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Transport Sustainability Index: An Application Multicriteria Analysis

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Abstract: The unrestricted consumption of fossil fuels negatively impacts the economic, social and environmental aspects, observed from a sustainable perspective. Therefore, it is necessary to develop and adopt skills that enable the monitoring and mitigation of risks to the environment. In view of this, we propose a method with multiple approaches emphasizing a three-dimensional perspective of energy consumption by diesel engines, which represent one of the main pollutants emitters in transport. As a methodology, fuzzy logic was adopted, together with a recognition system, in order to mitigate the uncertainties inherent to the applied data. The procedure was applied to the city of Rio de Janeiro, Brazil, with information collected from seven toll plazas and a radar with volumetric counting. The results indicate a good adherence of the sustainability index to real cases, allowing a better observation of changes in environmental criteria and a more efficient inspection in the application of good practices, in addition to enabling greater participation of society in the inspection and adoption of environmental criteria in transport.

Keywords: sustainable transport; sustainability index; recognition system; fuzzy logic; diesel

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1. Introduction

Population growth and concentration in urban centers increase the demand for services and, consequently, intensify the problems faced by cities. In terms of urban mobility, it can be said that such an increase calls for a transport system that promotes social well-being and quality of life, which requires changes and innovation among the interested parties [1]. By definition, transport represents the movement of passengers and/or freight, from one place to another at a given time [2–4], with a significant influence on access to other activities. However, this dynamic requires a high consumption of energy and materials that affect the conditions of the environment. As for the Brazilian scenario, the situation is further aggravated by the deficiency of proper transport policies, favoring the participation of road transport with the significant participation of trucks for the distribution of goods, in addition to the individual motorization for passenger transport [5].

According to Ferreira et al. [6], the annual consumption of primary energy fuel in Brazil is equivalent to 204 MtCO2e, with freight transport being responsible for 50% of greenhouse gas (GHG) emissions. In 2019, passenger transport represented approximately 20% of the fossil energy consumed in the country, especially in urban areas [7]. It should be noted that, as it is more energy efficient compared to gasoline [8], diesel remains the most used fuel in the Brazilian transport sector, with a share of 49% in 2019, projected to reach

51% in 2031 [9]. This fuel, however, is characterized by being one of the main emitters of carbon dioxide (CO_2), nitrogen oxide (NOx) and particulate matter (PM), which directly contribute to environmental degradation and have harmful effects on human health [10]. The impacts caused by atmospheric pollution produce an imbalance that, depending on the scale, can be irreversible [1,11].

In the environmental aspect, the adoption of fossil fuels, in an unrestricted way, leads to climate change and a decrease in air and soil quality. In social terms, the damage is related to respiratory and cardiovascular diseases, allergies and premature deaths [12]. In 2012, diesel-related emissions were recognized as carcinogenic by the World Health Organization [13]. Economically, losses can reach billions of dollars a year, as pointed out by a study prepared by [14], in partnership with the European Public Health Alliance (EPHA). It is clear then that regulations and skills development become gradually more necessary for the mitigation and monitoring of the risks to the environment [15,16]. Thus, to achieve sustainable development, it is necessary that infrastructure and urban services, such as transport, be treated as public and limited resources, whose planning covers the three dimensions of sustainability in an integrated way: environmental, social and economic [17]. Furthermore, sustainable transport planning recognizes that transportation decisions affect the whole society, so impacts should be considered in the planning [18], monitoring and control processes.

Therefore, the present research focuses on demonstrating a three-dimensional perspective of the aspect of energy consumption by diesel engines, with emphasis on fuzzy logic as an evaluation criterion. As input variables, the balance of vehicles, traveled intensity and fuel consumption are considered in a study applied in the city of Rio de Janeiro, Brazil. The objective is based on the description of a recognition system using the triple result in order to reduce the differences in government data, per year, combined with an analysis of regional efforts to neutralize the impacts arising from diesel emissions. It is understood that the use of multiple approaches allows the reduction of uncertainties in the results and more targeted actions of prediction and control [19].

The main contributions of the paper are as follows: (i) a sustainability index at the municipal level for road transport, considering the aspect of energy consumption by diesel engines; (ii) support for researchers, transport agents and government institutions in the process of evaluating and applying good practices since the method reduces data imprecision; and (iii) assistance in the decision-making and the development of emission reduction policies.

The rest of this work is structured as follows. Section 2 indicates the importance of fuzzy logic, associated with recognition systems, in the creation of monitoring indices and metrics, highlighting some studies in the literature on the subject. Section 3 describes the proposed methodological procedure. Section 4 presents the results and analyses. Finally, Section 5 clarifies the conclusions and recommendations for future research.

