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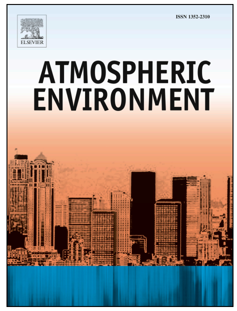

PM emissions from heavy-duty trucks and their impacts on human health

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PM EMISSIONS FROM HEAVY-DUTY TRUCKS AND THEIR IMPACTS ON HUMAN HEALTH

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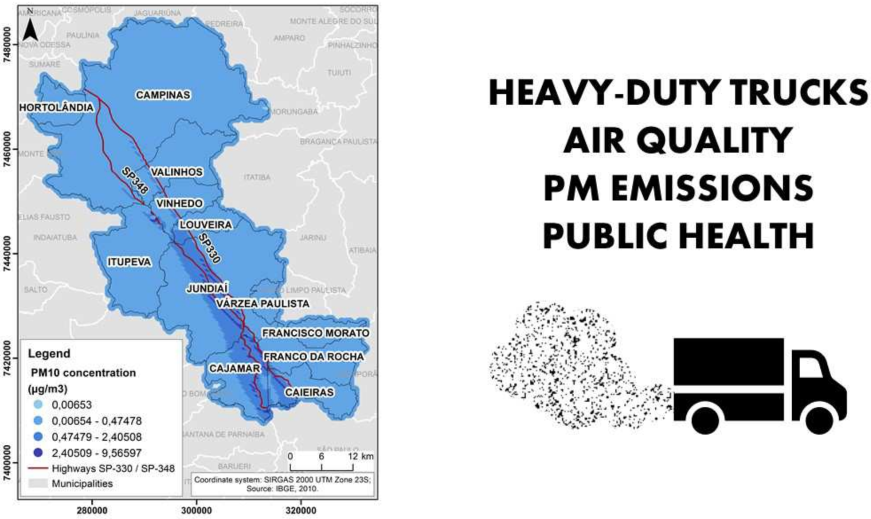
HIGHLIGHTS

- Public policies are needed to reduce air pollution in many sectors, not only in freight transport
- LNG helps to reduce PM emissions, but may not be sufficient to avoid attributable deaths in the vicinity of the expressways
- Only fuel replacement in heavy-duty vehicles used for freight transport in expressways is not enough to improve the health of the population

GRAPHICAL ABSTRACT



ABSTRACT

The Brazilian transport system is based on the use of highways and road heavy-duty trucks are the main type of vehicle to perform this activity. There are more than 1 million km of highways in the country and the search for alternative technologies to reduce emissions from the transport industry is increasing. The Blue Corridor research started to replace heavy-duty vehicles fueled by conventional diesel to liquefied natural gas (LNG) and its effect on pollutant emissions reductions. In this context, this paper aims at evaluating the atmospheric dispersion of particulate matter (PM) from road heavy-duty trucks in 12 cities in the São Paulo State, assessing the impacts of the replacement of full fleet powered by diesel to LNG and the effects on the health of the local population. The model AERMOD was used to simulate the dispersion of PM produced by heavy-duty vehicles fuel combustion and the methodology suggested by the World Health Organization (WHO) was used to analyze the number of deaths attributed to the PM emitted. Results showed some municipalities with high PM concentrations, which exceeded the limits suggested by WHO. In terms of health issues, cardiovascular diseases in a population older than 30 years were the main cause of death from PM emissions. When it comes to fuel replacement, LNG helps to reduce PM emissions, but considering this reduction alone is not sufficient to avoid attributable deaths.

Keywords: Particulate matter; heavy-duty trucks; air pollution; LNG; health impact; Air Quality Dispersion Model.

1. INTRODUCTION

Air pollution is an urban issue faced in different cities around the world (Figliozzi, 2017; Lurie et al., 2019; Zhao et al., 2018) and many epidemiological studies have shown that poor air quality is a risk factor for several outcomes in human health. According to the World Health Organization (WHO, 2018), 4.2 million premature deaths worldwide were caused by outdoor air pollution (Askariyeh et al., 2017; Baldauf et al., 2008; Finkelstein et al., 2004; Ozdemir, 2019; Wilhelm and Ritz, 2003) and several studies have shown the impact of particulate matter (PM) on the lung and systemic cardiovascular diseases (Bilenko et al., 2015; Liu et al., 2020; Wang et al., 2015). These effects include a decrease in lung function, an increase in the symptoms of asthma and chronic bronchitis, leading to more serious cardiopulmonary events, which result in increased hospitalizations and deaths (Isakov et al., 2009).

Given that vehicles are important sources of air pollution (Wen et al., 2017), understanding the magnitude of pollution that humans are exposed to is important to determine the effect of vehicle emissions on air quality near highways. In Brazil, outdoor air pollution from this sector is a major problem (Nogueira et al., 2019) and has become a public health concern.

To assess the population's exposure to emissions related to vehicle traffic considering time, distance from highways, meteorological and geographical conditions (Shabanpour et al., 2018; Shekarrizfard et al., 2016; Tong et al., 2020), several atmospheric dispersion models have been developed. These models allow the identification of individual source contributions to air pollution and assist in the design of effective strategies to reduce harmful air pollutants. One of these models is the AERMOD Model by EPA (US Environmental Protection Agency Regulatory) (Askariyeh et al., 2017), which is an important tool to manage air quality systems. AERMOD is a gaussian model and is still suggested as a reference model by regulatory agencies due to its simplicity of use (Maffia et al., 2020), including the Environmental Company of the State of São Paulo (CETESB) in Brazil.

One strategy to reduce harmful pollutants is the use of alternative fuels (Dey et al., 2018), especially in substitution of mineral diesel oil, which has one of the highest emissions factors within the available fuels for heavy-duty transport. Based on the statements above, this paper aims to estimate the deaths attributable to PM_{10} and $PM_{2.5}$ concentrations and analyze the dispersion of particulate matter by heavy-duty trucks in

Brazil and its effect on human health. To do so, this study uses the main highways in the state of São Paulo (Brazil) as a case study and estimates the population exposed to particulate matter and the consequent health impacts considering areas surrounding the area of study. Furthermore, this study analyzes a strategy to reduce pollution-related diseases by replacing diesel by liquefied natural gas (LNG) in road freight transport.

This paper is divided as such: Section 2 presents a literature review, section 3 presents the methodology, while section 4 brings the results and the appropriate discussions, with conclusions being drawn in section 5.

2. LITERATURE REVIEW

Particulate matter is a concept used for a large class of particles in the atmosphere. It also acts as a means of transport for other substances, such as hydrocarbons and metals, which are added to the particles (Kim et al., 2015). Size, chemical composition, and other properties, whether physical or biological, depending on the origin and transformations that these particles have undergone in the atmosphere. The measurement of particles is made according to their aerodynamic diameter, which can vary between 0.002 and 100 µm. Particles can be divided into ultrafine, which are less than 0.1 µm, fine ($PM_{2.5}$) with a diameter between 0.1 and 2.5 µm, large (PM_{10}) with a diameter up to 10 µm, and smoke (Daniel Vallero, 2008).

A major component of long-term health-related pollution is the fine particulate matter with an aerodynamic diameter equal to or below 2.5 µm ($PM_{2.5}$) (Liu et al., 2019). It is estimated that $PM_{2.5}$ exposure leads to millions of deaths globally every year (Burnett et al., 2014; Liu et al., 2019). Hoek et al. (2013) presented a review about the long-term air pollution exposure and their impacts on cardiorespiratory deaths and the results showed that long-exposure to $PM_{2.5}$ above the limits suggested by WHO (10 µg/m³ - annual mean) can increase around 11% the risks for cardiovascular diseases.

With the advancements of geospatial technologies, geospatial datasets are being increasingly used in health studies and accurate measurements of $PM_{2.5}$ concentrations and health statistics are the basis for reliable estimations of diseases burden attributable to $PM_{2.5}$, including cardiovascular, pulmonary, and cognitive effects (Liu et al., 2019; Nogueira et al., 2019).

Exposure to air pollutants is a risk factor for humans and many existing studies attempt to assess the relationship between air pollution and mortality using pollutant concentration data from air quality monitoring stations (Abe and El Khouri Miraglia, 2016; Andreão et al., 2018a; de Fatima Andrade et al., 2012; Martins et al., 2017a), on-site experiments (Nogueira et al., 2019), and meteorological models (Scovronick et al., 2016), such as AERMOD model used in this study. One example of AERMOD use for health effects was done by Tong et al. (2020), who analyzed the acute morbidity and the premature mortality in China in combination with the motor vehicle emission simulator (MOVES) model. Other authors like Sonawane et al. (2012) also use the AERMOD model to evaluate pollution reduction strategies for the transport sector, including the use of natural gas vehicles.

One limitation to do such studies in Brazil is the lack of measurements, with few stations, small-time series, and uneven availability of data, with pollutants lacking in several measuring stations. Air quality monitoring is in its infancy in Brazil and is still restricted and unsatisfactory in terms of territorial and temporal coverage, with measurements beginning in the year 2000 in São Paulo city (Andreão et al., 2018b). Although there has been an increase of $PM_{2.5}$ monitoring stations across the country, only 9 out of the 27 states have monitoring stations with 397 in total (IEMA, 2019a). For that reason, most of the studies related to pollutant emissions and atmospheric concentration fall within the Southeast region, where 80% of monitoring stations are found (IEMA, 2019b).

Recent works have tried to either understand pollutant emission profiles (Martins et al., 2017a; Suthawaree et al., 2012) and analyzes vehicles emissions (Briant et al., 2011; de Fatima Andrade et al., 2012; Misra et al., 2013; Nogueira et al., 2019; Shairsingh et al., 2018), or to establish health impacts from pollutant concentration through the estimation of premature deaths from diseases related to pollution (Abe and El Khouri Miraglia, 2016; Andreão et al., 2018a; Batterman et al., 2014; Scovronick et al., 2016). On a particular example of interest is the work done by (Rangel et al., 2018), due to their application of AERMOD in a Brazilian scenario. The authors estimated the volume of CO, P.M. $_{2.5}$, and NO_X generated and their dispersion in the atmosphere when burning sugarcane biomass in rural areas of Northeast Brazil, using the AERMOD model.

From the pollutant emissions profiles side, Martins et al. (2017) studied the extreme pollution events in Rio de Janeiro (RJ) and São Paulo (SP) metropolitan areas (MA) and compared the air quality of both MA. A higher concentration of pollutants, including $PM_{2.5}$, was more frequent during the winter and SP has a higher probability of experiencing extreme events for all pollutants. de Fatima Andrade et al. (2012) quantified the contributions that vehicles make to $PM_{2.5}$ concentration in 6 state capitals of Brazil. The project collected samples from these cities and found that in all cities vehicle emissions explained at least 40% of the $PM_{2.5}$ mass. Furthermore, only one capital (Recife) had concentrations lower than determined by the World Health Organization (WHO). Nogueira et al. (2019a) evaluated emissions from buses in 6 bus terminals in the urban metropolitan area of São Paulo (MASP). The study found that emissions of $PM_{2.5}$ from newer buses are lower and that the renovation of the bus fleet from Euro II to Euro V and the incorporation of electric buses had a noticeable impact on NO emissions.

