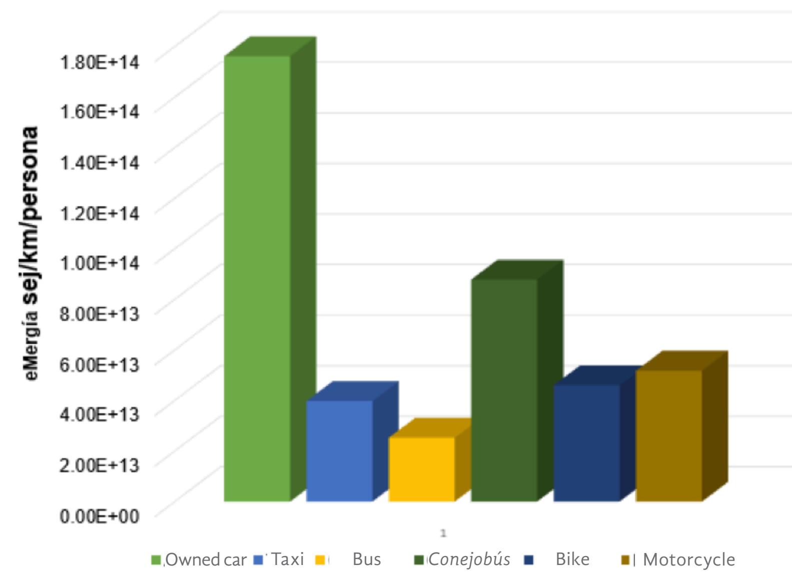


	Owned car	Taxi	Bus	*Conejobús*	Bike	Motorcycle
EMergy per kilometer per person per type of unit per year	**1.174E+14**	**1.136E+13**	**1.579E+12**	**1.464E+12**	**4.599E+13**	**5.181E+13**

Graph 2. EMergy/km/person index of urban mobility's different alternatives. Source: Own elaboration

The next alternative that contributes a low eMergy index to the system (see table 3 and graph 2) is the taxi, with 11.36E+12 sej/km/person, 4.9% of the total calculated index, 8 times more than the contribution from the *Conejobús*. It is also observed that, although the motorcycle and bike alternatives do not consume much energy for unit production, operation, and maintenance, nor fuel, they are the least efficient, since they contribute to the system 45.99E+12 sej/km/person (20% of the total) and 51.81E+12 sej/km/person (22.60% of the total) respectively. Finally, the least efficient alternative is that of the private vehicle, which contributes 51.1% of the total eMergy, this is because the occupancy rate is very low.

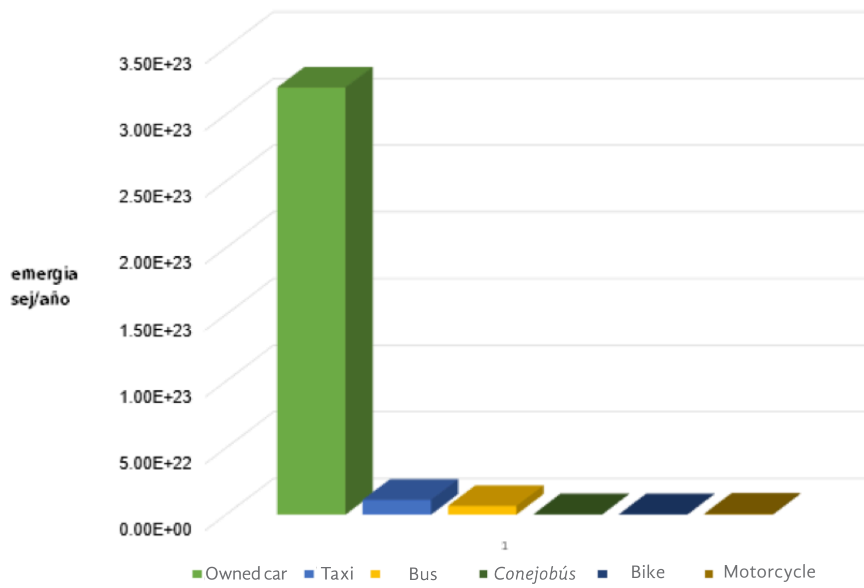
Table 3 also shows the eMergy index by type of alternative per kilometer, this calculation identifies which modality consumes more eMergy for each kilometer traveled daily. Although the bike is the alternative that consumes less eMergy in the system, it contributes a lot of eMergy per kilometer traveled, 45.99E+12 sej/km. The mobility alternatives that contribute the least eMergy to the system are taxi and bus, with 39.76E+12 sej/km and 25.26E+12 sej/km, respectively. It is observed that the bus is the modality that contributes the least eMergy to the system per kilometer traveled. Graph 3 shows these results.