2. Evaluation of Emissions with Fuzzy Logic

For environments with multiple decisions and results, the principles of fuzzy logic have a certain advantage over other closed systems, since they work with the concept of a partial truth [20]. The diffuse approach becomes relevant in situations where there is no availability of a conventional model for measurement or in more complex cases, in addition to enabling the reduction of uncertainties and subjectivity [21], the application of fuzzy logic reduces interference from temporal outliers, allowing moderate results with the use of several variables. However, although it allows dealing with the imprecise nature of some variables, its use is not limited only to these cases, also contemplating known and precise aspects to a certain extent for decision-making and the development of intelligent systems [22].

The recognition system, in turn, is a means of establishing balance patterns in relation to the aspects considered, in the case of this study, in terms of vehicle flow, intensity traveled and fuel consumption for diesel transport. This reference identifies the relationship between the increase in emissions and energy consumption, knowing that there is a strong correlation between these factors. Thus, together with the fuzzy logic, these systems point to a more realistic analysis of the occurrences, with emphasis on a more visual panorama that is easy to understand by those involved in the process and, consequently, of better applicability.

The biggest criticism, when there is a qualitative request in the decision-making, is related to the human decision, because the definition of the importance for each input variable is related to the accumulation of information on each decision maker, in this case, the decisions are influenced of behavioral factors related to experience, costs, strategy, etc., so that fuzzy logic reduces the overlaps of indicators and attributes [15]. In the impossibility of classifying some indicators in the face of human judgment, even knowing the necessary information, fuzzy logic allows knowing the linguistic variables and the membership functions for decision-making between the intermediate responses.

With regard to pollutant emissions, different studies in the literature show the adoption of fuzzy logic to monitor impacts. A study is developed to investigate the risk of possible failure modes [22], causes and effects of a device that quantifies carbon dioxide and methane emissions, based on the failure mode and effect analysis methodology. (FMEA) and fuzzy logic. The development of a tool to monitor air pollution is discussed, considering the artificial intelligence of fuzzy logic for gas sensors that clarifies the presence and concentration of monoxide and/or carbon dioxide efficiently [23]. A decision support tool is presented that uses the fuzzy logic of specialized knowledge to assist in the mitigation of CO_2 emissions in maritime transport, based on energy efficiency measures [24]. A predictive analysis of emissions in transport by buses powered by biodiesel is performed, considering the neuro-diffuse methodology in real time and the parameters of rotation per minute, temperature and absolute pressure [25]. A survey is conducted to assess sustainability performance in the environmental and social dimensions of a sustainable freight transport system [26]. To this end, a multi-criteria analysis is proposed for improving decision-making based on fuzzy logic, which allows for classifying the performance of each attribute in the model. Performance indices related to transportation, activities and the environment were collected to assess the overall sustainability of the transport system [27]. A fuzzy logic approach was used to reduce the imprecision and complexity of the information when calculating the proposed indicators. The method proved to be efficient for a broader perspective and the analysis of multiple systems. Pollutant emissions and fuzzy logic are also addressed in a study focused on maritime transport [28], where a method for optimizing the route and speed of lines ships is presented. Then, in order to minimize the total fuel cost and sulfur dioxide emissions, a combination of a two-stage iterative algorithm with the fuzzy logic method is performed.

As a differential, the present research presents the adoption of fuzzy logic from a three-dimensional perspective, together with the concept of a recognition system, for the evaluation of pollutant levels in road transport by diesel engines. Such a proposal allows us to understand the impacts from this fuel as well as the pattern over the years, in addition to proposing a reference metric for decision-making, which helps in the control and mitigation of the verified damages.

3. Methodology

The research proposal is to develop a sustainability index that uses regionalized data on the balance of vehicles on the city limits, intensity traveled and diesel consumption. The result is intended to support decision-making by managers in relation to the main attributes of CO_2 emissions in road transport with a focus on diesel consumption.

The methodological process is divided into two approaches: (i) the first in the characterization of data on the balance of vehicles at borders, intensity traveled and diesel consumption through circulation in a specific space and time. These data are specific to each city, as the modes and types of transport have characteristics that make standardization difficult. Refs. [29–32] highlights the difficulty of standardizing a model to assess emissions in cities, as each one has specific characteristics for data stratification, in which the focus must be on the methodological process; (ii) the second in the inference of the data with the application of fuzzy logic that allows us to know the linguistic variables and the functions of relevance for the taking of decisions between the intermediate answers. Fuzzy logic has the purpose of mitigating human errors [33], identifying and weighing the main variables [34], verifying and internalizing best practices [35]. The method is oriented towards the use of field data, but there are difficulties in obtaining them, so we recommend the use of representative references of a region through reports prepared by reliable institutions. The accuracy of the study depends on the reliability of the database and the source of previous reports and publications [36–38].