From the health impacts side, Scovronick et al. (2016) modeled the impacts on air quality and health of ethanol use and production in Brazil. The study takes into consideration not only ethanol consumption in vehicles but also sugarcane burning. Results from their study show that ethanol use would reduce 1100 life-years in the first year of analysis and 40,000 life-years and that gasoline has better pollution performance than ethanol if life-cycle is taken into consideration. Abe and El Khouri Miraglia (2016) calculated the avoided deaths from $PM_{2.5}$ abatement scenarios. The authors found that SP could reduce 5 thousand premature deaths and save USD 15 billion annually with health expenses if WHO $PM_{2.5}$ concentration standards were attained. Similarly, Andreão et al. (2018b) calculated the avoidable deaths of attaining WHO $PM_{2.5}$ concentration standards in 24 Brazilian cities. In their results, SP showed the highest number of avoidable deaths reaching 82 thousand from all causes in 2017.

These studies have provided important insights regarding air quality in Brazil and highlighted the importance of monitoring pollution and the resulting health impacts from high pollutant concentrations. However, most of the studies are deterministic by nature and do not include the uncertainties regarding spatial distribution. Different from previous studies, this study calculates attributable deaths using a Monte Carlo analysis, to take into account the spatial uncertainty when it comes to PM exposure.

Moreover, this study models the freight sector and analyzes the avoided deaths from the change in the fuel use status quo paradigm in Brazil, presenting an analysis of a practical pollution prevention measure.

3. NATURAL GAS AS A WAY TO REDUCE POLLUTION

The availability of domestic natural gas reserves improved fueling infrastructure, and state incentives helped promote the use of natural gas in the transportation sector around the world (Singh, 2015). Natural gas vehicles have increased in many captive heavy-duty fleet applications (Thiruvengadam et al., 2018), based mainly on the environmental benefits that natural gas could bring, regarding greenhouse gases and local pollutant emissions (Singh, 2015).

From the environmental perspective, natural gas is said to produce between 70% and 85% fewer toxic pollutants than gasoline and diesel vehicles, respectively, and a 10% greenhouse gases (GHG) emission reduction compared to diesel trucks (Arteconi and Polonara, 2013). The transport sector, therefore, is considered by many scholars as an option for natural gas to substitute diesel and other fuels (Josephs, 2015; Pfoser et al., 2016; Xian et al., 2015) due to its environmental benefits. Adding to this, Brazilian natural gas production has reached the highest levels in 2018 due to the pre-salt layer, and new uses are necessary to avoid wasting this resource since 75% of natural gas in Brazil is associated to natural gas, which is extracted with the extraction of oil (SEMSP, 2017).

When it comes to local pollutants, many studies have focused on natural gas as an alternative to the transport sector to reduce emissions. With the addition of oxidation catalysts, carbon monoxide (CO) emissions are reduced by 62% in comparison with uncontrolled natural gas engines (Thiruvengadam et al., 2018), leading to diesel-equivalent emissions(Stettler et al., 2016). Compared to gasoline, Chen et al. (2019) reviewed 5 experimental papers and all of them show CO reductions in dual-fuel engines running with natural gas. The same result was shown by Kalam et al. [40], who tested dual-fuel engines and found a 90% reduction when using natural gas in comparison to gasoline.

Nitrogen oxides (NOx) emissions differentials between natural gas and diesel engines are the most notable among the pollutants. A review made by M. E. J. Stettler et al. (2016) shows lower NOx emissions compared to diesel engines, and Thiruvengadam et al. (2018) say that, in the case of stoichiometric combustion, three-way catalysts are efficient in reducing NOx emissions to near-zero. M. Stettler et al. (2019) also showed lower average NOx emission factors for both spark-ignition and HPDI for freight trucks compared to diesel. However, the authors state that diesel trucks are meeting the latest NOx emissions standards with selective catalytic reduction, which reduces natural gas benefits. On the same note, Smajla et al. (2019) say LNG reduces NOx by 80%

compared to diesel and that LNG trucks with three-way catalysts have a lower break-specific emissions and Vermeulen et al. (2017) who tested 2 LNG trucks, found that NOx emissions were the same as diesel trucks.

Hydrocarbons emissions of natural gas trucks in comparison to diesel are reported as higher in M. E. J. Stettler et al. (2016), Thiruvengadam et al. (2018), and M. Stettler et al. (2019), due to the fuel methane content and leakage. Finally, PM emissions, on the other hand, has been reported to be lower in LNG trucks than diesel by (Thiruvengadam et al., 2018), (Stettler et al., 2019).

4. METHODOLOGY

To evaluate the health impacts from the fuel replacement of diesel by LNG, it was necessary to analyze PM_{10} and $PM_{2.5}$ concentrations through the atmospheric air pollution dispersion in 2016. First, a background concentration analysis was performed to evaluate the impacts on population health surrounded by the highways. It is important to note that this value covers different types of PM sources (industries, transport, combustion, environment, etc.). To evaluate the atmospheric dispersion, meteorological and traffic data, PM_{10} and $PM_{2.5}$ emissions factors, receptors, and locations data were used as input to the AERMOD model.

The AERMOD model is an air quality model recommended by the EPA, which applies to complex terrains and incorporates a new downwash algorithm - PRIME, which considers the effects of pollutant deposition. Thus, AERMOD is considered the best model of last generation Gaussian dispersion, whose formulation is based on the principles of the planetary boundary layer (EPA, 2005). For this reason, the Environmental Agency of the State of São Paulo, CETESB, recommends using this model to simulate environmental concentrations for periods of short and long exposure (CETESB, 2019).

The results from simulations and the background concentrations were used to calculate the concentration from the fleet replacement and attributable deaths to PM emissions. Details are found in subsections. Figure 1 shows a flowchart of the steps from the methodology.

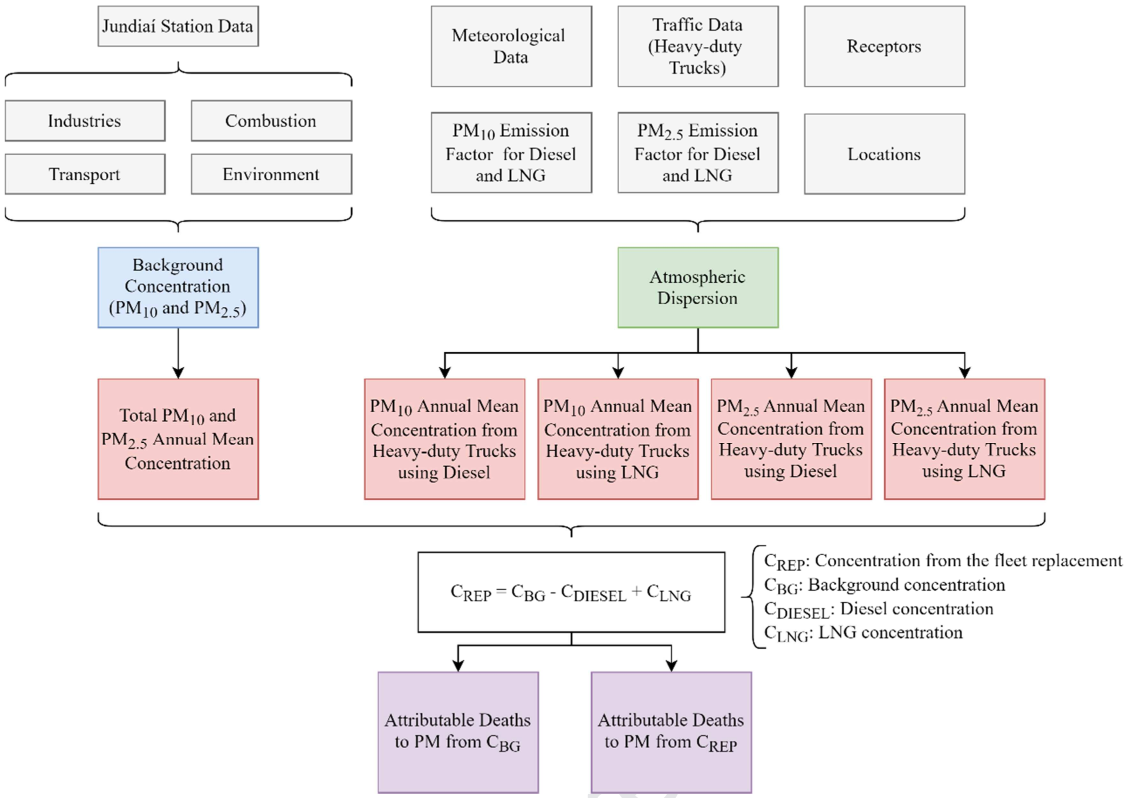


Figure 1 – Methodology flowchart.

4.1 Background concentration

First, to evaluate the impacts of PM atmospheric dispersion emissions from heavy-duty vehicles in both highways, there was a need for background concentration data. These values are important since there are other pollutant sources, which are not treated in the model (Borrego et al., 2006) and if not considered, it can be a source of uncertainty (Stein et al., 2007). According to EPA (2005), background data can be acquired from air quality monitoring stations and modeling output results. In the case of this work, estimate background concentrations was possible only for the city of Jundiaí, where there are meteorological and air quality data available. Since the spatial representativity technique used by the Environmental Company of the State of São Paulo - CETESB (2016) determined that measurements taken at Jundiaí station are representative for a range of 50 km and the other cities analyzed are located in a lower distance, the same background data was used for all cities.

The background concentration was calculated considering the methodology proposed by Tchepel et al. (2010) and Python programming language was used to model this part. As suggested by Tchepel et al. (2010), a time series of hourly averaged concentrations were used to calculate background PM_{10} concentration measured at the Jundiaí Station (CETESB, 2020) for 2016. The spectral analysis enables to evaluate the contribution of different frequencies of fluctuations on the time series and the Kolmogorov-Zurbenko (KZ) filter was used to remove frequencies higher than 0.0905 h^{-1} (12 h period). The filter consists of calculating a moving average of the time series with a subset of three consecutive values. This calculation is repeated three times, once on the unfiltered series and twice on the previously updated series. The background concentration is then determined by averaging the filtered time series. Here, the annual PM concentration average is determined by calculating the mean of the hourly values of the filtered series. The standard deviation was also calculated and showed a lower value than for the unfiltered series, as the filter removes high-frequency peaks.

In order to analyze the health impacts from the replacement of the full fleet of conventional heavy-duty vehicles using diesel by LNG, a Monte-Carlo analysis was developed to calculate a range of possible deaths associated with air pollution. To reach this goal, we calculate 10,000 times the concentrations considering background, diesel, and LNG contributions. To evaluate the concentrations due to the full replacement, Eq. 1 was performed.

$$C_{REP} = C_{BG} - C_{DIESEL} + C_{LNG} \quad (1)$$

Where: C_{REP} – Concentration from the full fleet replacement; C_{BG} – Background concentration; C_{DIESEL} – Diesel concentration from heavy-duty trucks using this fuel; C_{LNG} – LNG concentrations from heavy-duty trucks using this fuel. It is important to highlight that this equation results in the contribution of only primary PM emitted by the freight traffic on the two roads considered for 2016.

4.2 Air Quality Dispersion Model

Considering data availability and the importance of the southeast region, more specifically of the São Paulo state, this study focused on two highways that connect two important cities of the State, which compose the largest concession highway system in terms of revenues in the state of São Paulo and in Brazil (CCR, 2020). The stretch considered connects the city of São Paulo to Campinas and is composed of the highways Anhanguera (SP 330) and Bandeirantes (SP 348), shown in Figure 2. Data from the vehicle traffic was obtained with Brazilian Infrastructure Ministry, considering the number of heavy-duty trucks in 2016.