	Owned car	Taxi	Bus	*Conejobús*	Bike	Motorcycle
EMergy per type of alternative per km	1.762E+14	3.976E+13	2.526E+13	8.785E+13	4.599E+13	5.181E+13

Graph 3. EMergy per km index of urban mobility's different alternatives. Source: Own elaboration

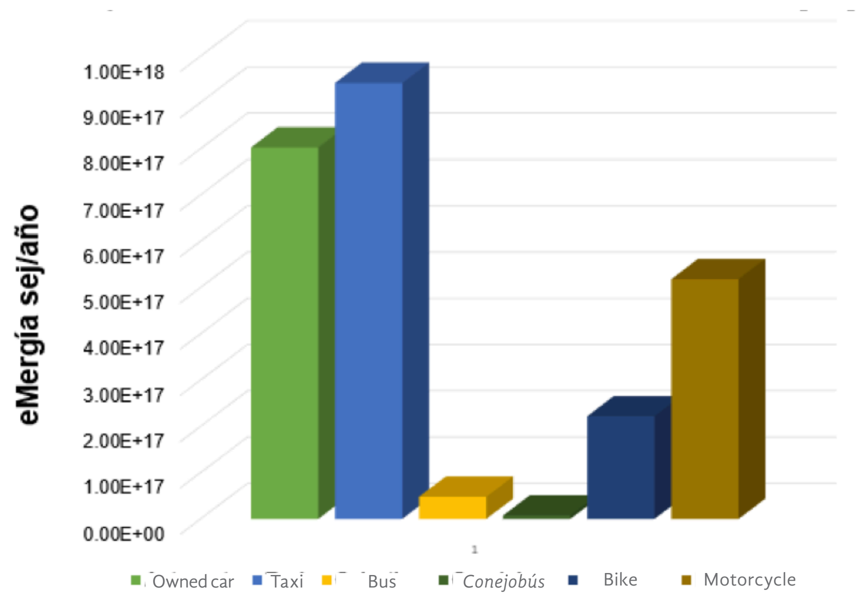
Two more indexes were calculated to know the footprint of all the urban mobility alternatives currently existing in Tuxtla Gutiérrez. The first index is the total eMergy of mobility by type of alternatives, for which it was obtained that the bike is the most efficient modality (see table 3), which is due to the reduced number of bikes that circulate in the city. This alternative contributes 2.87E+20 sej/year to the system, while the motorcycle contributes 7.77E+20 sej/year. Regarding public transport, the alternative that provides the most eMergy is the taxi (111.23E+20 sej/year), followed by the bus (65.24E+20 sej/year) and the *Conejobús* (3.65E+20 sej/year). As in the previously calculated indices, the alternative that contributes the most eMergy to the system is the private car with 3203.41E+20 sej/year. Graph 4 summarizes these results.