3.1. First Approach—Definition of Input Variables

This approach was divided into three distinct dimensions with data from different sources. This process avoids errors and statistical violations such as autocorrelation in formulating the results.

3.1.1. Vehicle Balance

Data on the balance of diesel vehicles in circulation on the city limits (*VB*) in space and time (*s.t*) are essential to reach the result, as the same vehicle can be counted several times. In the city of Rio de Janeiro, the fleet of diesel vehicles (*FD*), the balance of diesel vehicles entering (*BDE*) and the balance of diesel vehicles leaving (*BDS*) in the main toll plazas and radars at the ends of the city. This was important to measure the balance of flow-adjusted diesel vehicles (VB^A) circulating in the city limits through the flow rate of diesel vehicles (*RtD*). The result allows a knowing of how much of the fuel sold was actually consumed within the city and the commute movement of vehicles, demonstrated in Equations (1) and (2). With this, direct and indirect emissions from transport can be observed. Part of diesel emissions are destined for heating and electricity generation [39].

$$RtD_{s.t} = [(BDS - BDE)/FD] \tag{1}$$

$$VB^A = VB \cdot (1 - RtD) \;\therefore\; VB^A = [(BDS - BDE) \cdot (1 - RtD)] \tag{2}$$

3.1.2. Intensity Traveled

The second step is to calculate the average intensity traveled (*IT*), in km, by diesel vehicles in the city adjusted according to the flow rate of diesel vehicles (*RtD*). The data on the travel intensity of the road transport of passengers (*ITP*) and freight (*ITF*) are presented in Equation (3). The result was obtained by discounting the flow rate of diesel vehicles in relation to the intensity traveled.

$$IT_{s.t} = (ITP + ITF) \cdot (1 - RtD) \tag{3}$$

3.1.3. Diesel Consumption

The third step is used to measure diesel consumption in road transport. The top-down process can be used, but more accurate results are obtained from bottom-up data. Diesel consumption in transport (*DC*) is the product of the total volume of diesel sold (*DS*) discounting the flow rate of diesel vehicles.

$$DC_{s,t} = DS \cdot (1 - RtD) \tag{4}$$

The results of each dimension have different scales, so we normalized the data in order to compare the balance of vehicles, intensity traveled and diesel consumption on the same scale, always comparing the current moment between the periods of the maximum (worst scenario) and minimum (best scenario). The normalized result of each period of the dimensions corresponds to the input variables (*IV*) of the fuzzy logic, represented in

Equation (5). The input data were defined in the interval [1, 5]. This was useful to simplify the fuzzy relationship in the universe of discourse.

$$Norm_{IV} = 1 + \left[\left(\left(\frac{(IV_t - Min_{VE})}{(Max_{IV} - Min_{IV})} \right) \cdot 4 \right] \quad (5)$$

3.2. *Second Approach—Application of Fuzzy Logic*

The sustainability index must support the most important dimensions in transport, each one having a weight in relation to the operations. In this case, they are treated symmetrically. Traditional fuzzy logic has a high computational cost [40]. Since the proposed model must be used on bordering roads, instead of treating each indicator as an independent set, we decided to treat each transport sustainability dimension as a set, forming three input variables for the inference process. Decision-making with three indicators allows for reducing the cost of use and facilitates the knowledge of users [15].

Fuzzification, Inference and Defuzzification

The evaluation of the sustainability index in transport was checked in three dimensions. Each one had values with regional characteristics that cannot be standardized. However, the balance of vehicles, intensity traveled and diesel consumption were the dimensions that had the greatest impact based on the literature review, allowing a knowing of the effects of CO_2 emissions in the atmosphere. The sustainability index allows society to follow changes in a simplified way. Since the model is symmetrical, improving one indicator over another does not allow for higher gains in sustainability.

The classical variables u formed by d_i dimensions were transformed into a set of linguistic terms from the universe of discourse, where U represents the set of u variables for responses with levels from 1 to 5 ($d_i \subseteq U$), using the membership function μd_i: $U \rightarrow [0, 1]$. Therefore, the w represents the modification of the u variables to expand the universe of discourse to the range of 1 to 10. The sets $\mu w_i = 1, 2, \ldots, n$ in U were obtained by the fuzzification processes according to Equation (6), through the normalized data v as the input variables, where $\mu w(d_i)$ represents the degree to which the element d_i belongs to the fuzzy set $\mu(w)$. The formation in a single term formed by the set of questions for each aspect was necessary to reduce the cost of data processing. $Norm_i = v$ is the result of each dimension in *s.t* as input variables. The input variables of the universe of discourse $U_i = (u_1, u_2, \ldots, u_i)$ to obtain the fuzzified output variables $W_i = (w_1, w_2, \ldots, w_i)$, defined in the interval [0, 10], characterize the membership function μ_i: $UxW \rightarrow [0, 1]$, according to Equation (6).