Figure 2 – Highways and cities considered in this study.

To study the atmospheric dispersion around the highways, the software AERMOD (EPA, 2020), an Air Quality Dispersion Model developed by EPA (the United States Environmental Protection Agency) was used. It is a Gaussian plume model based on the turbulence structure of the planetary boundary layer and scale concepts, including the treatment of surface and elevated sources. However, AERMOD does not consider any chemical reactions and, therefore, here only primary PM is considered. EPA provides a set of preprocessors and here only AERMET, which is responsible for processing meteorological data, was used. Data such as surface characteristics, roughness, albedo, wind speed/direction, and temperature are provided for AERMET to pre-process the surface characteristics of the meteorological data.

AERMOD uses data from AERMET to calculate atmospheric dispersion. The software is capable to model different types of sources, whether they are punctual, volumetric, line, or area, which is the way that this study was processed. Table 1 shows the input data used to run the AERMET model.

Table 1 – Meteorological input data.

Parameter	Data	Source
Temperature Measurement Height	2 m	CETESB station (Jundiaí)
Wind Measurement Height	10 m	CETESB station (Jundiaí)
Wind Speed	Data considering the period 01/01/2016 to 12/31/2016	CETESB station (Jundiaí)
Boundary-Layer Height	Climatological height calculated by Sánchez et al. (Sánchez et al., 2020)	Sánchez et al. (Sánchez et al., 2020)

The stretch was divided into 28 pieces due to curves on the roads and to facilitate the analysis. Latitude and longitude from the initial and final points from each piece were identified using ArcGIS software and passed to AERMOD. The daily distribution of emissions for heavy-duty vehicles was used from the study performed by Andrade et al. (Nogueira et al., 2019). Using the data on vehicles counting at toll plazas, vehicles' average speed, PM emission factors, and highway width it was possible to calculate the daily emission rate, which is shown by Eq. 2.

$$DR = \frac{\left(EF_i \times Tot_v \times \frac{S_{avg}}{3600}\right)}{D \times W} \quad (2)$$

Where: DR – daily rate (g/sm²); EF_i – emission factor from the pollutant i (g/km); i – pollutant analyzed; Tot_v – number of vehicles; S_{avg} – average speed (km/h); D – the distance between initial and final points for each piece of a stretch; W – highway width. The highway width is needed because the model AERMOD simulates lines as areas and ask for a width.

PM emission factor data for heavy-duty vehicles powered by diesel was obtained from the Environmental Company of São Paulo State, called CETESB (CETESB, 2017) and heavy-duty vehicles powered by LNG was obtained from Mouette et al. (2019). An average of 0.07 gPM_{10}/km was used for Diesel, while an average of 0.0002 gPM_{10}/km was used for LNG. Although these values were used in other studies or even used as based to calculate emissions from heavy-duty trucks in CETESB, there is some uncertainties about the emission factors such as the engine characteristics, location, life cycle and other. Other point to be raised is that only PM_{10} emission factor was available. In order to estimate $PM_{2.5}$ emission factor, the relationship proposed by Ostro et al. (2004) was used. When all values are available, it is preferred to use the measurement data, but in cases without these, $PM_{2.5}$ can be estimated through the ratio between $PM_{2.5}$ and PM_{10}. Considering the case of exhaust emissions, this ratio is found in literature in a large range since between 0.5 to 1, since it depends on several parameters (EEA, 2012; Sã¡nchez-Triana et al., 2015). In order to cover the possibilities, the ratios of 0.5, 0.8, and 1 were considered in this paper.

The simulation was performed for the 2016 period (8,784 hours). Considering the entire area, 8,883 receptors have been placed, wherein each of them shows the simulated PM_{10} and $PM_{2.5}$ concentration on the annual time scale. It is worth mentioning that the replacement of diesel fuel by LNG was 100% for the cargo vehicle fleet. The simulation was performed for the 12 cities showed in Figure 2 using the AERMOD model. Each city was divided into receptors locations using a Cartesian grid with 500 meters between each grid point. Table 2 shows the number of receptors according to the city. The model was performed for PM_{10} and $PM_{2.5}$ for both fuels (diesel and LNG) using flat conditions for the terrain, as the location does not present a substantially complex terrain and 0.5 meters of height exhaust tailpipe. Results from AERMET preprocessors were also used to run the AERMOD model.

Table 2 – Population and number of receptors in each city.

City	2016 Population[1]	Population Density[1] (People/km^2)	Number of receptors
Caieiras	93,215	970	398
Cajamar	69,584	530	522
Campinas	1,144,862	1,439	3,177
Francisco Morato	164,718	3,350	193
Franco da Rocha	141,824	1,059	525
Hortolândia	209,139	3,359	251
Itupeva	51,082	255	807
Jundiaí	393,920	914	1,724
Louveira	41,700	754	225
Valinhos	116,308	784	600
Várzea Paulista	114,170	3,298	142
Vinhedo	69,845	855	319

[1](IBGE, 2016).

4.3 Estimating health impacts

Regarding the public health impacts from road freight transport, a methodology suggested by WHO (Ostro et al., 2004) was used to quantify the deaths attributable to air pollution. It is an environmental burden disease (EBD) model, which has great relevance for environmental health studies, as it can show the magnitude of the problems in the area and of encouraging the planning of preventive measures. This model considers the concept of the attributable fraction to estimate the number of lives saved if concentrations of particulate matter fulfilled the air quality standard.

To characterize the probability of occurrence of an event such as the case of an acquiring a disease, it is necessary, in epidemiological studies, to calculate the risk associated with this event. In this study, the Relative Risk (RR) is calculated, which shows how much the risk is higher in one group when it is compared to another. An RR of 1 suggests that there is no association between exposure and outcome. A RR greater than 1 suggests the existence of this association, and below 1, indicates a negative association. The risk functions for EBD are presented in Table 3.

Table 3 – Recommended health outcomes and risk functions.

Outcome and exposure metric	Relative Risk (RR)	Suggested β coefficient (95% CI)	Subgroup
Respiratory mortality and short-term exposure to PM_{10}	$RR = e^{[\beta(X - X_0)]}$	0,00166 (0,00034 – 0,0030)	Age < 5 years
Cardiopulmonary mortality and long-term exposure to $PM_{2,5}$	$RR = \left[\frac{X+1}{X_0+1}\right]^{\beta}$	0,15515 (0,0562 – 0,2541)	Age > 30 years
Lung cancer and long-term exposure to $PM_{2,5}$	$RR = \left[\frac{X+1}{X_0+1}\right]^{\beta}$	0,23218 (0,0853 – 0,37873)	Age > 30 years

Where: X – Current pollutant concentration (µg/m³); X_0 – Target pollutant concentration (10 µg/m³ for $PM_{2.5}$ and 20 µg/m³ for PM_{10}). Source: WHO. Environmental Burden of Disease Series, No. 5. Outdoor Air Pollution: Assessing the environmental burden of disease at national and local levels (Ostro et al., 2004).

The result of the RR enables the calculation of the Attributable Fraction shown in Eq. 3 and the number of cases associated with air pollution shown in Eq. 4.

$$AF = \frac{RR-1}{RR} \quad (3)$$

$$E = AF \times P \qquad (4)$$

Where: E – expected number of deaths due to air pollution; AF – attributable fraction; P – population exposed to a health effect.

The mortality data for childhood respiratory disease, elderly respiratory disease, cardiovascular disease, and cancer disease were obtained from the online mortality system (Codes J09-J18 and J20-J22, J09-J18 and J40-J47, I 60-I69 and I20-I25, C30 – C39, respectively) of the Brazilian Integrated Health System (SUS) (DATASUS, 2020) for each city by age group for 2016. Using Matlab, Monte-Carlo analysis was developed to calculate a range of possible deaths associated with air pollution. This provides a probability of associated deaths, not a deterministic value, which is necessary since the data from DATASUS does not provide information about people's location, or where they live, work, etc. Thus, there is uncertainty about the PM concentration that each person is exposed to since the concentration varies over each city area.

The data obtained from the AERMOD simulations were used to analyze the impacts on human health through the calculation of the attributable deaths to PM emissions. The attributable deaths were calculated 10,000 times, changing the PM concentration, based on the spatial distribution provided by AERMOD. These values were calculated considering the background concentrations and the scenario with full fleet replacement. The avoided deaths from the fleet replacement were calculated based on Eq. 5:

$$AVD = AD_{BG} - AD_{LNG} \qquad (5)$$

Where: AVD – Avoided deaths; AD_{BG} – deaths attributable to background PM concentration with the current fleet (100% diesel); AD_{LNG} - deaths attributable to background PM concentration with LNG fleet (100% LNG, replacement scenario).

5. RESULTS AND DISCUSSIONS

Results are separated into two topics: PM atmospheric dispersion and health impacts. Each one shows the results obtained for the highways stretch and the impacts of the replacement of road heavy-duty vehicles fueled with conventional diesel by LNG on background concentration.

5.1. PM atmospheric dispersion: heavy-duty vehicles in the Anhanguera-Bandeirantes complex

The transport of atmospheric pollutants is mainly driven by predominant wind flow. Figure 3 shows the wind rose produced with the wind data used by the AERMOD simulation. It is clear that the wind is more frequently from the SE direction in this region. This pattern has a substantial influence on the atmospheric dispersion of pollutants.

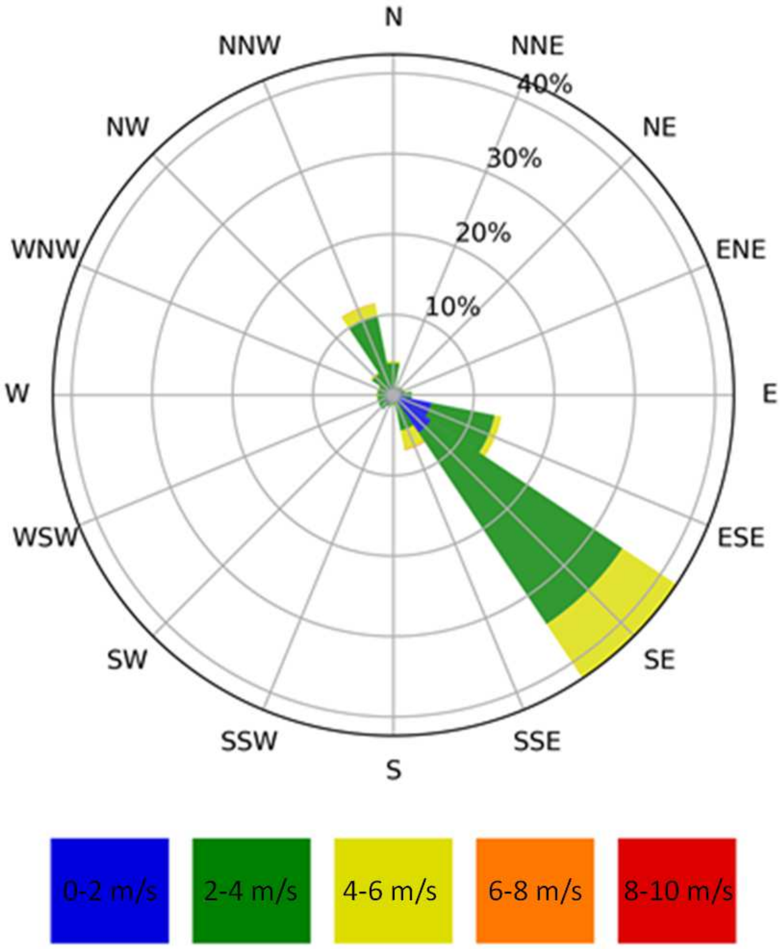


Figure 3 – Wind rose for CETESB station (Jundiaí) in 2016.