	Owned car	Taxi	Bus	*Conejobús*	Bike	Motorcycle
Total mobility eMergy per type of alternatives	**3.203E+23**	**1.112E+22**	**6.524E+21**	**3.648E+20**	**2.865E+20**	**7.771E+20**

Graph 4. Total mobility eMergy index per the alternatives type of urban mobility. Source: Own elaboration

The second index calculated is the total mobility eMergy of the different alternatives per person. It was found that the most efficient alternative was the Conejobús, which contributes 7.42E+15 sej/year/person to the system, followed by the bus that contributes with 48.05E+15 sej/year/person. Although the bicycle proved to be more efficient in some cases, it ranks third in efficiency since it participates with 221.94E+15 sej/year/person, an amount that is much higher than those of the Conejobús and the bus. In fourth place is the motorcycle, which contributes to the system 518.09E+15 sej/year/person, then there is the private car with 802.58E+15 sej/year/person, finally, the first place in inefficiency corresponds to the taxi that contributes with 942.06E+15 sej/year/person. It is worth mentioning that obtaining these two indexes, influences the amount of occupation of each alternative and the registered number of existing units for each modality greatly. This index is used to compare the amount of eMergy provided by each urban mobility alternative. Graph 5 presents these results.

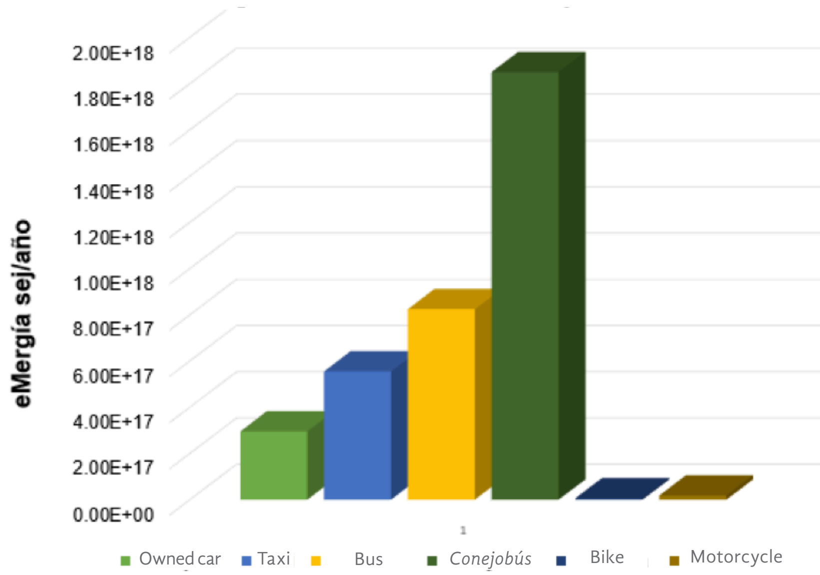


	Owned car	Taxi	Bus	*Conejobús*	Bike	Motorcycle
Total mobility eMergy through different alternatives per person	**8.026E+17**	**9.421E+17**	**4.805E+16**	**7.415E+15**	**2.219E+17**	**5.181E+17**

Graph 5. Total mobility eMergy index through different alternatives per person. Source: Own elaboration

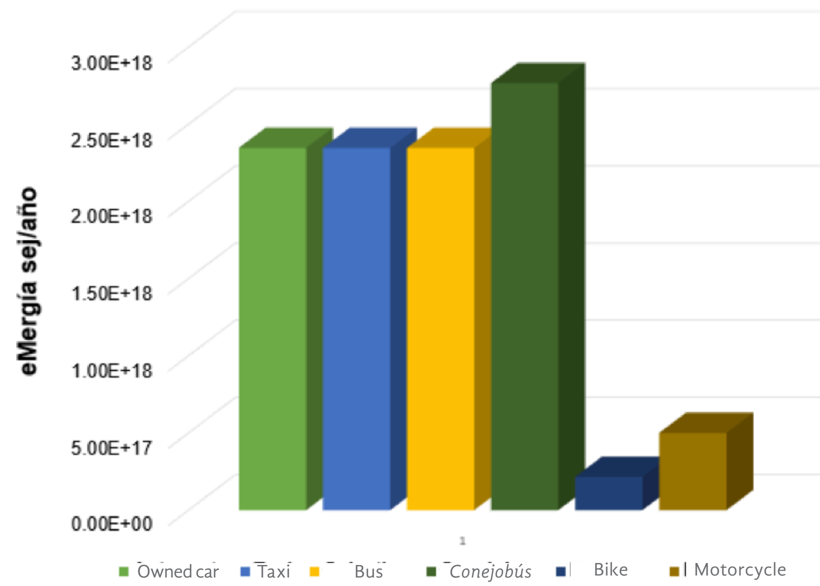
Graph 6 shows the results for the economic component index of acquired eMergy (M+S) by type of mobility. It is observed that the bicycle is the alternative that contributes the least eMergy to the system with 6.41E+15 sej/year, which indicates that this modality consumes little eMergy in terms of the purchase of inputs, a characteristic that makes it attractive. The private vehicle contributes with 294.90E+15 sej/year, the motorcycle participates with 17.80E+15 sej/year, the taxi with 555.15E+15 sej/year, the bus with 824.21E+15 sej/year, and the Conejobús with 1850.47E+15 sej/year, this last alternative is the one that contributes the most eMergy to the system.

