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Impacts on Human Health of Biofuels Use in the São Paulo Metropolitan Region

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Impacts on Human Health from the Use of Biofuels in the São Paulo Metropolitan Region

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Introduction

Environmental air pollution generates relevant health problems that affect especially the portion of the population that lives in large urban centers. The World Health Organization (WHO, 2019) estimates that air pollution in cities and rural areas annually causes 4.2 million premature deaths worldwide (2016 data). This mortality is mainly due to exposure to particulate materials, small particles with a diameter of less than or equal to 2.5 micron (μm) (PM2.5), which are related to the occurrence of cardiovascular and respiratory diseases, as well as to several types of cancer.

WHO estimates that in 2016, 58% of premature deaths related to environmental air pollution were caused by ischemic heart disease and stroke, 18% were caused by chronic obstructive pulmonary disease and acute lower respiratory infections, while 6% can be attributed to lung cancer[1]. Particulate matter is associated with an increased incidence of cancer, especially lung cancer, according to an assessment carried out in 2013 by the WHO International Agency for Research on Cancer (IARC). An association has also been observed between outdoor air pollution and increased urinary tract/bladder cancer (WHO, 2019).

Most sources of air pollution are far beyond the control of individuals, as pointed out by the WHO, which requires coordinated action by policymakers at the local, national and regional levels, in the different sectors involved: transport, energy, management of waste, urban planning and agriculture.

Seeking to contribute with relevant studies to support public policies focused on energy, the Energy Research Office (EPE) prepared an assessment of the impact on human health resulting from the use of biofuels in the transport sector.

This study will use the methodology described by the WHO, in its AirQ+ manuals, applying it to the Metropolitan Region of São Paulo (RMSP), chosen for the study due to the availability of data, with emphasis on the atmospheric pollution inventory (CETESB, 2018). For this, two macroanalyses will be carried out, the first focusing on the use of ethanol in light vehicles and the second on the addition of ester-based biodiesel to diesel B.

It should be noted that, although other pollutants also cause significant impacts on human health, this analysis will focus only on particulate matter, especially PM 2.5, which causes the greatest effect of all. The simulations ran are based on the 2018 RMSP fleet, the year in which the measurements were recorded.

[1] Some deaths can be attributed to more than one risk factor at the same time. For example, smoking and air pollution affect lung cancer. Thus, some deaths from this type of cancer could have been avoided by improving air quality or reducing tobacco smoking (WHO 2019).

1. Description

1.1. Public Policies for Biofuels

The Brazilian government has adopted public policies to develop and expand the production and use of biofuels in the country. Among them, the National Alcohol Program (PROALCOOL), in the 1970s, the insertion of flex fuel technology in 2003, the National Program for the Production and Use of Biodiesel (PNPB) in 2005 and, more recently, the National Biofuels Policy (RenovaBio). In addition, several public policies of tax differentiation have been applied to biofuels, in order to favor their competitiveness against fossil fuels (EPE, 2016).

Ethanol production in the country was boosted in the 1970s by Proálcool, which was fundamental to make ethanol production viable. After the end of the program, the volume of this biofuel commercialized dropped considerably, having resumed its growth with the introduction of flex fuel technology in light vehicles, as of 2003. Since 2015, the percentage of anhydrous ethanol in gasoline C has been set at 27%. In 2019, hydrous consumption reached a 30% share in the Otto cycle demand and total fuel ethanol represented 49%, both in gasoline equivalent (EPE, 2020c). In the last decade, the biofuel production grew by 26% (EPE, 2020; Salina, Almeida, & Bittencourt, 2019).

The PNPB, established through Law nº 11,097/2005 (BRASIL, 2005), was the instrument that inserted biodiesel in the Brazilian energy matrix. The program was based on three pillars: social inclusion through family farming, environmental sustainability and economic feasibility. Its objective was to enable the use of the various oilseeds existing in Brazil, according to the potential of each region, reducing economic inequalities between them. The creation of the Social Fuel Seal (SCS)[2], which requires that a minimum percentage of raw material be purchased from family farmers in order to qualify for tax benefits, has promoted social inclusion through income and employment generation (EPE, 2020a; Barroso & Alves, 2008). Between 2005 and December 2019, 40.7 billion liters of biodiesel were produced by the Brazilian industry (EPE, 2020).

In order to increase the competitive participation of biofuels in the Brazilian energy matrix, by bringing predictability to this segment, the National Biofuels Policy (RenovaBio) was enacted in 2017 (BRASIL, 2017), which encourages investments in the sector, in addition to helping the country meet Nationally Determined Contribution (NDC), under the Paris Agreement. RenovaBio intends to boost the production of various biofuels, such as ethanol, biodiesel, biogas and aviation biokerosene.

[2] Changed to Social Biofuel Seal by Decree No. 10,527 of October 22, 2020 (BRAZIL, 2020).

1.2. Particulate Material

According to (Ristovski, *et al.,* 2012), the emission of particulate matter involves a complex mixture of solid and liquid particles suspended in the atmosphere. As described (Belo, *et al.*, 2011), particulate matter can be classified according to its formation process. When it is emitted directly into the atmosphere, through natural or anthropogenic sources, it is called primary. If the particulate undergoes chemical reactions in the atmosphere involving gases, aerosols and water in a liquid or solid state, it is classified as a secondary particle. According to Marques *et al.* (2012), particulate matter whose size does not exceed 10 µm is represented by the symbol PM10. This is subdivided into a fine fraction, called breathable particle, or PM2.5, whose aerodynamic diameter is less than or equal to 2.5 µm, and a coarse fraction, which corresponds to a size between 2.5 µm and 10 µm, known as inhalable particle.

The main risk to human health is associated with the ability of the fine fraction of particulate matter to transfer toxic substances dissolved (absorption) in its body or adhered to its surface (adsorption) to the alveoli. The adsorbed compounds can return to the gas phase, and are sorbed by the organism through the diffusion process. Some compounds, such as sulfates, nitrates and some metals, can dissolve in the fluid present on the surface of the alveoli, crossing the alveolar barrier and reaching the bloodstream. The compounds absorbed in the particulate matter can be captured by the defense mechanism of the alveoli. All these processes can trigger an inflammatory response in the body (SALDIVA, 2007).

FERNANDES, *et al.* (2010) indicate that this fine fraction of particulate matter acts on the circulatory system, reaching the blood vessels through the lungs, causing severe damage to the system as a whole, leading to changes in heart rhythm, myocardial ischemia, and changes in blood coagulation. According to (Belo, *et al.*, 2011), the main mechanisms of pulmonary deposition are fixation, inertial impaction, diffusion and sedimentation. In fixation, gravity is primarily responsible for the deposition of particles. In the process called inertial impaction, the larger particles have difficulty following the curved paths, thus, they adhere to the mucous membranes of the upper airways. The diffusion process involves particles with an aerodynamic size of less than 1 µm. Due to their random movement, as a result of their gas pumping, the particles get to the lower airways, reaching the alveoli. Particles between 1 µm and 5 µm undergo the process of sedimentation, which occurs in the lower airways, reaching the terminal bronchioles.

According to (Maioli, 2011), fetuses, children under 5 years of age and the elderly are more susceptible to diseases caused by particulate matter, such as asthma, chronic obstructive pulmonary disease, pneumonia, respiratory tract infections, cardiac arrhythmias and coronary ischemic conditions. Studies have shown that children and the elderly make up the group related to the increase in hospital admissions due to respiratory diseases, thanks to the greater presence of particulate matter in the atmosphere (CANÇADO, *et al.*, 2006).

Finally, according to the study by (Carmo, *et al.*, 2010), the increase of 10 µg/m³ in the mass concentration of particulate matter in the southern region of the Brazilian Amazon was associated with increases of 2.9% and 2.6% in outpatient consultations for respiratory diseases of children on the sixth and seventh days after birth, subsequent to exposure.

2. Methodology

The methodological approach adopted for this study included evaluating the variation in particulate matter emissions, specifically PM2.5 resulting from the amount of biofuels used by vehicles in the municipalities of the Metropolitan Region of São Paulo. To analyze the impact on health through increasing the concentration of this material, the AirQ+ Tool was used, which will be described below.

2.1. Study Area

The Metropolitan Region of São Paulo, which includes 39 municipalities, was chosen due to the availability of data, especially the atmospheric pollution inventory, published by the Environmental Company of the State of São Paulo (CETESB, 2018). The region was established in 1973 and reorganized in 2011 by the São Paulo Legislative Assembly, which established the Development Council and grouped its municipalities into sub-regions (Assembléia Legislativa de São Paulo, 2011), according to Figure 1. According to (IBGE, 2019), in 2018, the region had 21.6 million inhabitants with a total GDP of 1.1 trillion reais.

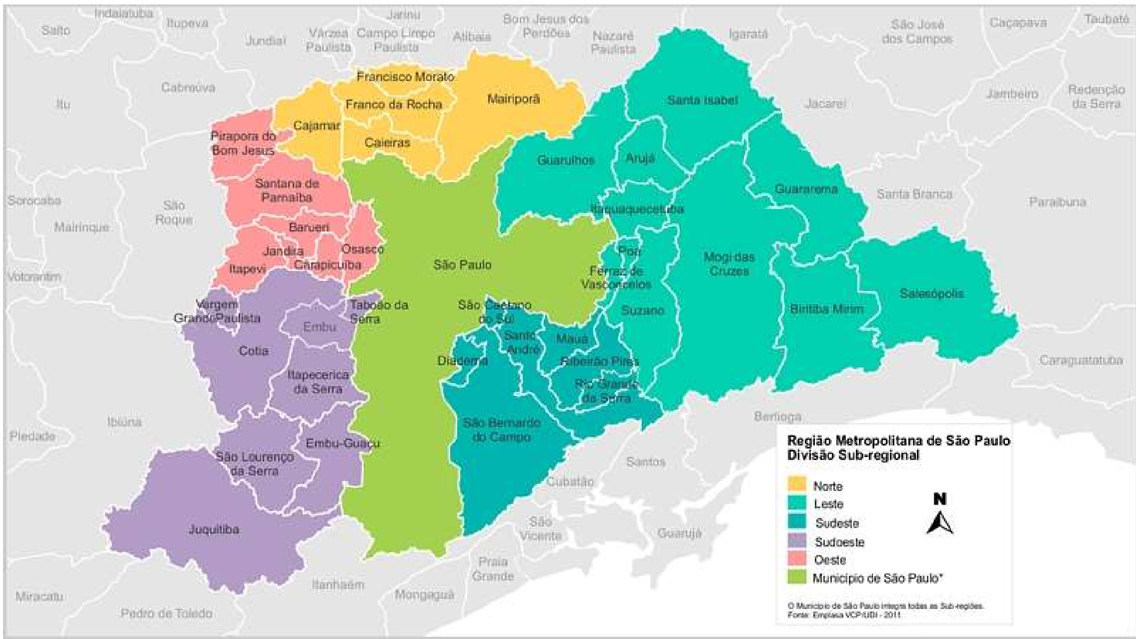

Figure 1 – Metropolitan Region of São Paulo
Source: (EMPLASA, 2019)

2.2. Data Used

The air quality data recorded at the stations that are part of the RMSP, from the perspective of particulate matter 2.5 (PM2.5), were obtained from CETESB. In 2018, the average annual concentration in the region was 18.53 µg/m³. Data referring to vehicle emissions from the RMSP fleet are available in the Air Quality Report in the State of São Paulo. The distribution of relative emission sources and their participation in PM2.5 concentration are as follows: total vehicles 37%, biomass combustion 7%, secondary aerosols 51% and particle resuspension 5%. In this way, any simulation tested here would only have an impact on the share related to vehicular emissions, 37% (CETESB, 2018).

Data regarding fuel consumption (gasoline C, hydrated ethanol and diesel B), for the municipalities that are part of the RMSP, were obtained through the National Agency of Petroleum, Natural Gas and Biofuels (ANP, 2019), in order to estimate particulate matter emissions. It was also necessary to identify the vehicle emission rate (g/km) for each type of vehicle and fuel under analysis (CETESB, 2018).

For the emission rate of hydrated ethanol, an estimate of (Vicentini, de Melo, Loureiro, Moreira, & Alves, 2015) was adopted. To obtain the emission rates of ester-based biodiesel, a study from the State University of Goiás was used (Barroso & Alves, 2008).

To estimate the population of the RMSP, data from the IBGE (IBGE, 2019) were adopted, which are available by municipality. In this way, the total population of the RMSP is obtained by adding the age pyramids of the necessary municipalities. The mortality rate by age group was obtained by the system (DATASUS, 2019).

2.3. AirQ+ Tool

The estimate of the impact on human health from exposure to PM2.5 was prepared using the AirQ+ tool version 1.3, which was designed to calculate the health impacts of air pollution on a given population. All calculations performed by AirQ+ were based on methodologies and concentration-response functions established by epidemiological studies, as in (Bahrami Asl, *et al.*, 2018), (Yarahmadi, *et al.*, 2018) and (Ansaria & Ehrampoush, 2019). The response functions used in the software were based on a systematic review of all studies available up to 2013, organized by the WHO. AirQ+ calculates the proportion and attributable number of cases (deaths and hospitalizations) per 100,000 inhabitants. To quantify the long-term effects of PM2.5, the following data were used: (i) air quality, annual average, for long-term exposure purposes; (ii) population at risk, as the total number of adults over 30 years of age; (iii) health data, such as baseline rates of health outcomes in the population; and (iv) the cutoff value for the concentration of the pollutant to be considered (10 $\mu g/m^3$), as recommended by the WHO (2017). It should be noted that the present study uses the methodology described by the WHO, without proposing to change or validate it.