$$\mu_{v_i}(u, w) = \vee \mu_{u_i}(u, v) \wedge \mu_{w_i}(v, w) \quad (6)$$

The result attributes to the pertinence function the objective of evaluating the best point in linguistic terms. The parameter a represents the first part of the base of the triangle, b the center and c the second part of the base of the triangle, useful for the formation of the functions of max and min. The x represents the membership degree to the set of the parameters. The term "low emission" is a decreasing function (*df*) as demonstrated in Equation (7), while the terms "acceptable emission", "moderate emission" and "high emission" are triangular functions (*trf*) in Equation (8), and the term "extreme emission" is an increasing function (*if*) in Equation (9). The output variables W are rated in five levels: "excellent", "very good", "good", "regular" and "poor". Since the evaluation of the requirements has the same objective, the universe of discourse has the same weight w_i for all dimensions. The input blocks are called an average estimator, so they allow the application of data as a set of fuzzy singletons.

$$df(x, a, c) = \min\left(1, \max\left(0, \left(\frac{c - x}{c - a}\right)\right)\right) \quad (7)$$

$$trf(x,a,b,c) = \min\left(\max\left(0, \left(\frac{x-a}{b-a}\right)\right), \; max\left(0, \left(\frac{c-x}{c-b}\right)\right)\right) \tag{8}$$

$$if(x,a,c) = \min\left(1, \max\left(0, \left(\frac{x-a}{c-a}\right)\right)\right) \tag{9}$$

$U_n =$	Low emission (x) = $df(u;1;2)$,	1 if u = 1 0 if u $\neq$ 1
	Acceptable emission (x) = $trf(u;1;2;3)$,	1 if u = 2 0 if u $\neq$ 2
	Moderate emission (x) = $trf(u;2;3;4)$,	1 if u = 3 0 if u $\neq$ 3
	High emission (x) = $trf(u;3;4;5)$,	1 if u = 4 0 if u $\neq$ 4
	Extreme emission (x) = $if(u;4;5)$,	1 if u = 5 0 if u $\neq$ 5

$W =$
Excellent = $df(w;1;3)$
Very good = $trf(w;1;3;5)$
Good = $trf(w;3;5;7)$
Regular = $trf(w;5;7;9)$
Poor = if(w;7;9)

The inference rules are distributed in four blocks (B), following vehicle balance (VB^AB); intensity traveled (ITB); and diesel consumption (DCB). This process comprises the input variables. The RB comprises a result block derived from the defuzzification process to obtain a crisp value. The three blocks with the conditional statements [IF], [IS] and [THEN] structure the interaction rules for the linguistic variables in each dimension. The average of the dimensions form the result of the output variables [THEN], classified as follows:

[IF] (<0.3 = E), [IS] Excellent;
[IF] ($\geq$0.3 < 0.5 = VG), [IS] Very Good;
[IF] ($\geq$0.5 < 0.7 = G), [IS] Good;
[IF] ($\geq$0.7 < 0.9 = R), [IS] Regular;
[IF] ($\geq$0.9 = P), [IS] Poor.

In the inference process, operations are performed for all rules λ_i through Equation (10), and the output values form the fuzzy variables according to Equation (11). The output fuzzy set $\mu_i''(w)$ is the sum of each result $\mu_i'(w)$, since this process occurs for all rules, as presented in Equation (12).

$$\lambda_i = \mu_{VB^A,IT,DC}(u_i) \bigwedge \mu_{VB^A,IT,DC}(v_i) \tag{10}$$

$$\mu_i'(w) = min[\lambda_i, \mu_i(w)] \tag{11}$$

$$\mu''(w) = max\left[u_1'w,\ u_2'w,\ u_3'w, \ldots u_i'w\right] \tag{12}$$

The center of gravity was used as a defuzzification method, [41,42] and proved to be excellent for determining midpoints and rationalizing distribution errors. W^0 is the transport sustainability index resulting from the interaction of the three dimensions for each $s.t$ analyzed in Equation (13).

$$W^0_{s.t} = \sum_i \mu''(w_i)w_i / \sum_i \mu''(w_i) \tag{13}$$

The rating R is the nominal variable W, important to facilitate application and improve the acceptance of the assessment among companies, customers and government. Triangular fuzzy logic allows faster outputs, unlike trapezoidal logic, in which changes occur more slowly, precisely because of its greater amplitude in the design of the fuzzy set, which is less adequate for models with overlaps. Thus, Equation (14) defines the values of each rating through the difference of the ratio of the maximum value W^0 of the analyzed period and the number of ratings n.