Regarding the ecological component (R+N), the alternative that contributes less eMergy to the system is the bike with 21.55E+16 sej/year. Next is the motorcycle with 50.03E+16 sej/year, while the Conejobús participates with 276.71E+16 sej/year. Finally, the alternatives of the private vehicle, taxi, and bus have the same emergetic contribution 234.74E+16 sej/year. It should be mentioned that, in the urban mobility of the city of Tuxtla Gutiérrez, Chiapas, renewable sources of energy do not intervene, for this reason, only non-renewable sources were considered in the calculations. Graph 7 summarizes these results.



	Owned car	Taxi	Bus	*Conejobús*	Bike	Motorcycle
Acquired eMergy economic component (M+S), per type of mobility	**2.949E+17**	**5.551E+17**	**8.242E+17**	**1.850E+18**	**6.408E+15**	**1.780E+16**

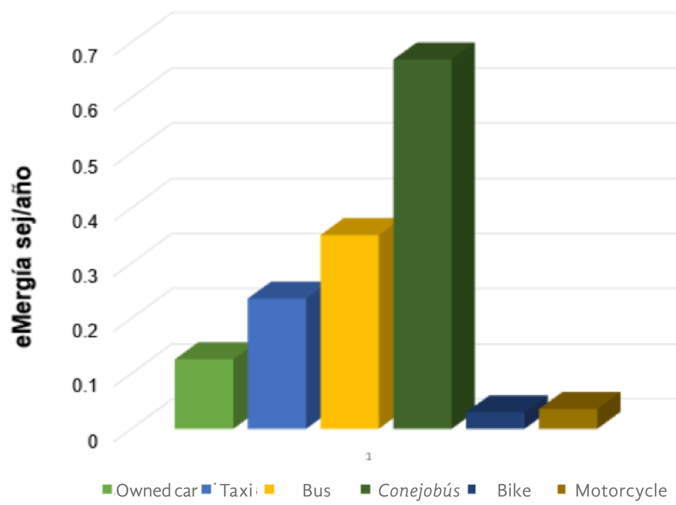
Graph 6. Unit eMergy economic component (M+S). Source: Own elaboration



	Owned car	Taxi	Bus	*Conejobús*	Bike	Motorcycle
Free eMergy ecologic component (R+N), per type of mobility	**2.347E+18**	**2.347E+18**	**2.347E+18**	**2.767E+18**	**2.155E+17**	**5.003E+17**