PM atmospheric dispersion, emitted by heavy-duty trucks in the Anhanguera-Bandeirantes complex, was simulated using AERMOD to evaluate the pollutant behavior, route, and which cities could be more affected. Figure 4 shows the mean concentrations considering PM_{10} emissions only from road heavy-duty vehicle traffic, fueled by conventional diesel (current fleet, on the left) and LNG (right). The influence of wind direction is noticed in the concentration pattern. It is expected that the highest concentration is found near the roads, which are the source of pollution. As the predominant wind direction is mainly aligned with the road's orientation, the concentration is even higher near the roads, with less dispersion in the southwest-northeast axis. Another issue to be highlighted is that highways areas, especially for the Bandeirantes, there are a few buildings, which contribute to air pollution dispersion.

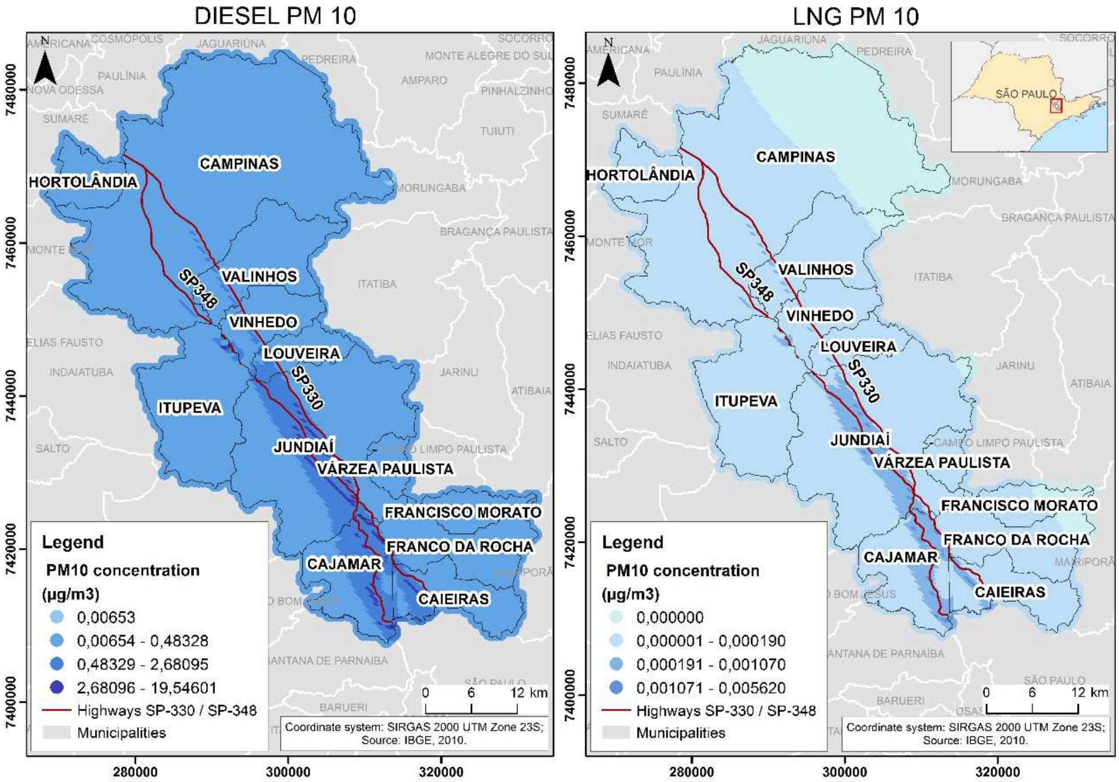


Figure 4 –Annual PM_{10} concentration from trucks emissions using Diesel (left) and LNG (right)

Note that the simulated concentrations vary from place to place. As expected, the highest concentrations are located close to the highways (highlighted in darker blue. As the model shows, the concentrations decrease as dispersion increases; meaning that the further away from the highways, the plume dispersion increases, and PM concentrations decrease.

Figure 4 also shows that the results vary from 0.0065 µm/m³ to 19.54 µm/m³ for diesel, highlighting the lowest concentration in the city of Campinas, far from the highway, while the highest concentration is in the city of Jundiaí (19.54601µm/m³), close to the Bandeirantes highway (SP-348), followed by Cajamar (16.19795µm/m³), close to the Anhanguera highway (SP-330). For LNG, the range was from 0 µm/m³ to 0.00562µm/m³, with the lowest concentration found in Campinas (1.158 receptors), Francisco Morato (44 receptors), Franco da Rocha (63 receptors), Jundiaí (9 receptors) and Valinhos (29 receptors), far from the highways; and the largest concentration was in Jundiaí close to the Bandeirantes highway. It is also observed that the lowest concentration of PM_{10} for diesel is higher than the highest concentration for LNG fuel, showing a reduction in particulate material when the fuel replacement is performed. It is important to notice that here only the PM directly emitted from the freight traffic in Anhanguera and Bandeirantes roads is considered.

Figure 5 illustrates the results of annual mean concentrations considering $PM_{2.5}$ emissions from diesel and LNG, based on the same conditions and period of PM_{10}.

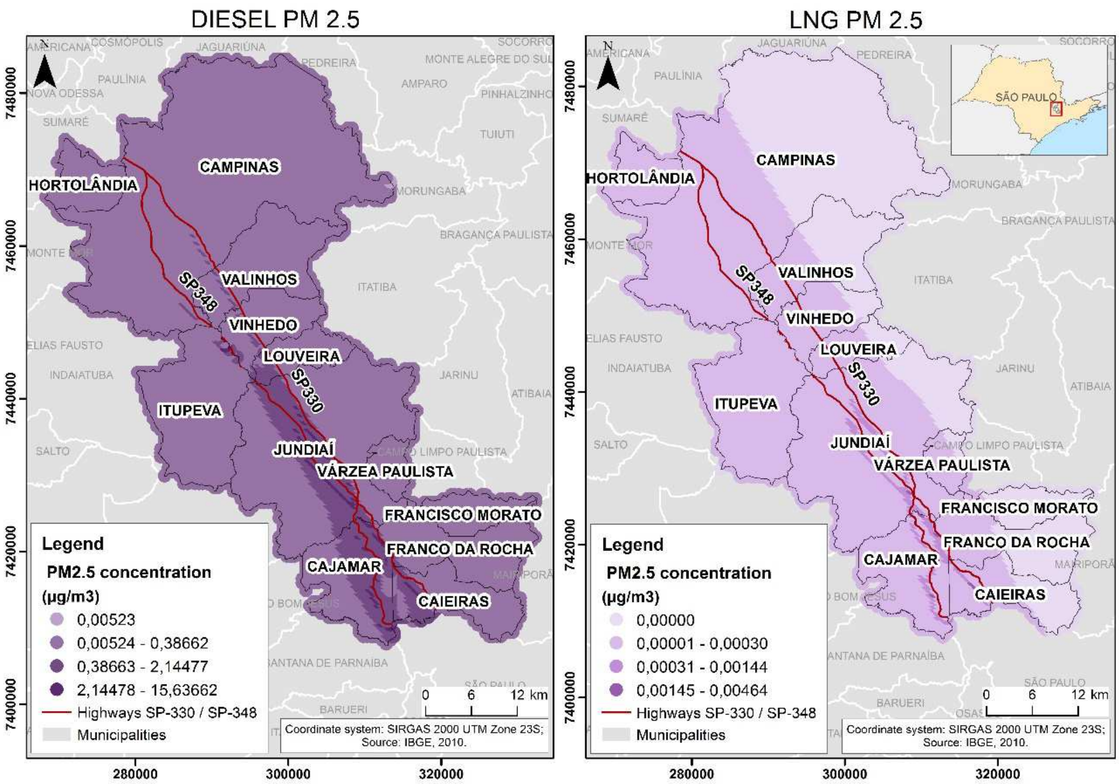


Figure 5 – Annual $PM_{2.5}$ concentration from trucks emissions using Diesel (left) and LNG (right)

Similarly, as expected since $PM_{2.5}$ emissions were estimated based on PM_{10} emissions, the simulated concentrations for $PM_{2.5}$ vary according to the proximity and distance to the highways. In general, the lowest values are far from the highways, while the highest values are close to them (highlighted in darker purple). Moreover, the simulations showed that fuel replacement can reduce $PM_{2.5}$ emissions and impacts for the surrounded neighborhood.

For diesel, the variation corresponds to the ranges from 0.0052 µm/m³ to 15.63 µm/m³, as shown in Figure 5, with the lowest value for Campinas, far from the highways, and the highest value in Jundiaí, close to the highway Bandeirantes. For LNG, the variation ranges from 0 µm/m³ to 0.0046 µm/m³, with the lowest value away from the highways, in part of the municipalities of Caieiras (144 receptors), Campinas (1616 receptors), Várzea Paulista (19 receptors), Vinhedo (44 receptors), Francisco Morato (188 receptors), Franco da Rocha (315 receptors), Itupeva (2 receptors), Jundiaí (263 receptors), Louveira (66 receptors) and Valinhos (335 receptors), and the highest value located in the municipality of Jundiaí, close to the Bandeirantes highway.

One issue to be mentioned about the concentration results found using AERMOD model is that it is directly dependent on emission factor of heavy-duty vehicles. Considering the sector and technologies for the road freight transport, there are some gaps about pollutant emissions factor and how these values are used in the scientific community. Experimental works (Adam et al., 2017; Alamia et al., 2016; Ogunkoya and Fang, 2015) with different type of fuels have been done around many countries, but each one has specific characteristic and maybe, cannot be considered for everywhere. However, some papers use these results as a starting point for other research, without consider the differences. Thus, in this paper, PM emissions factor used were considering the values used by CETESB in Brazil.

5.2. Health impacts

To evaluate the air pollution impacts on human health from PM emissions, the methodology proposed by Ostro et al. (2004) was used to calculate the attributable deaths for lung cancer, cardiovascular and respiratory diseases in the elderly and children. As previously mentioned, the attributable deaths were calculated for all 12 cities surrounded by highways Anhanguera and Bandeirantes.

It is worth to remember that other pollutant does impact human health in different ways, but the idea of this paper is to evaluate the health impact regarding PM from road freight transport. In this case, as already mentioned, only the primary pollutant was considered. Although other pollutants directly impact the human health, such as the case of black carbon – PM major component from incomplete combustion

(Watson and Valberg, 2001), the methodology proposed by WHO (Ostro et al., 2004) considers the whole PM_{10} and $PM_{2.5}$ to quantify deaths attributable to air pollution due to a short and long exposure. Regarding the global emissions of black carbon, it is estimated that road transport contributes approximately 10%, with on-road diesel engines emitting more than 85% in the transport sector (Zheng et al., 2016), as future research, it is interesting to estimate the contribution of black carbon and the impacts on human health.

Figure 6 shows the attributable deaths to PM emissions for the background concentrations (24.63 $\mu m PM_{10}/m^3$), which includes the emissions from diesel trucks, for all cities analyzed. This phase of the process was necessary since the background concentration accounts for PM emissions from different sources. Considering the background concentration, only this value exceeds the annual mean (20 $\mu m PM_{10}/m^3$) target by WHO.