$$R_{s.t} = (max/n) \tag{14}$$

The best practice for acceptance is the self-assessment of environmental criteria, through an efficient communication channel, in which all those involved will observe the sustainability index as a selection criterion [43–45]. The unification and dissemination of knowledge must meet the objectives and satisfy the stakeholders directly or indirectly in the supply chain [46,47]. The transformation requires effort in developing testing protocols, strategic review and performance verification in management practices, with the purpose of reducing the emission of greenhouse gases (GHG) from transport. The sustainability perspective requires multiple approaches and criteria in decisions to reduce the uncertainties of results [48,49], in order to develop a rating that presents a holistic and non-interventionist view of business activities.

The evaluation method takes place over time, since the recording of emissions in transport activities ex-ante and ex-post in the data consists of observing the traditional functionality for a period of time. Therefore, after mapping, the comparison by periods is called business-as-usual (BAU). This method allows managers to apply good improvement practices and develop skills to anticipate environmental risks, ensuring the formulation of proactive ideas in the preparation of strategies and the optimal allocation of resources.

4. Application and Evaluation

Field data were extracted from seven toll plazas and a radar sensor with volumetric count in five cities bordering the city of Rio de Janeiro, in both directions. The period of data collection comprised from 2001 to 2020. Figure 1 identifies the location of the balance of vehicles leaving and entering the city, delimiting the research. The analyzed region has an area of 1,200,329 km^2 and an estimated population of 6.8 million inhabitants, with a density of 5.6 thousand inhabitants/km^2 [50].

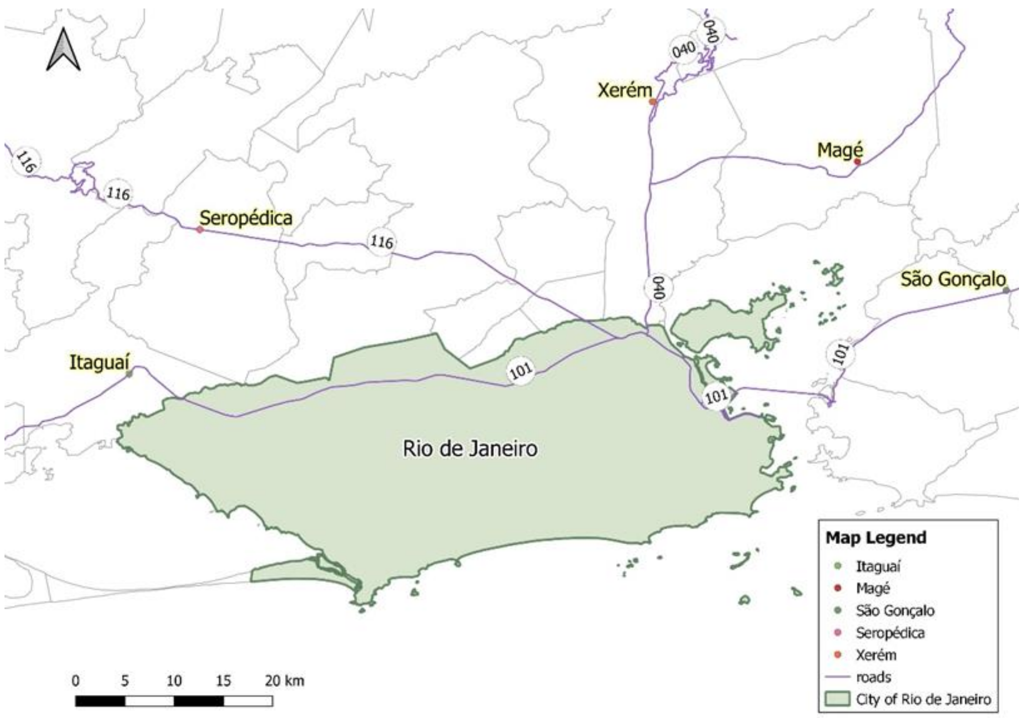

Figure 1. Toll plazas and radar location for data extraction. Itaguaí has radar with volumetric count.