Graph 7. Unit eMergy ecologic component (R+N). Source: Own elaboration

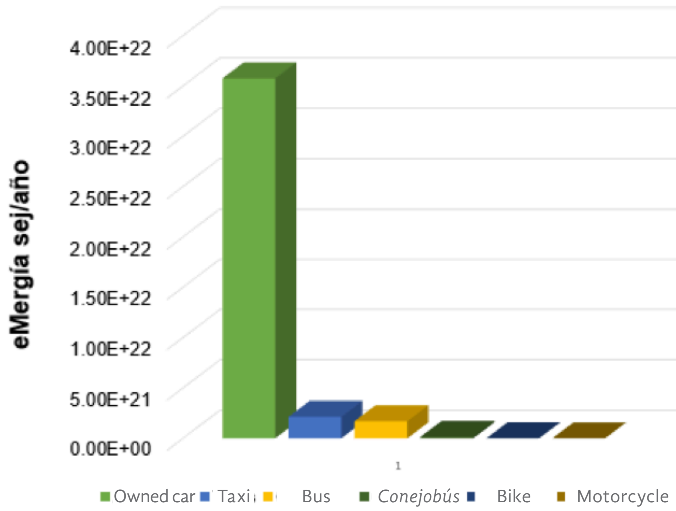
The results for the investment rate (IT) are presented below. It is appropriate to mention that the larger the index, the more it depends on purchased or imported inputs than on local resources. Graph 8 shows that the alternative with the lowest investment rate is the bike with 0.0297, followed by the motorcycle with 0.0356. In third place is the private vehicle whose investment rate is 0.126. The taxi shows an investment rate of 0.236, the bus of 0.351, and the Conejobús of 0.669. As seen, the Conejobús has the highest investment rate.



	Owned car	Taxi	Bus	*Conejobús*	Bike	Motorcycle
Investment rate (econ/ecol) (M+S)/(R+N) per type of mobility	**0.126**	**0.236**	**0.351**	**0.669**	**0.030**	**0.036**

Graph 8. Unit investment rate (M+S)/(R+N). Source: Own elaboration

The results of the economic component of the acquired eMergy (M+S) index for all mobility in general in its different alternatives are shown below (see graph 9). Once again, the bike is the alternative that contributes the least eMergy to the system with 8.27E+18 sej/year, a result that indicates that in this mobility alternative (where the total number of registered bikes is considered), too much eMergy is not consumed in the purchase of inputs. The motorcycle modality contributes with 26.27E+18 sej/year, the taxi with 217.32E+18 sej/year, the bus with 1695.39E+18 sej/year, and the Conejobús with 146.19E+18 sej/year. The Conejobús is the one that contributes the least eMergy to the system, unlike what was found for the unit calculation (graph 7) where this alternative was the one that contributed the most eMergy. Finally, the private vehicle participates with 35752.00E+18 sej/year, the highest contribution of eMergy to the system.

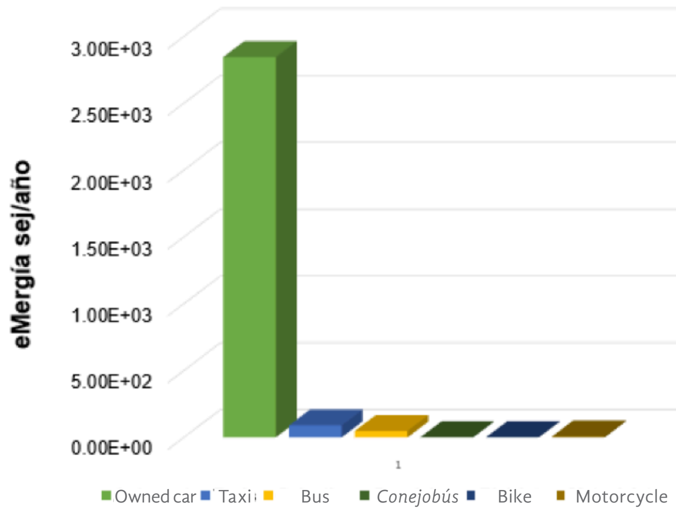


	Owned car	Taxi	Bus	*Conejobús*	Bike	Motorcycle
EMergy economic component (M+S), per all units	**3.575E+22**	**2.127E+21**	**1.695E+21**	**1.462E+20**	**8.272E+18**	**2.670E+19**