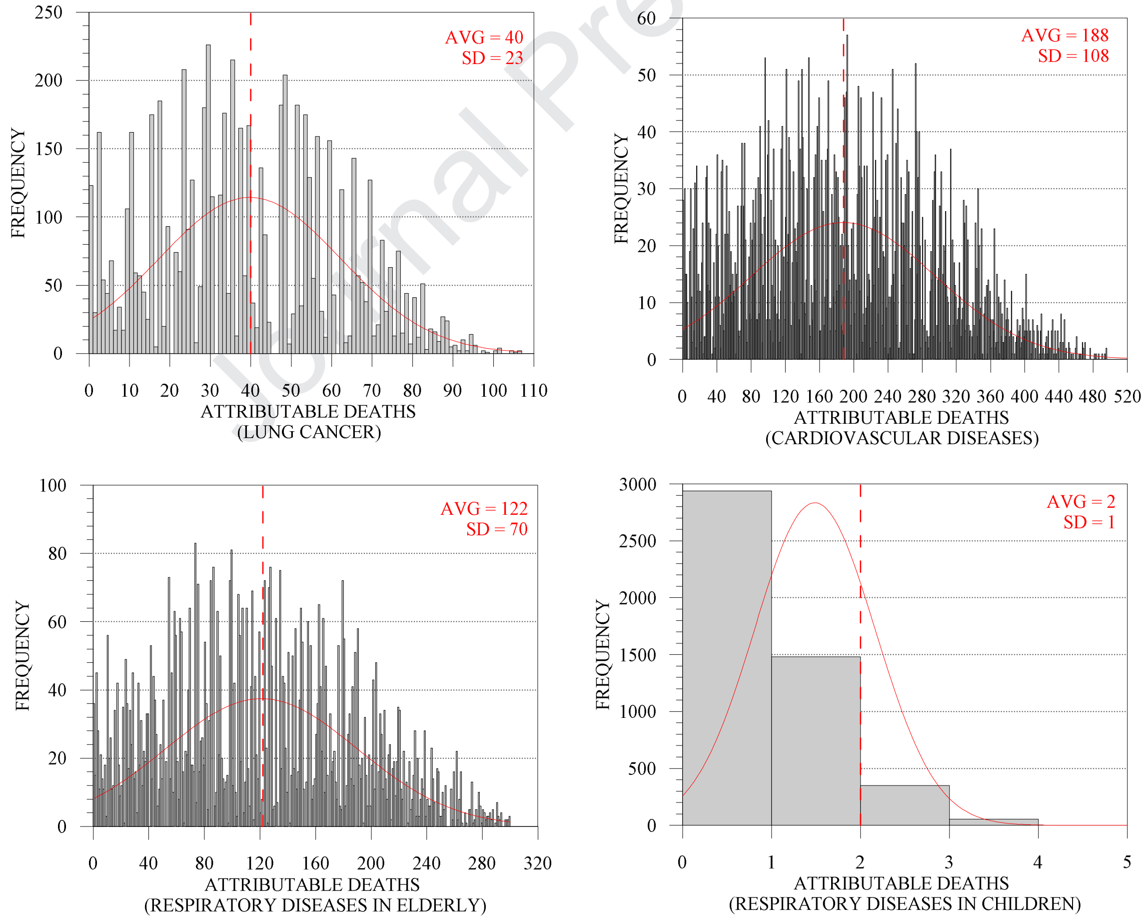


Figure 6 – Attributable deaths to PM concentration due to lung cancer (top-left), cardiovascular diseases (top-right), respiratory diseases in elderly (bottom-left), and respiratory diseases in children (bottom-right).

Considering the diseases analyzed, Figure 6 shows that cardiovascular problems presented the highest number of deaths attributable to PM concentration with an average of 188 deaths, ranging from 8 to 296 deaths in 2016. The results found in the study presented by (Rodrigues et al., 2015) for the São Paulo State also found the highest values for cardiovascular diseases, representing one of the major air pollution effects on human health. Followed by respiratory diseases in elderly people, ranging from 52 to 190 deaths and lung cancer, with a range from 18 to 62 deaths attributable to PM concentration. The lowest number of attributable deaths regards respiratory diseases in children, with 1 death attributable to PM concentration.

Considering the use of LNG in road heavy-duty trucks in the highways analyzed, Figure 7 shows the deaths attributable to PM concentration if 100% of road heavy-duty fleet fueled by conventional diesel would be replaced by road heavy-duty vehicles using LNG. It is possible to note that the behavior of the attributable deaths to PM emissions considering only the use of LNG is similar to the values from PM background emissions, with only the use of diesel, presented in Figure 6. Cardiovascular diseases represent the major causes of deaths attributed to PM emissions even with the replacement of 100% of the road heavy-duty trucks fleet using LNG.

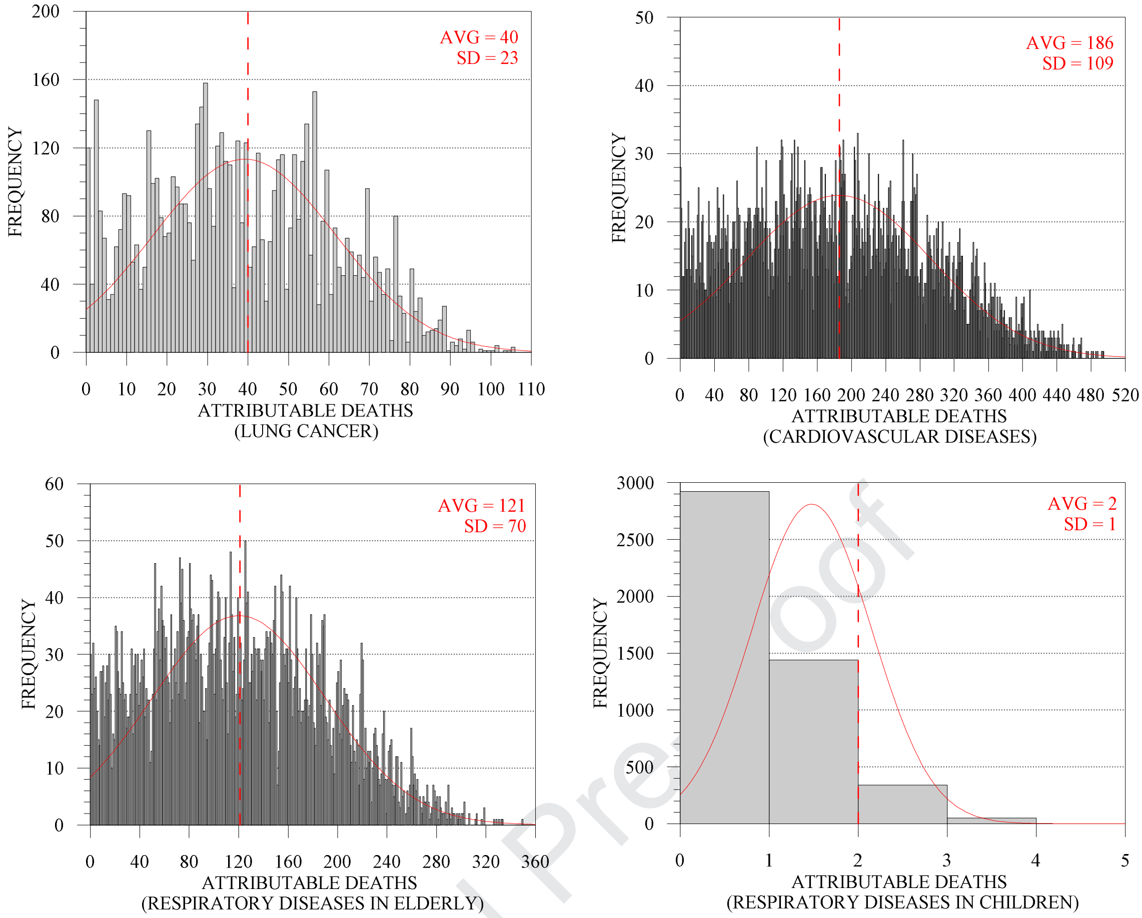


Figure 7 – Attributable deaths to PM concentration considering the LNG substitution due to lung cancer (top-left), cardiovascular diseases (top-right), respiratory diseases in elderly (bottom-left), and respiratory diseases in children (bottom-right).

The results have shown that even with a full fleet replacement, the number of expected deaths would not change in the period. Therefore, this item needs to be considered alongside other measures in the transport sector to guarantee a decrease in the number of deaths. Figure 8 shows the deaths that could be avoided in the replacement scenario. In Figure 8, the attributed deaths to PM emissions are around 1 or 2, varying according to the disease. These results represent a starting point to discuss the need for public policies in different areas to incentivize emissions reductions, not only of PM but also of other pollutants, such as carbon monoxide and nitrogen oxides.

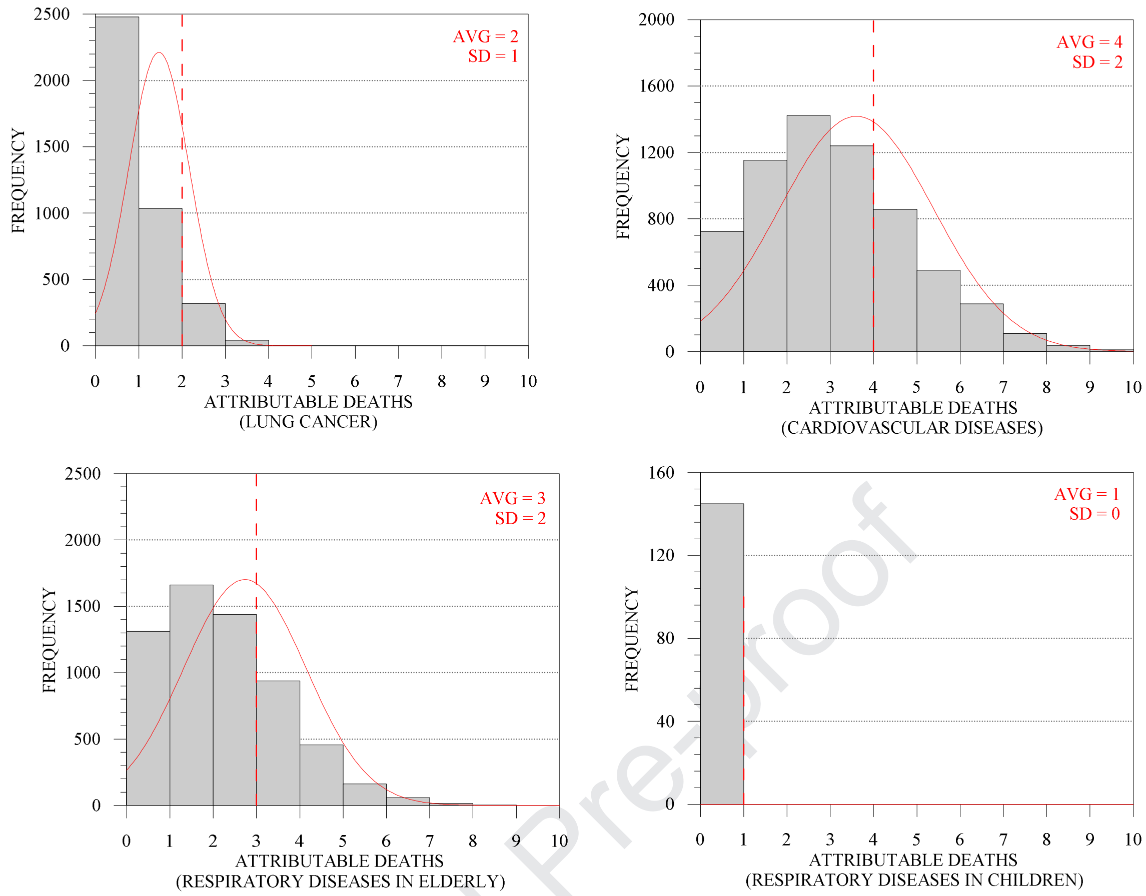


Figure 8 – Reduction of attributable deaths due to the fuel replacement for lung cancer (top-left), cardiovascular diseases (top-right), respiratory diseases in elderly (bottom-left), and respiratory diseases in children (bottom-right).