4.1. Analysis of Input Variables

In the first approach, the balance of vehicles indicated that, on average, 8.13% more vehicles left the city than entered the city. For each year, the variable *RtD* has small oscillation (Appendix A), but in 2010, the volume of vehicles that left the city was 27.81% (indicated by the dashed line in Figure 2). This change was due to the effects of the start-up of an oil refinery beyond the city of São Gonçalo, where most of the trucks moved outside the city limits. This change was due to the effects of a refinery after the city of São Gonçalo, where most of the trucks moved outside the city limits. For the same intensity of vehicles, a higher diesel consumption was necessary from that period onward, when PROCONVE P6 (Program for Control of Air Pollution by Motor Vehicles) was instituted, similar to "Euro 4", with the objective of reducing pollutant emissions from motor vehicles, promote national technological development, improve fuel characteristics and establish conditions for evaluating the results achieved [51]. From 2012 onward, there were constant declines in fuel consumption in relation to intensity and in 2022, PROCONVE P8 was implemented, similar to "Euro 6", in both cases, improving the efficiency of the engines and reducing fuel consumption.

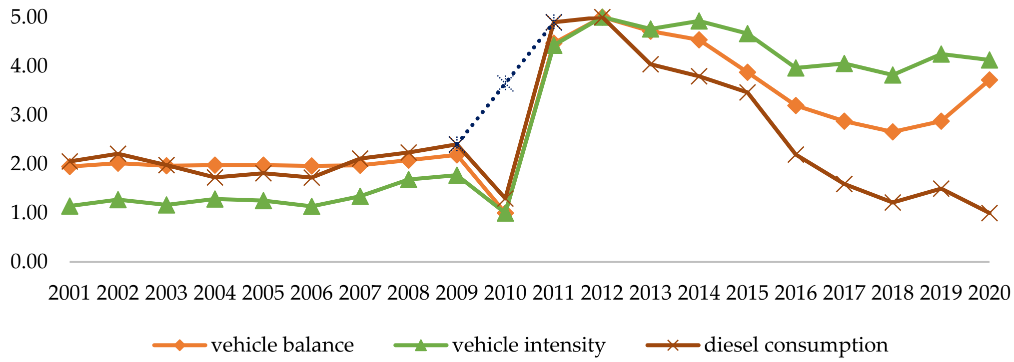

Figure 2. Evolution of normalized input variables in the interval [1, 5].

The balance of vehicles demonstrated an upward trend in 2018, shifting part of emissions to other regions. As more vehicles left and entered the city, the increasing interaction posed greater risks of emissions. The *RtD* for vehicle flow rebates was important to discount CO_2 emissions that do not originate from diesel sold within the city. The impact of diesel emissions from sources other than road transport was approximately 2%, considered in the modeling.

The intensity traveled by diesel freight and passenger vehicles showed the same decrease in 2010, with recovery in the following years. This indicator is significant to measure the particulate matter emitted from fuel combustion, tires, brakes and pavement. Although there are development policies to encourage the use of electric vehicles, progress in this respect will not totally eliminate particulate matter. The distance traveled has a strong relationship with economic activity and CO_2 emissions, so the interaction of the other indicators enhances the effects of lower emissions.

Diesel consumption for road transport was 2.5% in Brazil and 45% in the state, respectively. Diesel engines have greater energy efficiency compared to flexfuel engines (gasoline/ethanol), but they emit more CO_2, nitrogen oxide (NOX) and particulate matter (PM). However, for freight vehicles, due to the greater force necessary for displacement, diesel is more economical than other fuels [8]. Trucks are subject to time restrictions in the centroid, so it requires a greater number of urban freight vehicles (UFV) to meet the demand and maintain the level of service.

4.2. Analysis of the Fuzzy Application

The normalized input variables, vehicle balance, vehicle intensity and diesel consumption interact to form the input parameters for each *t.s* [1, 5], $Ui = (u1, u2, \dots, ui)$ and output [1, 10] and $Wi = (w1, w2, \dots, wi)$, according to the sub-criterion and criterion rules. Table 1 presents the W^0 results (sustainability index) for each analyzed year.

Data simulation (Appendix A) was performed with *Matlab® R2022a*. The maximum W^0 in the selected period was 8.94, so using Equation (14), the crisp amplitude value for the rating was 1.79. Data were classified into five levels: excellent (E), <1.79; very good (VG), ≤3.58; good (G), ≤5.37; regular (R), ≤7.16; and poor (P), <8.94. It can be seen that, until 2010, the sustainability index presented results below 3.52. With the implementation of

PROCONVE P6 and the displacement of part of the vehicles for the construction of the oil refinery, there was a large reduction in the three dimensions analyzed in the period studied, in which an index of 1.16 (an excellent rating) was achieved, but until 2014 there was an average increase of 6.10% in the sales of diesel vehicles, during which the rating was poor, with greater interactions in border activities, displacement and fuel consumption. As of 2015, the levels of interactivity between the three dimensions were reduced, increasing the environmental gain from the reduction of CO_2 emissions and the efficiency at the transport momentum (t.km; p.km), due to a lower number of trips for the displacement.