Graph 9. EMergy economic component (M+S) per all units. Source: Own elaboration

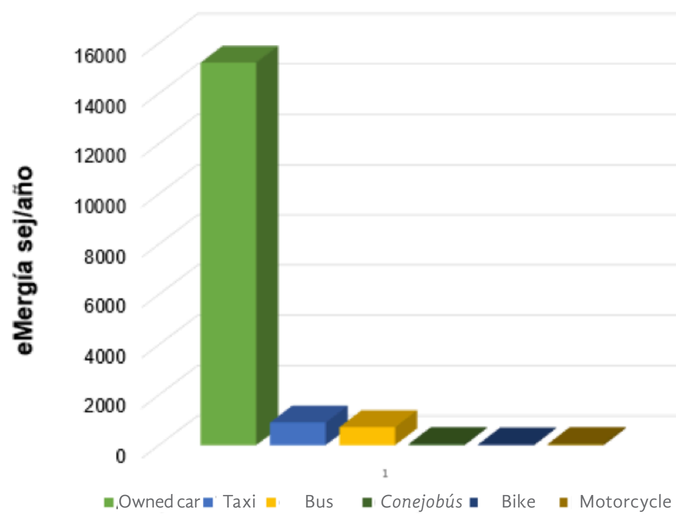
Graph 10 summarizes the results for the ecological component (R+N) of all the existing alternatives. The modality that contributes the least eMergy to the system is the *Conejobús* with 218.60E+18 sej/year, followed by the bike that contributes with 278.25E+18 sej/year. The motorcycle participates with 750.44E+18 sej/year, the private vehicle is the alternative that contributes more eMergy to the system with 284589.39E+19 sej/year. The taxi participates with 8995.39E+18 sej/year and the bus with 4828.68E+18 sej/year. It should be mentioned that the alternative that contributes less eMergy to the system is the *Conejobús* and not the bike, which is because there are fewer *Conejobús* buses units than bicycles. That is, if there were more registered *Conejobús* units, the index obtained would have been higher. It should be noted that urban mobility modalities do not use renewable sources of energy, therefore only the non-renewable source was considered.

Next, graph 11 presents the results for the investment rate (TI). It is appropriate to indicate that the larger the index, the greater the amount of eMergy purchased per resident eMergy unit, that is, the higher the index, the more dependent it is on purchased or imported inputs than on local resources. It can be seen that the bike is the alternative with the lowest investment rate with 38.38, followed by *Conejobús* with 52.83, this last contribution was greater in the unit evaluation (graph 8) than in the evaluation for all units (graph 11). Next, the motorcycle with an investment rate of 53.36, the bus with 722.23, the taxi with 906.23, and the private car with 15230.21, again this last modality is the one with the highest investment rate.



	Owned car	Taxi	Bus	*Conejobús*	Bike	Motorcycle
EMergy economic component (M+S), per all units	**2.846E03**	**8.995E+01**	**4.829E+01**	**2.186E+00**	**2.783E+00**	**7.504E+00**

Graph 10. EMergy ecologic component (R+N) per all units. Source: Own elaboration



	Owned car	Taxi	Bus	*Conejobús*	Bike	Motorcycle
Investment rate (econ/ecol) (M+S)/(R+N) per all units	**15230.21**	**906.23**	**722.23**	**52.83**	**38.38**	**53.36**

Graph 11. Investment rate (MS)/(R+N) per all units. Source: Own elaboration

CONCLUSION

The growing use of petroleum-derived fuels, together with current mobility patterns in Tuxtla Gutiérrez, has a significant influence on the city's environmental environment. This situation affects climate change, global warming, the deterioration of the ozone layer, air and noise pollution, and particularly in the population that travels daily to carry out their daily activities. In all this, the transport sector has a high share of responsibility since it causes non-sustainability in urban mobility in Tuxtla Gutiérrez.