Through the Monte Carlo simulation, it was possible to find a range of attributable deaths for each disease analyzed and also the accumulated probability. Figure 9 shows the accumulated probability of avoided deaths according to the disease. For lung cancer, there is a 100% chance that less than 5 deaths per year would be reduced. For cardiovascular diseases, the maximum would be 14 deaths, but with a 90% chance of fewer than 5 deaths being avoided. Regarding respiratory diseases in the elderly, there is a 100% chance that less than 10 deaths would be avoided in the replacement scenario. Finally, there is no chance for diesel substitution for LNG alone to avoid any deaths due to respiratory diseases in children. These results point out that the other sources that contribute to the background concentration have a substantially higher impact in public health for this area than the road freight traffic, suggesting that other measures are needed to improve air quality in this cities, maybe including changing fuel for local traffic heavy-duty vehicles and buses.

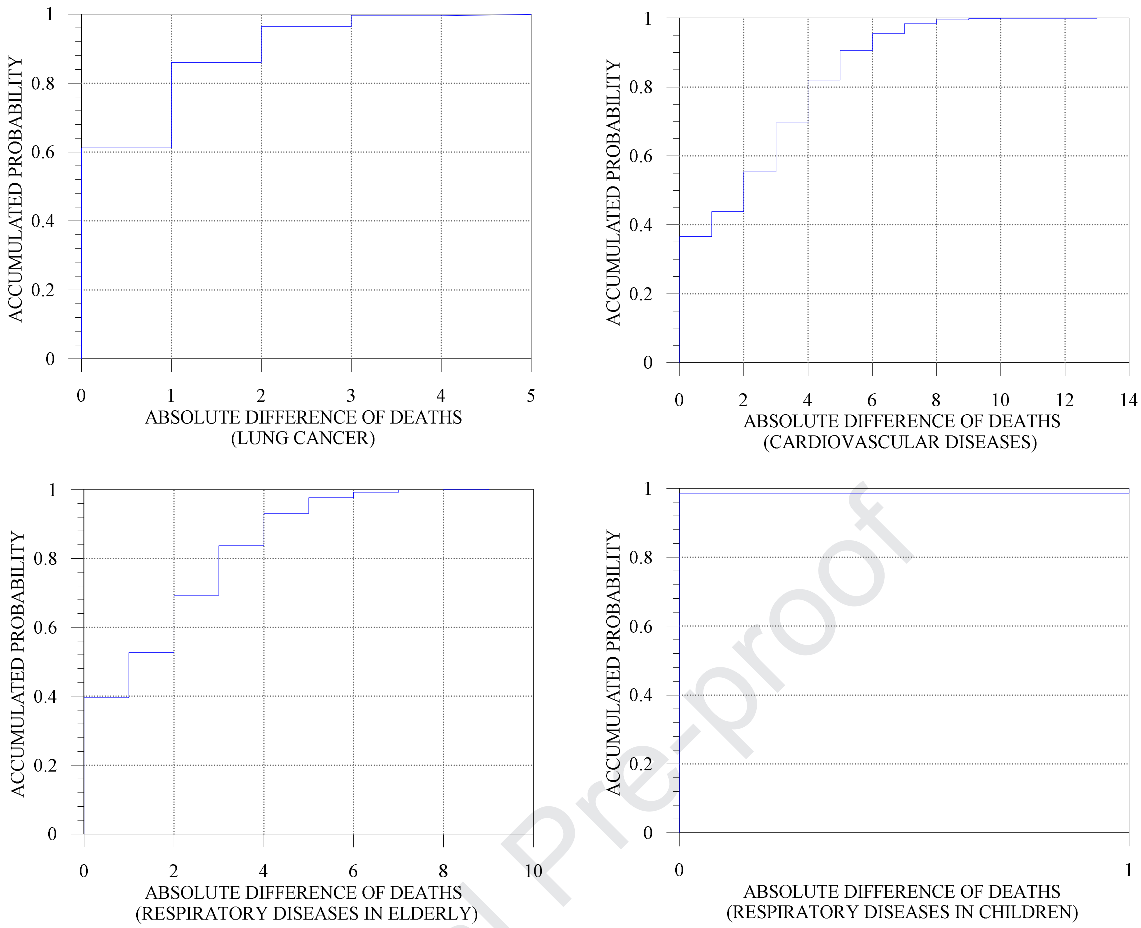


Figure 9 – The accumulated probability of deaths from LNG replacement for lung cancer (top-left), cardiovascular diseases (top-right), respiratory diseases in elderly (bottom-left), and respiratory diseases in children (bottom-right).

As previously mentioned in the methodology, three different ratios of $PM_{2.5}$ and PM_{10} were considered to calculate $PM_{2.5}$ emissions. Figure 10 shows the accumulated probability of deaths avoided for each disease. It was observed that the difference between $PM_{2.5}$ / PM_{10} ratios is small. In the case of lung cancer, considering all ratios, there is a 100% chance that less than 6 deaths per year would be reduced with LNG replacement. For cardiovascular diseases, the maximum number of deaths avoided is 14. For respiratory disease in the elderly, the maximum number of avoided deaths is 12 and in children, 1 death would be avoided for the three $PM_{2.5}$ and PM_{10} ratio.

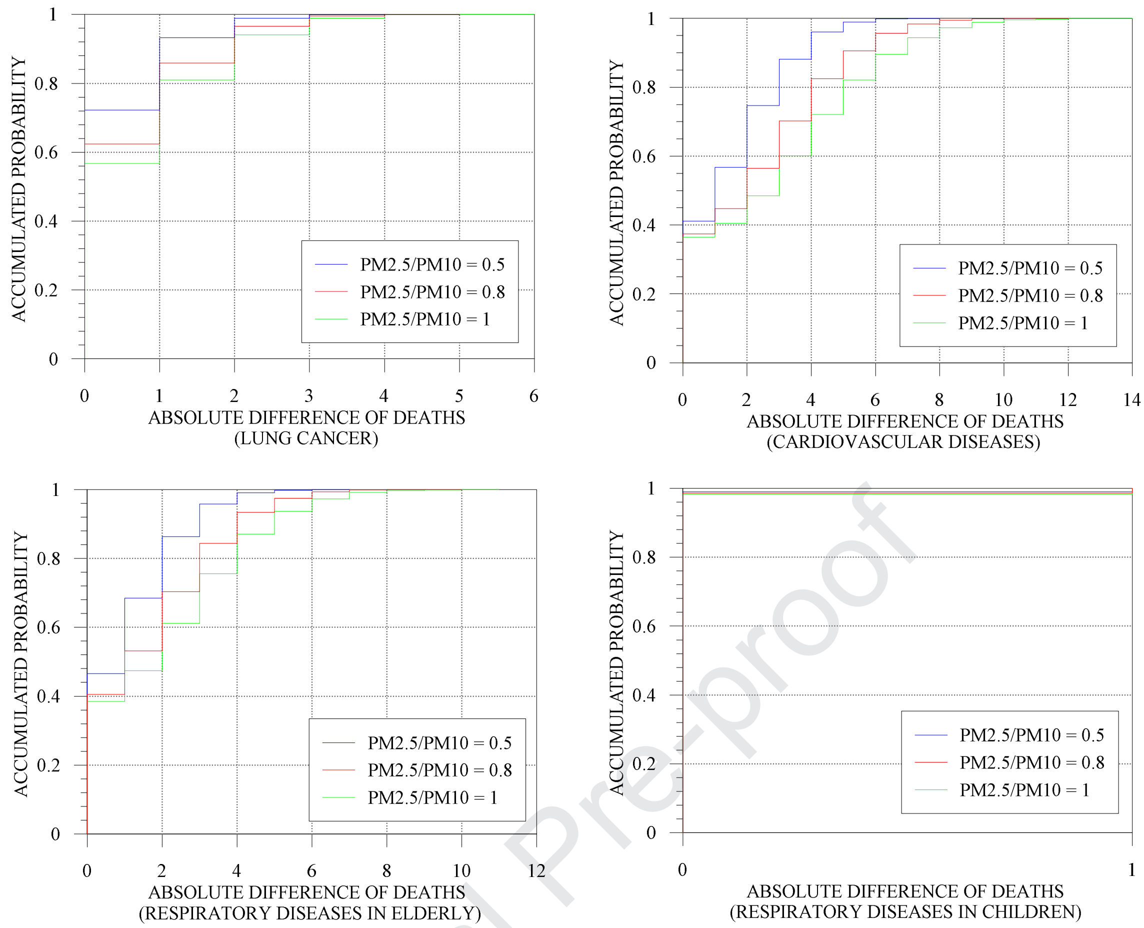


Figure 10 - The accumulated probability of deaths from LNG replacement for lung cancer (top-left), cardiovascular diseases (top-right), respiratory diseases in elderly (bottom-left), and respiratory diseases in children (bottom-right) considering the different ratio between $PM_{2.5}$ and PM_{10}.

6. LIMITATIONS AND FUTURE RESEARCH SUGGESTIONS

The results simulated by AERMOD were consistent and it was possible to evaluate PM atmospheric dispersion in this work. Besides, the concentrations found in the model output enabled to evaluate the health impacts of PM emitted by freight traffic in Anhanguera and Bandeirantes roads. Other studies demonstrated the good performance of AERMOD (Heist et al., 2013; Huertas et al., 2017; Perugu et al., 2016; Wen et al., 2017; Zhang et al., 2019). However, some input data associated with the present study have limitations. First, vehicle count data covers only the road freight sector, without considering other types of vehicles in the study. Another issue to consider is the emission factor, making it necessary to approximate PM emission factors considering all vehicles. Besides, there are other sectors responsible for PM emissions, such as industries, which make it difficult to analyze emissions only from cargo vehicles. Another limitation concerns the meteorological and air quality data. The State of São Paulo does not have comprehensive coverage of meteorological stations and not all of them measure all types of pollutants. Therefore, a meteorological station that covers all municipalities in the study area was chosen. The simulation of pollutants concentration by AERMOD is unable to reproduce secondary pollutants, formed by the chemical reactions in the atmosphere. These secondary pollutants, particularly secondary PM, also cause great impact on human health, especially when considering long term exposure, and may affect larger areas. Nevertheless, a photochemical model is required to perform this investigation and it is outside the scope of the present work. This research is especially useful to understand the relationship between traffic dynamics and air quality. Future research is suggested to differentiate the impact of each type of vehicle for studies on highways, as well as to study other types of pollutants, including secondary PM, that affect human health and the environment.