Table 1. Transport sustainability index and rating.

Year	Inputs			Outputs	Rating
	Balance	**Intensity**	**Consumption**	W^0	
2001	1.95	1.14	2.05	2.93	VG
2002	2.02	1.27	2.21	3.06	VG
2003	1.97	1.16	1.98	2.96	VG
2004	1.98	1.29	1.73	2.61	VG
2005	1.98	1.25	1.81	2.73	VG
2006	1.96	1.14	1.72	2.60	VG
2007	1.97	1.34	2.11	2.95	VG
2008	2.08	1.68	2.24	3.24	VG
2009	2.19	1.77	2.40	3.52	VG
2010	1.00	1.00	1.30	1.16	E
2011	4.47	4.42	4.89	7.71	P
2012	5.00	5.00	5.00	8.94	P
2013	4.71	4.76	4.04	8.18	P
2014	4.54	4.92	3.79	7.84	P
2015	3.87	4.66	3.46	6.59	R
2016	3.20	3.96	2.19	5.46	R
2017	2.87	4.05	1.59	4.61	G
2018	2.66	3.82	1.21	4.26	G
2019	2.87	4.24	1.50	4.58	G
2020	3.72	4.12	1.00	5.00	G

Notes: normalized data on balance, intensity and consumption of diesel vehicles as input variables [1, 5] *U* and output variable [1, 10] W^0 as sustainability index. E = excellent; VG = very good; V = good; R = regular; and P = poor.

Figure 3 demonstrates the relationship of the three dimensions with the sustainability index in transport. It can be seen that the result of 8.94 came from a maximum of input variables. From that year onwards, the decrease in the index was mainly caused by the decrease in the consumption of fuel, while the other variables had a low volatility, so the efficiency program allowed an improvement in the sustainability index.

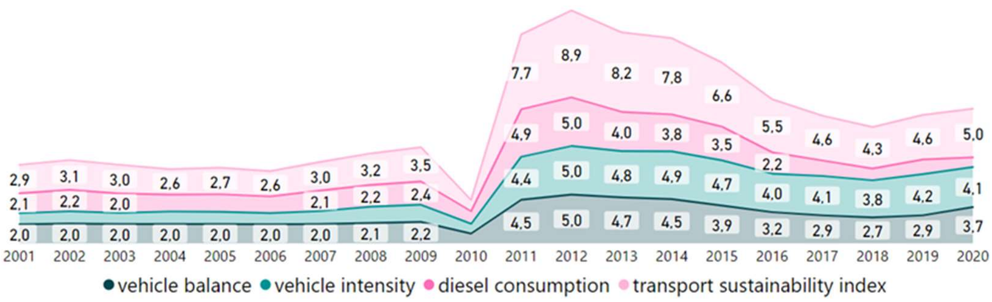

Figure 3. Interaction of dimensions of the transport sustainability index.

The sustainability index is an instrument that contributes to the adoption by companies of standards and improved conduct regarding the environment, increasing competitiveness globally as companies, through behavior change, choose to become more efficient in relation to transport. The goals of supply chain management paradigms are to become lean, resilient and green [47,52], since these are considered strategic processes, where there is a gap in the participation of companies in social issues and joint solutions [53].

4.3. Results and Discussion

With regard to the drop in CO_2 emissions mentioned above from 2015 onwards, one of the aspects that may have favored this situation is the reduction in freight and passenger transport trips of diesel vehicles due to the intensified use of services per application [54]. However, it is important to emphasize that this demand migration did not necessarily reflect lower emission rates in the transport sector as a whole, only in terms of diesel. The growth in CO_2 emissions can also be attributed to the change in consumption patterns caused by the intensification of electronic commerce, which increases the number of deliveries, and in turn the number of trips by freight vehicles.

Considering current emissions and the government's target for 2030, the necessary reduction in CO_2 levels is challenging. Among the actions required by the city of Rio de Janeiro for decarbonization, the 20% participation in the public passenger fleet of non-emitting vehicles stands out [55]. However, a large part of the fleet would still have conventional engines, not causing a substantial mitigation of pollution. Another municipal proposal is related to the revision of the legislation aimed at the transport of freight until 2026, in order to restrict the circulation and operation of vehicles emitting greenhouse gases.

In an ideal reduction scenario, emissions should converge to a continuous decline, so as not to require an intense effort for actions and measures that make the proposed objective feasible. Faced with climate change and the perception of the levels of pollutants generated, the establishment of strategies based on consolidated planning is fundamental for the adoption of more realistic sustainability practices. Likewise, activities related to ongoing monitoring and periodic reviews are strong allies in favor of confirming or revising policies, to achieve better results.