According to the results presented in this work, it is concluded that the current urban transport system, in its different modalities, is not sustainable. It was found that the alternative mobility that consumes the least eMergy is the bicycle with 22.19 E+16 sej/year, which represents 1.58% of the total eMergy consumed by the system. In contrast, the alternative mobility that consumes the most eMergy is the Conejobús with 461.76 E+16 sej/year, 32.81% of the total eMergy. The calculation of the eMergy index per kilometer per person by the type of unit shows that the Conejobús is the most efficient modality given that the eMergy index per kilometer per person is 1.46E+12 sej/km/person, 0.6% of all the eMergy per kilometer per person of all the alternatives. In second and third place are the bus (1.58E+12 sej/km/person) and bikes (45.99E+12 sej/km/person), 0.7% and 20% respectively of the total.

The eMergy index by type of alternative per kilometer allows us to identify that the alternative that contributes the most eMergy to the system is the private vehicle 176.16E+12 sej/km (41.27%), followed by public transport and motorcycles, with emergetic contributions, respectively, of 87.85E+12 sej/km (20.58%) and 51.81E+12 sej/km (12.14%). It was found that although the bike is the alternative that consumes the least eMergy of the system, it contributes a lot of eMergy per kilometer traveled, 45.99E+12 sej/km (10.77%). The results for the total eMergy mobility index by type of alternatives indicate that the bicycle is the most efficient modality, with 2.87E+20 sej/year (0.08%), followed by Conejobús 3.65E+20 sej/year (0.11 %), and by the motorcycle 7.77E+20 sej/year (0.23%). As with the previous indexes, the alternative that contributes the most eMergy to the system is the private car with 3,203.41 E+20 sej/year (94.38%). On the other hand, the index of the total eMergy mobility of the different alternatives per person indicates that the most efficient alternative is the Conejobús, which contributes to the system 7.42E+15 sej/year/person (0.29%), followed by the bus which contributes 48.05E+15 sej/year/person (1.89%). Although the bike proved to be more efficient in some cases, it occupies the third place in efficiency since it participates with 221.94E+15 sej/year/person (8.74%), an amount that is much higher than those of the Conejobús and the bus. It must be kept in mind that urban mobility must be economic, ecological, and equitable. The intersection of these three conditions supposes an environment in which it is possible to live better or with a certain quality of life, a situation that Tuxtla Gutiérrez does not comply with. As has been shown, most of the inhabitants of this city prefer the use of internal combustion vehicles, particularly their owned cars, which implies a great consumption of space and energy. In addition, the use of these vehicles causes polluting emissions, noise, traffic accidents, and road congestion. Consequently, it is confirmed that the urban mobility of Tuxtla Gutiérrez is not sustainable.

This situation can be reversed, or at least slow down its growth, taking into account the following recommendations: reducing the use of imported resources and increasing the use of renewable energies, reducing energy consumption in transportation, mainly owned vehicles - to reduce its eMergy-, delay or stop urban dispersion to avoid long routes, create multimodal transport systems -according to the rates obtained-, that is, create a transport system in which the entry of private vehicles is not allowed in the areas of greater circulation, make public transport more efficient and create the adequate infrastructure for the massive use of bikes, which, according to the results achieved, is the most convenient alternative for urban mobility.

It should be remembered that the bike is the most convenient option for traveling short distances and that public transport is the most convenient option for traveling long distances. Thus, it would be convenient for Tuxtla Gutiérrez to integrate these two modalities so that people can make long trips door to door without having to use private vehicles. Integrating bikes with public transport implies having places to store bikes in bus stations or places close to them and enabling these systems so that people can transport their personal bikes through different areas of the city. The intention is that users of one mode or another stop using their private vehicles and start using public transport and bikes. A future line of work should propose this multimodal transport system, to articulate these two means of transportation, and thus be able to carry out the operations of transferring people more quickly and efficiently, considering the rates calculated in this work. Additionally, it is suggested that together with the emergetical analysis of urban mobility modalities, life cycle analyses (LCA) be carried out with units of equivalent tons of carbon dioxide emitted per unit of mobility per kilometer per person per year, to have another more direct measurement method that relates the effect of mobility with climate change.

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