7. CONCLUSIONS

This paper evaluated the air pollution dispersion considering the emissions from heavy-duty trucks and the impacts on human health due to the short and long-term exposure. Modeling urban air pollution represents an important component to quantify the adverse effects of traffic emissions on public health. Results show the spatial distribution of pollutants PM_{10} and $PM_{2.5}$, highlighting that the largest emissions related to diesel and LNG are concentrated along with the receptors close to the highways, while the concentrations of pollutants decrease as the distance from the road increases as concluded by Misra et al. (2013). Also, concentrations vary along the highways, showing higher concentrations in specific cities such as Jundiaí and Cajamar, which can be explained by the intense flow of cargo vehicles in certain sections of the road. It is worth remembering that these concentrations from the AERMOD simulations cover only the emissions from heavy-duty trucks and these values reach almost the targets established by WHO for PM_{10} and $PM_{2.5}$. From the public health side, the fleet replacement showed that the substitution of diesel for LNG in the full fleet avoids, on one hand, deaths in lung cancer, cardiovascular diseases, and other respiratory diseases in elderly people, but does not eliminate all deaths. On the other hand, however, accumulated probability showed that, when considering only primary PM, there is

100% chance to reduce only 1 death due to respiratory diseases in children with full fleet replacement. This comes to show that other measures to reduce PM emissions must be in place together in addition to the substitution of the road transport fleet, including the change of local traffic to less-pollutant vehicles and the implementation of public policies aiming to reduce emissions in different sectors than transport (civil construction, industry, and agriculture, for example).

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REFERENCES

Abe, K.C., El Khouri Miraglia, S.G., 2016. Health impact assessment of air pollution in São Paulo, Brazil. Int. J. Environ. Res. Public Health 13. https://doi.org/10.3390/ijerph13070694

Adam, A., Ramlan, N.A., Jaharudin, N.F., Hamzah, H., Othman, M.F., Mrwan, A.A.G., 2017. Analysis of combustion characteristics, engine performance and exhaust emissions of diesel engine fueled with upgraded waste source fuel. Int. J. Hydrogen Energy 42, 17993–18004. https://doi.org/10.1016/j.ijhydene.2017.04.021

Alamia, A., Magnusson, I., Johnsson, F., Thunman, H., 2016. Well-to-wheel analysis of bio-methane via gasification, in heavy duty engines within the transport sector of the European Union. Appl. Energy 170, 445–454. https://doi.org/10.1016/j.apenergy.2016.02.001

Andrade, M. de F., de Miranda, R.M., Fornaro, A., Kerr, A., Oyama, B., de Andre, P.A., Saldiva, P., 2012. Vehicle emissions and PM 2.5 mass concentrations in six

Brazilian cities. Air Qual. Atmos. Heal. 5, 79–88. https://doi.org/10.1007/s11869-010-0104-5

Andreão, W.L., Albuquerque, T.T.A., Kumar, P., 2018a. Excess deaths associated with fine particulate matter in Brazilian cities. Atmos. Environ. 194, 71–81. https://doi.org/10.1016/j.atmosenv.2018.09.034

Andreão, W.L., Albuquerque, T.T.A., Kumar, P., 2018b. Excess deaths associated with fine particulate matter in Brazilian cities. Atmos. Environ. 194, 71–81. https://doi.org/10.1016/j.atmosenv.2018.09.034

Arteconi, a., Polonara, F., 2013. LNG as vehicle fuel and the problem of supply: The Italian case study. Energy Policy 62, 503–512. https://doi.org/10.1016/j.enpol.2013.08.016

Askariyeh, M.H., Kota, S.H., Vallamsundar, S., Zietsman, J., Ying, Q., 2017. AERMOD for near-road pollutant dispersion: Evaluation of model performance with different emission source representations and low wind options. Transp. Res. Part D Transp. Environ. 57, 392–402. https://doi.org/10.1016/j.trd.2017.10.008

Baldauf, R., Thoma, E., Hays, M., Shores, R., Kinsey, J., Gullett, B., Kimbrough, S., Isakov, V., Long, T., Snow, R., Khlystov, A., Weinstein, J., Chen, F.L., Seila, R., Olson, D., Gilmour, I., Cho, S.H., Watkins, N., Rowley, P., Bang, J., 2008. Traffic and meteorological impacts on near-road air quality: Summary of methods and trends from the Raleigh near-road study. J. Air Waste Manag. Assoc. 58, 865–878. https://doi.org/10.3155/1047-3289.58.7.865

Batterman, S., Chambliss, S., Isakov, V., 2014. Spatial resolution requirements for traffic-related air pollutant exposure evaluations. Atmos. Environ. 94, 518–528. https://doi.org/10.1016/j.atmosenv.2014.05.065

Bilenko, N., Brunekreef, B., Beelen, R., Eeftens, M., Hoogh, K. De, Hoek, G., Koppelman, G.H., Wang, M., Rossem, L. Van, Gehring, U., 2015. Associations between particulate matter composition and childhood blood pressure — The PIAMA study. Environ. Int. 84, 1–6. https://doi.org/10.1016/j.envint.2015.07.010

Borrego, C., Tchepel, O., Costa, A.M., Martins, H., Ferreira, J., Miranda, A.I., 2006. Traffic-related particulate air pollution exposure in urban areas. Atmos. Environ. 40, 7205–7214. https://doi.org/10.1016/j.atmosenv.2006.06.020

Briant, R., Korsakissok, I., Seigneur, C., 2011. An improved line source model for air pollutant dispersion from roadway traffic. Atmos. Environ. 45, 4099–4107. https://doi.org/10.1016/j.atmosenv.2010.11.016

Burnett, R.T., Arden Pope, C., Ezzati, M., Olives, C., Lim, S.S., Mehta, S., Shin, H.H., Singh, G., Hubbell, B., Brauer, M., Ross Anderson, H., Smith, K.R., Balmes, J.R., Bruce, N.G., Kan, H., Laden, F., Prüss-Ustün, A., Turner, M.C., Gapstur, S.M., Diver, W.R., Cohen, A., 2014. An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. Environ. Health Perspect. 122, 397–403. https://doi.org/10.1289/ehp.1307049

CCR, 2020. The Anhangüera-Bandeirantes system [WWW Document]. URL http://ri.ccr.com.br/en/faq/autoban/ (accessed 4.1.20).

CETESB, 2020. Qualar [WWW Document]. URL https://qualar.cetesb.sp.gov.br/qualar/home.do

CETESB, 2019. MANUAL PARA ELABORAÇÃO DE ESTUDOS AMBIENTAIS COM AIA v.02_19.

CETESB, 2017. EMISSÕES VEICULARES 2017 NO ESTADO DE SÃO PAULO. São Paulo.

CETESB, 2016. CLASSIFICAÇÃO EXPEDITA DA REPRESENTATIVIDADE ESPACIAL DAS ESTAÇÕES DE MONITORAMENTO DA QUALIDADE DO AR DA CETESB NO ESTADO DE SÃO PAULO.

Chen, H., He, J., Zhong, X., 2019. Engine combustion and emission fuelled with natural gas: A review. J. Energy Inst. 92, 1123–1136. https://doi.org/10.1016/j.joei.2018.06.005

Daniel Vallero, 2008. Fundamentals of Air Pollution, 4th ed.

DATASUS, 2020. Informações de saúde [WWW Document]. URL http://datasus.saude.gov.br/

de Fatima Andrade, M., de Miranda, R.M., Fornaro, A., Kerr, A., Oyama, B., de Andre, P.A., Saldiva, P., 2012. Vehicle emissions and PM 2.5 mass concentrations in six Brazilian cities. Air Qual. Atmos. Heal. 5, 79–88. https://doi.org/10.1007/s11869-010-0104-5

Dey, S., Caulfield, B., Ghosh, B., 2018. Potential health and economic benefits of banning diesel traffic in Dublin, Ireland. J. Transp. Heal. 10, 156–166. https://doi.org/10.1016/j.jth.2018.04.006

EEA, 2012. PM2.5/PM10 emissions ratios, total and for road transport [WWW Document]. URL https://www.eea.europa.eu/data-and-maps/figures/pm2-5-pm10-emissions-ratios-total-and-for-road-transport

EPA, 2020. AERMOD [WWW Document]. URL https://www.epa.gov/scram/air-quality-dispersion-modeling-preferred-and-recommended-models

EPA, 2005. Revision to the guideline on air quality models: Adoption of a preferred general purpose (flat and complex terrain) dispersion model and other revisions. Fed. Regist. 70, 68218–68261.

Figliozzi, M.A., 2017. Lifecycle modeling and assessment of unmanned aerial vehicles (Drones) CO2e emissions. Transp. Res. Part D Transp. Environ. 57, 251–261. https://doi.org/10.1016/j.trd.2017.09.011

Finkelstein, M.M., Jerrett, M., Sears, M.R., 2004. Traffic air pollution and mortality rate advancement periods. Am. J. Epidemiol. 160, 173–177. https://doi.org/10.1093/aje/kwh181

Heist, D., Isakov, V., Perry, S., Snyder, M., Venkatram, A., Hood, C., Stocker, J., Carruthers, D., Arunachalam, S., Owen, R.C., 2013. Estimating near-road pollutant dispersion: A model inter-comparison. Transp. Res. Part D Transp. Environ. 25, 93–105. https://doi.org/10.1016/j.trd.2013.09.003

Hoek, G., Krishnan, R.M., Beelen, R., Peters, A., Ostro, B., Brunekreef, B., Kaufman, J.D., 2013. Long-term air pollution exposure and cardio-respiratory mortality: A review. Environ. Heal. A Glob. Access Sci. Source 12. https://doi.org/10.1186/1476-069X-12-43

Huertas, I., Valencia, A., Huertas, M.E., 2017. Vehicular road in fl uence areas 151, 108–116. https://doi.org/10.1016/j.atmosenv.2016.12.006

IBGE, 2016. Brazilian Institute of Geography and Statistics [WWW Document]. URL http://cidades.ibge.gov.br/xtras/home.php (accessed 5.10.17).

IEMA, 2019a. Qualidade do Ar [WWW Document]. URL http://qualidadedoar.org.br/ (accessed 2.10.20).

IEMA, 2019b. Qualidade do Ar [WWW Document].

Isakov, V., Touma, J.S., Burke, J., Lobdell, D.T., Palma, T., Rosenbaum, A., Özkaynak, H., 2009. Combining regional- and local-scale air quality models with exposure models for use in environmental health studies. J. Air Waste Manag. Assoc. 59, 461–472. https://doi.org/10.3155/1047-3289.59.4.461

Josephs, S., 2015. The per-mile Costs of Operating Compressed Natural Gas Trucks: Experience from 16 Million Miles with the Cummins ISX12G.