The sustainability index allows for a better observation of changes in environmental criteria and a more efficient analysis of the flow of information for the application of good practices. Efficiency in this model is aimed at greater participation by society. The visualization of business behavior by consumers is enhanced with a greater environmental awareness of society.

5. Conclusions and Recommendations

This paper proposes a three-dimensional perspective of energy consumption by diesel engines in light of sustainability, with emphasis on fuzzy logic as an evaluation tool. The proposed method corresponds to a recognition system using the triple result to reduce the uncertainties about the available annual data. Such systems, together with the principles of fuzzy logic, allow analysis that is more objective and closer to the real scenario, contributing to more assertive decision-making. Regarding the relevance of this study, we highlight the development of a sustainability index at the municipal level for road transport, considering the mainCO_2 emission factors from diesel. The sustainability index allows the construction of maps with the places with the highest emissions and the development of emission reduction policies by public and private agents. The tests to validate the model were carried out in a study applied in the city of Rio de Janeiro, Brazil.

The result of the application showed that the approach is satisfactory, demonstrating that it is possible to achieve greater equilibrium in the distribution of information and mitigate the uncertainties inherent in the data from the multi-criteria analysis. The rating based on the results was important to allow the development of standards and voluntary actions in the formulation of solutions with the objective of informing consumers of the commitment of the entities with the environment, since they aim to encourage the engagement of all involved for the purpose of environmental standards for products and services. Furthermore, the sustainability index of transport presented here is a relevant indicator for researchers, transport agents and government institutions in the process of evaluating and applying good practices, since the particular analysis of only one of the variables may not realistically represent the levels of emissions, as occurred in 2020, when fuel consumption had a lower value, in contrast to the intensity and balance of vehicles. It is also worth noting that the index facilitates the control by the municipalities and managers since the high cost of research for cities does not allow many to monitor the impacts, toward development and analysis the historical series of emission mitigation policies.

As a suggestion for future research, we recommend the adoption of a real-time database, which would allow transport companies and government entities to simultaneously monitor the index as a type of sustainability sensor. This measure would contribute to the agility of actions and strategies in the present period instead of dealing with information in historical series. Finally, we propose applying the method in smaller cities, in order to identify possible barriers to the implementation and collection of data, even if only annually.

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Appendix A. Normalized Balance, Intensity and Consumption Data of Diesel Vehicles

Vehicle Balance			Intensity Traveled		Diesel Consumption	
RtD	VB^A	VB^A NORM [1, 5]	*IT*	*IT* NORM [1, 5]	*DC*	*DC* NORM [1, 5]
0.06	2,561,917	1.95	1937	1.14	905,323,526	2.05
0.06	2,589,724	2.02	1983	1.27	927,209,094	2.21
0.06	2,569,146	1.97	1944	1.16	894,705,799	1.98
0.06	2,574,665	1.98	1987	1.29	859,731,268	1.73
0.06	2,573,924	1.98	1976	1.25	871,510,959	1.81
0.05	2,568,228	1.96	1934	1.14	859,029,612	1.72
0.06	2,572,903	1.97	2007	1.34	913,432,539	2.11
0.07	2,615,963	2.08	2128	1.68	930,908,678	2.24
0.07	2,659,964	2.19	2160	1.77	954,060,106	2.40
0.28	2,175,790	1.00	1886	1.00	799,317,518	1.30

Vehicle Balance			Intensity Traveled		Diesel Consumption	
RtD	VB^A	VB^A NORM [1, 5]	*IT*	*IT* NORM [1, 5]	*DC*	*DC* NORM [1, 5]
−0.08	3,588,417	4.47	3098	4.42	1,302,267,471	4.89
−0.06	3,805,589	5.00	3302	5.00	1,317,006,201	5.00
0.04	3,688,243	4.71	3216	4.76	1,182,317,567	4.04
0.09	3,616,482	4.54	3274	4.92	1,148,170,615	3.79
0.11	3,346,560	3.87	3182	4.66	1,101,918,744	3.46
0.16	3,070,557	3.20	2935	3.96	924,756,125	2.19
0.15	2,939,549	2.87	2966	4.05	840,852,072	1.59
0.14	2,851,125	2.66	2884	3.82	788,000,045	1.21
0.13	2,939,580	2.87	3034	4.24	827,588,104	1.50
0.08	3,282,191	3.72	2992	4.12	758,068,398	1.00

Notes: VB^A = balance of flow-adjusted diesel vehicles; *RtD* = flow rate of diesel vehicles (difference between leaving and entering the city limits); *IT* = intensity traveled; *DC* = diesel consumption; and Norm [1, 5] = data normalization.

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