2.4. Assumptions of the Simulations

To measure the impact of the use of biofuels in the Otto cycle[3], four routes were constructed, with different shares of ethanol in the transportation sector. In all cases, the benchmark Otto cycle demand is that performed in 2018 in the RMSP. The GA route considers that there is no demand for hydrated or anhydrous ethanol, only the consumption of gasoline A. Its objective is to compare the total effect of reducing PM emissions resulting from the consumption of ethanol. In the GC route, there is a mixture of 27% of anhydrous ethanol in gasoline C, but there is no demand for hydrated ethanol. The GC_EH route reflects the demand observed in 2018 for hydrous ethanol and gasoline

[3] The fuels that make up the Otto cycle are: gasoline C (gasoline A + anhydrous ethanol), hydrated ethanol and natural vehicular gas (NGV).

C, with a 27% anhydrous mixture. In turn, the GC_EH+10 route simulates a 10% increase in the consumption of hydrated ethanol, to the detriment of gasoline C.

In order to measure the impact of biofuel policies for the Diesel cycle in the RMSP, four ester-based biodiesel addition routes were also constructed. The first considers that there is only the consumption of diesel A. In the second case, there is 10% of biodiesel in the mixture, as observed in 2018. The third case adopts 12% and the last considers 15% of biofuel addition (as provided for in the CNPE schedule for 2023).

3. Results and discussion

3.1. Ethanol

According to (CETESB 2018), the PM2.5 emission rate varies according to the vehicle, with the average weighted by the circulating fleet powered by gasoline C, equal to 1.62mg/km. In order to estimate the emission rate for ethanol consumed in flex-fuel vehicles and motorcycles, a proportion of 50% of gasoline C emission rate was adopted, according to a study by SIMEA (Vicentini, *et al.* 2015. Then, the weighted average was calculated according to the fleet of each vehicle, obtaining a value of 0.33 mg/km.

The results for the proposed scenarios can be seen in Table 1, in which the concentration of PM2.5 particulates in the atmosphere, its reduction compared to that observed in 2018, the percentage decrease in the share of particulates emitted by the transport sector, the variation in life expectancy in relation to that observed in the RMSP in 2018 (GC_EH route) and, finally, the variation in the number of deaths per year are presented.

Table 1 - Impacts on the Human Health from the Use of Ethanol

	PM2.5 Particulate Concentration (μg/m³) in the atmosphere	% variation in the atmosphere (PM2.5)	% variation related to the transportation sector (PM2.5)	Variation in life expectancy (days)	Variation in the number of deaths per year
GA route	19.02	2.6%	7.2%	-13	371
GC route	18.70	1.0%	2.6%	-6	152
GC_EH* route	18.53	0.0%	0.0%	0	0
GC_EH+10 ** route	18.47	-0.3%	-0.9%	1	-43

Source: Prepared by EPE

Notes: * São Paulo in 2018, reference route

** Consumption of hydrated ethanol 10% higher than in 2018

The comparison between the GA and GC_EH routes shows the impact of the use of anhydrous and hydrated ethanol fuel in 2018[4]. There is a 2.6% drop in total PM2.5 pollution in the atmosphere (corresponding to 7.2% of particulate concentration associated with the transportation sector). It is estimated that this consumption of ethanol, *ceteris paribus*, prevents 371 deaths per year, and the population has its life expectancy increased by 13 days, from birth. If there were a 10% increase in hydrous demand compared to 2018 (called GC_EH+10 route), there would be 43 fewer deaths per year and life expectancy would increase by 1 more day, when compared to the GC_EH route.

3.2. Ester-Based Biodiesel

Similar to regular gasoline, diesel also has a mandatory percentage of biofuel, with the exception of waterway transportation, export bunkers and self-production in the transformation sector. Since March 2020, the current percentage of blending biodiesel in diesel B is 12%, with a schedule set to reach 15% by 2023 (EPE, 2020). The amount of your emission fee varies for different types of heavy vehicles, trucks and city buses. Thus, the weighted average emission rate of the diesel cycle vehicle fleet is 7.53 mg/m³, the highest among the analyzed fuels (CETESB 2018). To obtain the emission rates of ester-based biodiesel, a study from the State University of Goiás was used (Barroso & Alves 2008), which reports the reduction of particulate matter for different mixing levels. Thus, using the average emission rate of B10 diesel, the average emission rate of ester-based biodiesel of 4 mg/m³ was obtained through linear interpolation (EPE, 2020a). In the base year of the study, 2018, this percentage was 10% (B10 route). The results of the simulations for the Metropolitan Region of São Paulo are presented in Table 2.

Table 2 - Impacts on the Human Health from the use of Ester-Based Biodiesel

	PM2.5 Particulate Concentration (µg/m³) in the atmosphere	% variation in the atmosphere (PM2.5)	% variation related to the transportation sector (PM2.5)	Variation in life expectancy (days)	Variation in the number of deaths per year
B0 route	18.85	1.7%	4.8%	-9	244
B10 route	18.53	0.0%	0.0%	0	0
B12 route	18.48	0.3%	-0.7%	1	-33
B15 route	18.39	-0.8%	-2.0%	4	-104

Source: Prepared by EPE

The comparison between routes B0 and B10 shows the impact of the use of ester-based biodiesel, resulting from the PNPB incentive in 2018. It appears that, without the use of biofuel, the concentration of particulates in the atmosphere from the transportation sector would be 4.8% higher than that recorded in 2018, while the total pollution of PM2.5 in the atmosphere would be 1.7% higher. It is estimated that this program prevented 244 deaths per year, and that the population gained 9 days of life from birth. If the percentage of biodiesel in diesel B were to reach 15%, there would be 104 fewer deaths per year and life expectancy would increase by another 4 days, when compared to the B10 route.

[4] In addition to public policies to encourage the use of ethanol (mandatory percentage, tax differentiation, etc.), this biofuel is also influenced by the sugar market, since a large part of the sugar-energy industry uses the same input for its production.

3.3. Implicit Value in Improving the Quality of Life

The objective of this item is to assess the implicit value in improving the quality of life with the use of biofuels. For this, the methodology used by WHO was taken as a benchmark. It includes a recommendation to aid in governmental decision-making, in relation to the cost/benefit of a policy, in order to measure its economic effectiveness, suggesting an analysis based on *per capita* GDP. The Organization considers those policies that have a cost of up to three times the impact of GDP per capita by the length of life expectancy as a criterion indicative of good potential. For example, Brazil's GDP *per capita* in 2018 was approximately BRL 32,000.00. Thus, a policy with a cost of up to BRL 96,000.00 per capita, which would add one year of life to the population, would meet this criterion.

Although this paper does not propose an analysis of the economic feasibility of the policies, only their implicit values will be presented and not their costs, according to this recommendation, for the population of the RMSP. Thus, Table 3 and Table 4 present the analyzed simulations, with their respective implicit values in billions of reais – BRL – (nominal values referring to 2018). In the second column of the tables, the annual value of GDP per capita is weighted by the number of days added to life expectancy, multiplied by the number of inhabitants in the RMSP. The third column presents what would be the cost limit of each public policy so that they meet the criterion indicative of good potential, as recommended by the WHO, that is, the previous value multiplied by three.

It should be noted that the supply of ethanol is influenced by the price of sugar in the international market, since the sugar-energy industry uses the same input for both products. Thus, the present work assesses the implicit value in improving the quality of life resulting from the consumption of ethanol, and does not isolate the impact of public policies for this biofuel (such as, for example, the mandatory percentage).

In Table 3, we see that the basis is the GC_EH route, which is representative of the scenario observed in 2018 in the RMSP. We found that, if there were no use of ethanol, the impact on the economy would be negative by approximately BRL 25 billion in relation to the base scenario. On the other hand, a 10% increase in hydrous consumption would generate an additional positive impact of approximately BRL 2 billion.

Table 3 - Economic impact of ethanol consumption

	Economic impact due to variation in life expectancy (billion BRL)	WHO recommendation for policy effectiveness* (billion BRL)
GA route	-24.61	-73.85
GC route	-11.36	-34.08
GC_EH route	-	-
GC_EH+10 route	1.89	5.68

Source: Prepared by EPE

The benchmark for biodiesel in 2018 is B10. Compared to a scenario in which there would be no addition of biodiesel (B0), there would be a negative impact of BRL 17 billion due to the reduction in the life expectancy of the population. With the B15 route, there would be a gain of over BRL 7.6 billion, as shown in Table 4.

Table 4 - Economic impact of biodiesel consumption

	Economic impact due to variation in life expectancy (billion BRL)	WHO recommendation for policy effectiveness* (billion BRL)
B0 route	-17.04	-51.12
B10 route	-	-
B12 route	1.89	5.68
B15 route	7.57	22.72

Source: Prepared by EPE

4. Final Considerations

The development of sustainable energy sources has gained great importance around the world due to the urgent need to reduce greenhouse gas emissions in order to mitigate the effects of climate change and assist in the search for energy safety. In this situation, biofuels stand out as an important alternative to fossil fuels, as they offer environmental and socioeconomic advantages, contributing to the generation of employment and income throughout the Brazilian territory, and to the Gross Domestic Product (GDP), specifically, the agricultural one. Brazil is the largest producer of ethanol from sugarcane, and the third largest producer of biodiesel in the world. The impact on the economy of the biofuels sector in Brazil is considerable and has very positive effects, as reported by (Antunes, Chandel, Terán-Hilares, Milessi, & Travalia, 2019).

The inclusion of biofuels in the transportation matrix, largely responsible for fuel demand and an important GHG emitter in the global economy, is becoming more and more relevant. Observing the various gains obtained at a global level, the local impacts also deserve attention. This analysis was restricted to gauging the effect on human health resulting from the emission of particulate matter of 2.5 microns, through simulations in the AirQ+ software package, through variations in the consumption of biofuels in alternative routes to that carried out in 2018 in the Metropolitan Region of São Paulo.

The results indicate that the use of ethanol has a high positive impact on human health from the point of view of particulate emissions, contributing to a 7.2% reduction in particulate concentration associated with the transportation sector, and with a 13-day increase in life expectancy of that population. It is estimated that, annually, 371 deaths due to complications from particulate pollution in the RMSP are avoided. A 10% increase in the use of ethanol was also tested to meet the demand of the Otto cycle, which resulted in a 0.3% decrease in particulate emissions from light vehicles in that region.

The addition of biodiesel to diesel A also had a significant impact on human health in terms of particulate emissions, as indicated by the results of this study. In 2018, the addition of 10% of biodiesel avoided 4.8% of emissions from the transportation sector in the RMSP and contributed to the increase of nine days in the life expectancy of the population, in addition to reducing 244 deaths annually. In an alternative route of adding 15% of ester-based biodiesel to diesel, there would be an additional 2% reduction in vehicular emissions of particulate matter, in addition to an increase of another four days in life expectancy from birth, and it would also avoid another 104 deaths per year.

Finally, an assessment was made of the value implicit in improving the quality of life due to the use of biofuels to replace their fossil analogues, resulting from the implementation of public policies, according to the WHO methodology. This impact would be in the order of BRL 25 billion for ethanol and BRL 17 billion for biodiesel, taking 2018 and the RMSP as a reference. In the case of ethanol, it is worth noting that, for this study, the impact of public policies could not be assessed in isolation, given the influence of the sugar market, considering only the value resulting from its consumption.

It is noteworthy that future studies should consider the synergistic effects of the use of ethanol and biodiesel, concomitantly, on the impacts on human health, on life expectancy and on the implicit value of improving the quality of life. These results may be more significant with the intensification of the consumption of new biofuels in the transport sector.

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Appendix A – Methodology

Here, some methodological aspects used to obtain the described results will be detailed.

Emissions

Data on air quality, from the perspective of particulate matter 2.5 (PM2.5), were obtained from the Environmental Company of the State of São Paulo (CETESB) for the stations that are part of the Metropolitan Region of São Paulo (RMSP). Considering that each station has its own hourly measurement, a daily average was made, weighted by the weight of each post for a period of one year, to obtain an estimate of the equivalent concentration of the RMSP, whose value was 18.53 µg/m³ for the year 2018. It is important to note that, in the absence of PM2.5 data, data related to PM10 are available, whose ratio is 60% from PM10 to PM2.5 (CETESB, 2018).

Relative vehicular emission

Data regarding the relative vehicular emission of the RMSP fleet are available in the Air Quality Report in the State of São Paulo (CETESB, 2018). The total vehicles category is also segmented by category and by vehicle fuel, with the relative participation of PM10 and PM2.5 emissions, see Table 5. Thus, it is possible to know the emission for each vehicle separately. It is important to note that CETESB does not have data on emissions related to ethanol, therefore, 0% was considered for that fuel.

Table 5 – Relative vehicular emissions for PM_{10} and $PM_{2.5}$

Category	Fuel		PM_{10} emission (%)	$PM_{2.5}$ emission (%)
Automobiles	C Gasoline		0.71	0.66
	Ethanol Flex		--	--
	Gasoline Flex		0.68	0.63
Light Commercial Vehicles	C Gasoline		0.14	0.13
	Ethanol Flex		--	--
	Gasoline Flex		0.10	0.09
	Diesel		4.61	4.26
Trucks	Semi-light vehicles	Diesel	1.27	1.18
	Light vehicles		5.08	4.70
	Medium-sized vehicles		4.11	3.80
	Semi-heavy vehicles		5.59	5.17
	Heavy vehicles		5.21	4.82
Bus	Urban	Diesel	8.27	7.65
	Minibus		1.66	1.54
	Road vehicles		0.75	0.69
Motorcycles	C Gasoline		1.75	1.62
	Ethanol Flex		--	--
	Gasoline Flex		0.12	0.11
Total			**40.02**	37.05

Source: CETESB, 2018.

Modeling of environmental concentration

To model the air quality in the RMSP, translated by the variation in the emission rate of fuels, two methods will be used: the first one based on changing the share of renewables in commercial fuels and the second on changing the consumption profile.

Change in the share of renewables in commercial fuels

As previously mentioned, gasoline C (27% anhydrous) and diesel B (currently 12% biodiesel) have a percentage of renewable fuels in their composition, a mandatory blend stipulated through specific legislation, which contribute to the reduction of emissions of greenhouse gases and local pollutants. Thus, to calculate the variation in PM concentration, based on the change in the mandatory percentages of biofuels, the mathematical relationship taken from (Saldiva & de André, 2014) is used.

$$TE'_X = \frac{(TE_{x,avera} \quad - TE_{y,average} * A_d)}{1 - A_d}$$

Equation 1 - Emission rate after changing the mandatory mixture

$$A\% = \frac{(TE'_X - TE_{x,average})}{TE_{x,average}}$$

Equation 2 - Estimated variation of PM concentration

Where:

TE'_X is the emission rate of fuel “x”, in mg/km, after changing the mandatory mixture (A_d).

A_d is the percentage of mixture of fuel “y” in fuel “x”.

$TE_{x,\ average}$ is the average emission rate of fuel “x”, in mg/km.

$TE_{y,\ average}$ is the average emission rate of fuel “y”, in mg/km.

The % is the estimated variation of the $PM_{2.5}$ concentration for fuel “x”.

In short, when fuel “x” is regular gasoline, fuel “y” will be anhydrous ethanol, and when fuel “x” is diesel, fuel “y” will be biodiesel.

Variation in fuel consumption pattern

In order to carry out the modeling calculations, considering the change in the consumption pattern, it is necessary to make a volumetric equivalence between the fuels through their average consumption in m^3; these data were provided by CETESB. We then have the relations available in Equation 3.

$$Vg_{eq} = Vet * 0.73$$

$$Vd_{eq} = Vet * 1.33$$

$$Vg_{ed} = Vd * 0.55$$

Equation 3 - Volumetric relationships among different fuels

Where:

Vg_{eq} is the volume of regular gasoline equivalent to travel the same distance as ethanol-powered vehicles.

Vd_{eq} is the equivalent volume of diesel B to travel the same distance as vehicles powered by hydrated ethanol.

Vg_{ed} is the volume of regular gasoline equivalent to travel the same distance as diesel B.

Vet is the volume of hydrated ethanol to be replaced by regular gasoline.

Vd is the volume of diesel B to be replaced by regular gasoline.

Thus, we can estimate the variation of the environmental concentration of $PM_{2.5}$ in µg/m3 using Equation 4, based on (Saldiva & de André, 2014).

$$\Delta MP_{2.5} = MP_{2.5} * \left(\frac{Vx_{eq}}{Vx_{original}} \right)$$

Equation 4 - Estimated variation of PM concentration

Where:

$\Delta PM_{2.5}$ is the expected change in the environmental concentration of $PM_{2.5}$ due to the substitution of fuel “x” for “y”.

$PM_{2.5}$ is the original $PM_{2.5}$ concentration assigned to fuel “x”.

Vx_{eq} is the equivalent volume of fuel “x” to travel the same distance as vehicles powered by fuel “y”.

Vx_{ori} is the original “x” fuel volume.

The total variation of the environmental concentration of the fuel under analysis is the sum of the portions referring to the variation of the mandatory blends of biofuels and the variation in the consumption profile.

Health impact estimate

The calculations to estimate the health impacts are made in two steps that will be grouped up later. The first uses the WHO software package AirQ+ for population mortality and life expectancy. For the second stage, hospitalizations, the WHO software package will not be used, as its calculation method, called “DALY – Disability Adjusted Life Years”, does not explicitly return the number of hospitalizations, but the number of years lost due to morbidity. Thus, we used the mathematical modeling of hospitalizations (AIH) provided by SUS (Brazilian Unified Health System) in its DATASUS system.

Mortality

The impact of environmental $PM_{2.5}$ concentration on population mortality and life expectancy will be evaluated using AirQ+. The initial software configuration is shown in Figure 2.

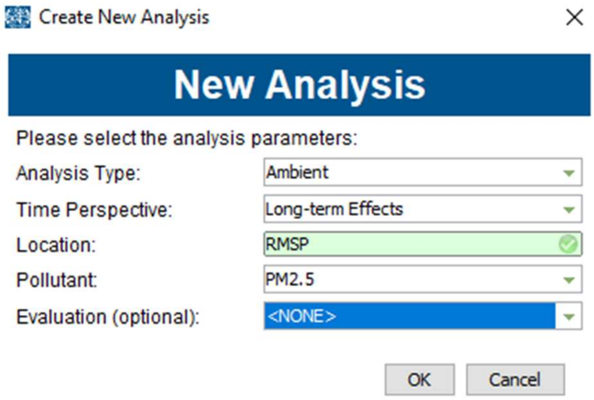

Figure 2 - Create a new analysis

For the configurations of total population of the region and area, the values of 21,571,281 people and 7,948.96 km² were used, respectively. For the analysis of the number of deaths, the "Impact Evaluation" analysis of the software was used, where the configuration parameters are in Figure 3.

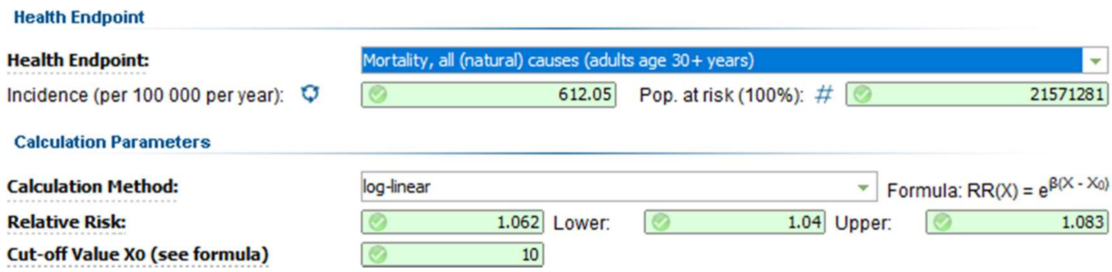

Figure 3 - Parameters of the "Impact Evaluation" analysis

For the item "Health Endpoint" (causes of mortality), the option of cases for adults over 30 years was selected (the software converts the units to 100,000/year) and 100% of the population at risk was considered. The relative risk (RR) is the indicator recommended by the WHO for PM2.5, whose environmental concentration value is 10 µg/m³.

For the analysis of life expectancy, the "*Life Table Evaluation*" analysis of the software was used, where the configuration parameters are in Figure 4, below:

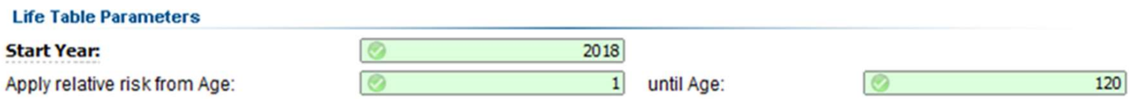

Figure 4 - Parameters of the "Life Table Evaluation" analysis

The data were obtained from the (IBGE, 2019) system, where information by municipality is available, and the total population of the RMSP was obtained by adding the age pyramids of the required municipalities. The mortality rate by age group was obtained by the system (DATASUS, 2019).

Impact on hospitalizations

In this item, the methodology for calculating the impact of the environmental concentration of $PM_{2.5}$ on the morbidity of the population that results in hospital admissions (AIH) will be presented. Information on quantity of AIH, average cost of AIH, and average time of AIH can be found in (DATASUS, Hospitalizations by category and age group, n.d.).

The cases referring to the impacts of the concentration of $PM_{2.5}$ on the health of the population were segregated into two types of diseases, respiratory and cardiovascular cases, as they are more easily associated with air pollution.

To measure hospitalizations attributed to the variation of particulate matter in atmospheric concentration, Equation 5 (Saldiva & de André, 2014) was used.

$$AIH' = \left(e^{\beta \Delta MP} - 1\right) AIH_{total}$$

Equation 5 - Variation in the number of hospitalizations

Where:

AIH' are the variations in the number of hospitalizations due to the change in the concentration of particulate matter for each type of disease and age group.

β is the regression coefficient for each disease case and age group;

ΔMP is the variation of environmental concentration of PM2.5;

AIH_{total} is the total number of hospitalizations by type of disease and age group.

The β coefficient was obtained in different studies and also from the WHO itself. The β values with an asterisk were taken from (Saldiva & de André, 2014), which provides the sources of each coefficient. When regression coefficients for certain age groups were not found, an estimate was performed using the standard regression coefficient, found within the WHO software, with a fixed value of 0.0060. All values are available in Table 6.

Table 6 - Epidemiological regression coefficient of exposure to $PM_{2.5}$

Age range	Respiratory (µg/m³ variation)	Cardiovascular (µg/m³ variation)
0-4	0.0047*	0.0060
5-9	0.0060	0.0060
10-14	0.0060	0.0060
15-19	0.0060	0.0060
20-29	0.0060	0.0060
30-39	0.0060	0.0060
40-49	0.0024*	0.0016*
50-59	0.0024*	0.0016*
60-69	0.0044*	0.0024*
70-79	0.0063*	0.0027*
80 or more	0.0063*	0.0027*

Source: OMS, 2018.

Since SUS represents only a portion of all hospital admissions, and its complement comes from the private health network, it is necessary to estimate the number of admissions from the latter. This value can be estimated using Equation 6 (Saldiva & de André, 2014).

$$AIH_{private} = AIH_{public}\left(\frac{1}{1 - CR} - 1\right)$$

Equation 6 - Estimation of AIH's in the private system

Where:

AIHprivate is the estimated number of hospitalizations in the private system.

AIHpublic is the number of admissions added or reduced due to the variation in the concentration of particulate matter for each type of disease and age group.

CR is the rate of coverage of the private health system, provided in (DATASUS, Coverage of the private system, n.d.).