Kim, K.H., Kabir, E., Kabir, S., 2015. A review on the human health impact of airborne particulate matter. Environ. Int. https://doi.org/10.1016/j.envint.2014.10.005

Liu, S., Xing, J., Wang, S., Ding, D., Chen, L., Hao, J., 2020. Revealing the impacts of transboundary pollution on PM 2 . 5 -related deaths in China. Environ. Int. 134, 105323. https://doi.org/10.1016/j.envint.2019.105323

Liu, Y., Zhao, N., Vanos, J.K., Cao, G., 2019. Revisiting the estimations of PM 2.5 - attributable mortality with advancements in PM 2.5 mapping and mortality statistics. Sci. Total Environ. 666, 499–507. https://doi.org/10.1016/j.scitotenv.2019.02.269

Lurie, K., Nayebare, S.R., Fatmi, Z., Carpenter, D.O., Siddique, A., Malashock, D., Khan, K., Zeb, J., Hussain, M.M., Khatib, F., Khwaja, H.A., 2019. PM 2.5 in a megacity of Asia (Karachi): Source apportionment and health effects. Atmos. Environ. 223–233. https://doi.org/10.1016/j.atmosenv.2019.01.008

Maffia, J., Dinuccio, E., Amon, B., Balsari, P., 2020. PM emissions from open field crop management: Emission factors, assessment methods and mitigation measures – A review. Atmos. Environ. https://doi.org/10.1016/j.atmosenv.2020.117381

Martins, L.D., Wikuats, C.F.H., Capucim, M.N., de Almeida, D.S., da Costa, S.C., Albuquerque, T., Barreto Carvalho, V.S., de Freitas, E.D., de Fátima Andrade, M., Martins, J.A., 2017a. Extreme value analysis of air pollution data and their comparison between two large urban regions of South America. Weather Clim. Extrem. 18, 44–54. https://doi.org/10.1016/j.wace.2017.10.004

Martins, L.D., Wikuats, C.F.H., Capucim, M.N., de Almeida, D.S., da Costa, S.C., Albuquerque, T., Barreto Carvalho, V.S., de Freitas, E.D., de Fátima Andrade, M., Martins, J.A., 2017b. Extreme value analysis of air pollution data and their comparison between two large urban regions of South America. Weather Clim. Extrem. 18, 44–54. https://doi.org/10.1016/j.wace.2017.10.004

Misra, A., Roorda, M.J., MacLean, H.L., 2013. An integrated modelling approach to estimate urban traffic emissions. Atmos. Environ. 73, 81–91. https://doi.org/10.1016/j.atmosenv.2013.03.013

Mouette, D., Machado, P.G., Fraga, D., Peyerl, D., Borges, R.R., Brito, T.L.F., Shimomaebara, L.A., dos Santos, E.M., 2019. Costs and emissions assessment of a Blue Corridor in a Brazilian reality: The use of liquefied natural gas in the transport sector. Sci. Total Environ. 668, 1104–1116. https://doi.org/10.1016/j.scitotenv.2019.02.255

Nogueira, T., Dominutti, P.A., Vieira-Filho, M., Fornaro, A., de Fatima Andrade, M., 2019. Evaluating atmospheric pollutants from urban buses under real-world conditions: Implications of the main public transport mode in são paulo, Brazil.

Atmosphere (Basel). 10. https://doi.org/10.3390/atmos10030108
Ogunkoya, D., Fang, T., 2015. Engine performance, combustion, and emissions study of biomass to liquid fuel in a compression-ignition engine. Energy Convers. Manag. 95, 342–351. https://doi.org/10.1016/j.enconman.2015.02.041
Ostro, B., Prüss-üstün, A., Campbell-lendrum, D., Corvalán, C., Woodward, A., 2004. Outdoor air pollution Assessing the environmental burden of disease at national and local levels.
Ozdemir, H., 2019. Mitigation impact of roadside trees on fine particle pollution. Sci. Total Environ. 659, 1176–1185. https://doi.org/10.1016/j.scitotenv.2018.12.262
Perugu, H., Wei, H., Yao, Z., 2016. Integrated data-driven modeling to estimate PM2.5 pollution from heavy-duty truck transportation activity over metropolitan area. Transp. Res. Part D Transp. Environ. 46, 114–127. https://doi.org/10.1016/j.trd.2016.03.013
Pfoser, S., Aschauer, G., Simmer, L., Schauer, O., 2016. Facilitating the implementation of LNG as an alternative fuel technology in landlocked Europe: A study from Austria. Res. Transp. Bus. Manag. 18, 77–84. https://doi.org/http://dx.doi.org/10.1016/j.rtbm.2016.01.004
Rangel, M.G.L., Henríquez, J.R., Costa, J.A.P., de Lira Junior, J.C., 2018. An assessment of dispersing pollutants from the pre-harvest burning of sugarcane in rural areas in the northeast of Brazil. Atmos. Environ. 178, 265–281. https://doi.org/10.1016/j.atmosenv.2018.02.006
Rodrigues, C.G., Vormittag, E. da M., Araújo, P., Cavalcante, J.A., Saldiva, P.H.N., 2015. Projeção da mortalidade e internações hospitalares na rede pública de saúde atribuíveis à poluição atmosférica no Estado de São Paulo entre 2012 e 2030. Rev. Bras. Estud. Popul. 32, 489–509.
Sã¡nchez-Triana, E., Enriquez, S., Larsen, B., Webster, P., Afzal, J., 2015. Sustainability and Poverty Alleviation: Confronting Environmental Threats in Sindh, Pakistan.
Sánchez, M.P., Oliveira, A.P. De, Varona, R.P., Tito, J.V., 2020. Rawinsonde Based Analysis of the Urban Boundary Layer in the Metropolitan Region of São Paulo , Brazil. Earth Sp. Sci. https://doi.org/10.1029/2019EA000781
Scovronick, N., França, D., Alonso, M., Almeida, C., Longo, K., Freitas, S., Rudorff, B., Wilkinson, P., 2016. Air quality and health impacts of future ethanol production and use in São Paulo State, Brazil. Int. J. Environ. Res. Public Health

13. https://doi.org/10.3390/ijerph13070695

SEMSP, 2017. Dados Gás, Petróleo e Derivados. São Paulo.

Shabanpour, R., Javanmardi, M., Fasihozaman, M., Miralinaghi, M., Mohammadian, A., 2018. Investigating the applicability of ADAPTS activity-based model in air quality analysis. Travel Behav. Soc. 12, 130–140. https://doi.org/10.1016/j.tbs.2017.02.004

Shairsingh, K.K., Jeong, C.H., Wang, J.M., Evans, G.J., 2018. Characterizing the spatial variability of local and background concentration signals for air pollution at the neighbourhood scale. Atmos. Environ. 183, 57–68. https://doi.org/10.1016/j.atmosenv.2018.04.010

Shekarrizfard, M., Faghih-Imani, A., Hatzopoulou, M., 2016. An examination of population exposure to traffic related air pollution: Comparing spatially and temporally resolved estimates against long-term average exposures at the home location. Environ. Res. 147, 435–444. https://doi.org/10.1016/j.envres.2016.02.039

Singh, K., 2015. Pathways for Developing a Natural Gas Vehicle Market. Cent. Strateg. Int. Stud. 85, 80–93. https://doi.org/10.1016/j.enpol.2015.05.012

Smajla, I., Sedlar, D.K., Drljača, B., Jukić, L., 2019. Fuel switch to LNG in heavy truck traffic. Energies 12. https://doi.org/10.3390/en12030515

Sonawane, N. V., Patil, R.S., Sethi, V., 2012. Health benefit modelling and optimization of vehicular pollution control strategies. Atmos. Environ. 60, 193–201. https://doi.org/10.1016/j.atmosenv.2012.06.060

Stein, A.F., Isakov, V., Godowitch, J., Draxler, R.R., 2007. A hybrid modeling approach to resolve pollutant concentrations in an urban area. Atmos. Environ. 41, 9410–9426. https://doi.org/10.1016/j.atmosenv.2007.09.004

Stettler, M., Woo, M., Ainalis, D., Achurra-Gonzalez, P., Speirs, J., 2019. Natural Gas as a Fuel for Heavy Goods Vehicles.

Stettler, M.E.J., Midgley, W.J.B., Swanson, J.J., Cebon, D., Boies, A.M., 2016. Greenhouse Gas and Noxious Emissions from Dual Fuel Diesel and Natural Gas Heavy Goods Vehicles. Environ. Sci. Technol. 50, 2018–2026. https://doi.org/10.1021/acs.est.5b04240

Suthawaree, J., Sikder, H.A., Jones, C.E., Kato, S., Kunimi, H., Mohammed Hamidul Kabir, A.N., Kajii, Y., 2012. Influence of extensive compressed natural gas (CNG) usage on air quality. Atmos. Environ. 54, 296–307. https://doi.org/10.1016/j.atmosenv.2012.01.066

Tchepel, O., Costa, A.M., Martins, H., Ferreira, J., Monteiro, A., Miranda, A.I., Borrego, C., 2010. Determination of background concentrations for air quality models using spectral analysis and filtering of monitoring data. Atmos. Environ. 44, 106–114. https://doi.org/10.1016/j.atmosenv.2009.08.038

Thiruvengadam, A., Besch, M., Padmanaban, V., Pradhan, S., Demirgok, B., 2018. Natural gas vehicles in heavy-duty transportation-A review. Energy Policy 122, 253–259. https://doi.org/10.1016/j.enpol.2018.07.052

Tong, R., Liu, J., Wang, W., Fang, Y., 2020. Health effects of PM2.5 emissions from on-road vehicles during weekdays and weekends in Beijing, China. Atmos. Environ. 223, 117258. https://doi.org/10.1016/j.atmosenv.2019.117258

Vermeulen, R., Verbeek, R., Goethem, S. van, Smokers, R., 2017. Emissions testing of two Euro VI LNG heavy-duty vehicles in the Netherlands : tank-to-wheel emissions 39.

Wang, C., Tu, Y., Yu, Z., Lu, R., 2015. PM 2 . 5 and Cardiovascular Diseases in the Elderly : An Overview 8187–8197. https://doi.org/10.3390/ijerph120708187

Watson, A.Y., Valberg, P.A., 2001. Carbon Black and Soot: Two Different Substances. AIHAJ - Am. Ind. Hyg. Assoc. 62, 218–228. https://doi.org/10.1080/15298660108984625

Wen, D., Zhai, W., Xiang, S., Hu, Z., Wei, T., Noll, K.E., 2017. Near-roadway monitoring of vehicle emissions as a function of mode of operation for light-duty vehicles. J. Air Waste Manage. Assoc. 67, 1229–1239. https://doi.org/10.1080/10962247.2017.1330713

WHO, 2018. Ambient (outdoor) air pollution [WWW Document]. URL https://www.who.int/en/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health

Wilhelm, M., Ritz, B., 2003. Residential proximity to traffic and adverse birth outcomes in Los Angeles County, California, 1994-1996. Environ. Health Perspect. 111, 207–216. https://doi.org/10.1289/ehp.5688

Xian, H., Karali, B., Colson, G., Wetzstein, M.E., 2015. Diesel or compressed natural gas? A real options evaluation of the U.S. natural gas boom on fuel choice for trucking fleets. Energy 90, 1342–1348. https://doi.org/10.1016/j.energy.2015.06.080

Zhang, S., Wu, Y., Yan, H., Du, X., Max Zhang, K., Zheng, X., Fu, L., Hao, J., 2019. Black carbon pollution for a major road in Beijing: Implications for policy interventions of the heavy-duty truck fleet. Transp. Res. Part D Transp. Environ. 68, 110–121. https://doi.org/10.1016/j.trd.2017.07.013

Zhao, B., Zheng, H., Wang, S., Smith, K.R., Lua, X., Aunan, K., Gu, Y., Wang, Y., Ding, D., Xing, J., Fu, X., Yang, X., Liou, K.-N., Hao, J., 2018. Change in household fuels dominates the decrease in PM2.5 exposure and premature mortality in China in 2005-2015. PNAS 115, 12401–12406.

Zheng, X., Wu, Y., Zhang, S., Baldauf, R.W., Zhang, K.M., Hu, J., Li, Z., Fu, L., Hao, J., 2016. Joint measurements of black carbon and particle mass for heavy-duty diesel vehicles using a portable emission measurement system. Atmos. Environ. 141, 435–442. https://doi.org/10.1016/j.atmosenv.2016.07.013

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: