Correlation Between Fine Particulate Matter and Traffic Type and Density in Curitiba, Brazil

by
Costanza Fantoni

A THESIS

submitted to

Oregon State University

Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Chemistry
(Honors Scholar)

Honors Baccalaureate of Science in Environmental Science
(Honors Scholar)

Presented June 5, 2019
Commencement June 2019

AN ABSTRACT OF THE THESIS OF

Costanza Fantoni for the degree of Honors Baccalaureate of Science in Chemistry and Honors Baccalaureate of Science in Environmental Science presented on June 5, 2019. Title: Correlation between Fine Particulate Matter and Traffic Type and Density in Curitiba, BZ.

Abstract approved:____

Perry Hystad

Traffic exhaust is an important source of air pollution. This exposure assessment study examined traffic related air pollution in Curitiba, Brazil, and is particularly relevant due to 75% of the population using diesel public transportation. Traffic density was tabulated, and vehicle-type was distinguished based on their fuel type (diesel or gasoline) at four sampling locations in Curitiba. Concurrently, fine particulate matter ($PM_{2.5}$) ambient air levels were monitored and recorded using AirBeam, a low cost $PM_{2.5}$ monitor. By performing linear regression analyses, it was found that there exists a moderate to strong correlation between traffic density and $PM_{2.5}$ concentration (R^2=0.74). Rain events played a significant role in removing suspended particulates from the air (R^2 increased 0.6333 once the sampling location affected by a rain event from removed from the data set). Modeling the asymmetrical impact that diesel (y=0.3543x+7.7634) and gasoline (y=0.0798x+3.3743) vehicles have on $PM_{2.5}$ resulted in a slope ratio of 4.4, interpreted as 1 diesel vehicles having a similar impact as 4.4 gasoline vehicles on pollutant concentration.

Key Words: fine particulate matter, diesel, gasoline, public transportation

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I understand that my project will become part of the permanent collection of Oregon State University, Honors College. My signature below authorizes release of my project to any reader upon request.

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Costanza Fantoni, Author

INTRODUCTION

Fine particulate matter, or $PM_{2.5}$, is an air pollutant that is comprised of microscopic aerosols and solids that have a mean aerodynamic diameter of 2.5 micrometers.[1] $PM_{2.5}$ is capable of remaining suspended in the air, with sizes varying from very small (0.01μm) as in tobacco smoke and smog, to its defining maximum size of 2.5μm, as in atmospheric dust, settling dust, and mold spores[2]. The source of particulate matter can be both natural and anthropogenic. The origins of the particles affect their spatial distribution, persistence in the environment, and the effectiveness of amelioration strategies targeted towards their reduction and removal. Reducing particulate matter influx into ambient air is instrumental in maintaining human and ecosystem health, due to the plethora of adverse effects $PM_{2.5}$ possesses.

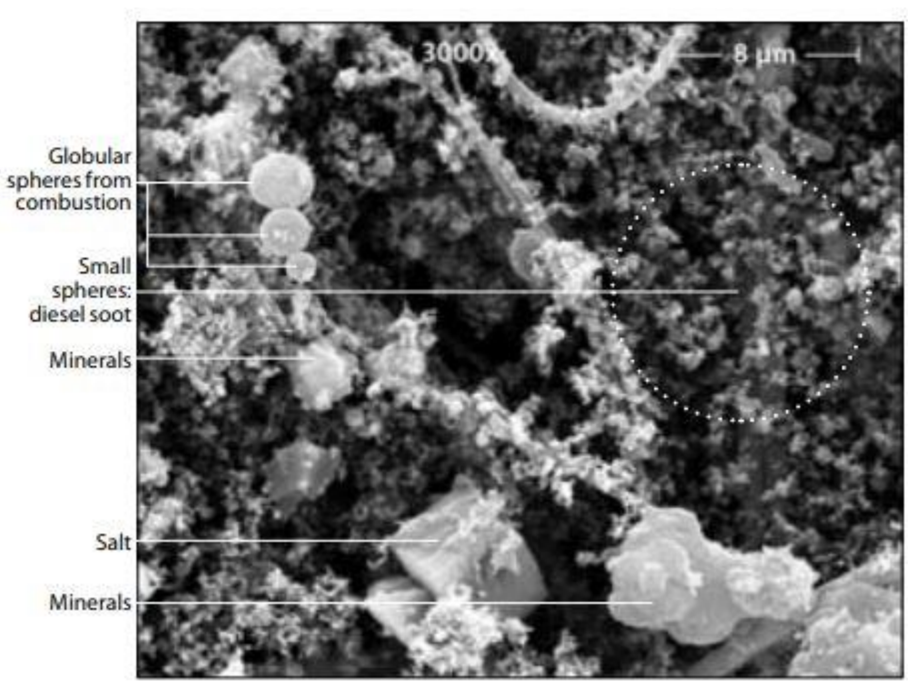

Figure 1. Electron micrograph of PM sampled on a filter near a street; diesel soot (small grey spheres)[3].

Environmental effects of $PM_{2.5}$ pollution span from reducing visibility to contributing to the acidification of streams, lakes and rain because particulate matter may contain sulfate aerosols[4]. Fine particulate matter is also able to affect the natural environment through altering the nutrient cycle and damaging crops and vegetation[2], both by abrasion and by clogging stomata which ultimately interferes with photosynthesis[4]. The persistence of particulate matter in the atmosphere also has implications for radiative forcings[5], which directly and indirectly affect the Earth's climate. Naturally occurring particulate matter such as volcanic ash, plant-exuded particulates, and sea spray are all part of the nutrient and climatic cycle. Fine particulates suspended in air become a severe threat to human and environmental health only when the natural phenomena involved are accelerated and exacerbated by human action, like the strengthening of dust storms and wildfires. The wind movement of dust is a natural event, but aridification is magnifying this transport of material, causing severe adverse events in regions surrounding expanding deserts. The same is occurring for the transport of fire-generated particulate matter due to the increase in frequency and intensity of droughts and seasonal burning events. However, one tenth of this pollutant's emissions are purely anthropogenic[6], and sources include factory operations, smokest ... rtation.

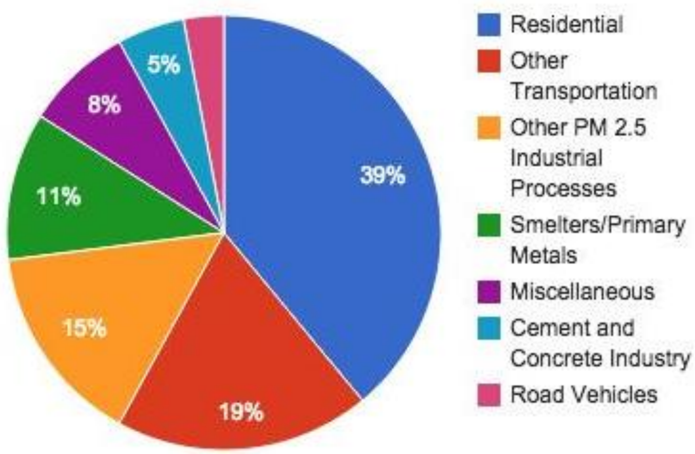

Figure 2. Ontario Fine Particulate Matter Emissions by Sector - 2012 Estimates[13].

Particulate matter adverse effects on human health are somewhat more tangible. Both acute and chronic health effects of inhalation have been studied extensively. $PM_{2.5}$ is designated as a Group I carcinogen[7]. The disproportionate effect it has on human health is because of its size, which enables it to enter the body unaltered and penetrate the blood stream and respiratory system[8]. This is carried out so effectively as to cause an excess of cardiovascular complications[9] like heart attack, stroke, coronary obstructive pulmonary disease; and respiratory tract conditions like lung cancer, bronchitis, and asthma[10].

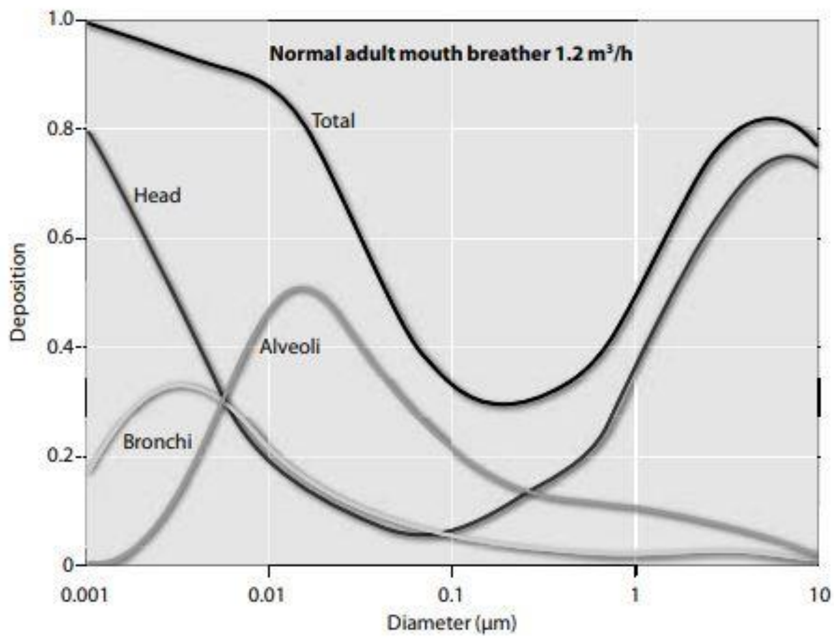

Figure 3. Deposition probability of inhaled particles in the respiratory tract according to particle size[3].

The World Health Organization established the Air Quality Guideline for annual average $PM_{2.5}$ concentration at a maximum of 10 μg/m^3 based on health effects evidence[11]. 95% of the world's population lives in areas exceeding WHO's guideline for healthy air, and 60% of the world's population lives in areas that don't meet the minimum levels of $PM_{2.5}$ of 35 μg/m^3. As a large percentage of humanity is exposed to fine particulate matter, the disease burden on humanity from this specific type of pollutant is enormous, and $PM_{2.5}$ is ranked as the sixth leading risk factor for premature death globally[11].

Not only is there a difference in how much different sources $PM_{2.5}$ may emit, but there is also a difference in $PM_{2.5}$ toxicity may affect human health based on its origin. Epidemiological studies on the toxicity of fine particulate matter, suggest that combustion sources are the greatest threat to human health[35]. Combustion-derived particulate matter has the highest toxicity potential because they are often rich in transition metals and organic compounds and have a relatively high surface area. A study conducted in the urban area of Istanbul proved the presence of toxic substances absorbed on particulate matter[36].

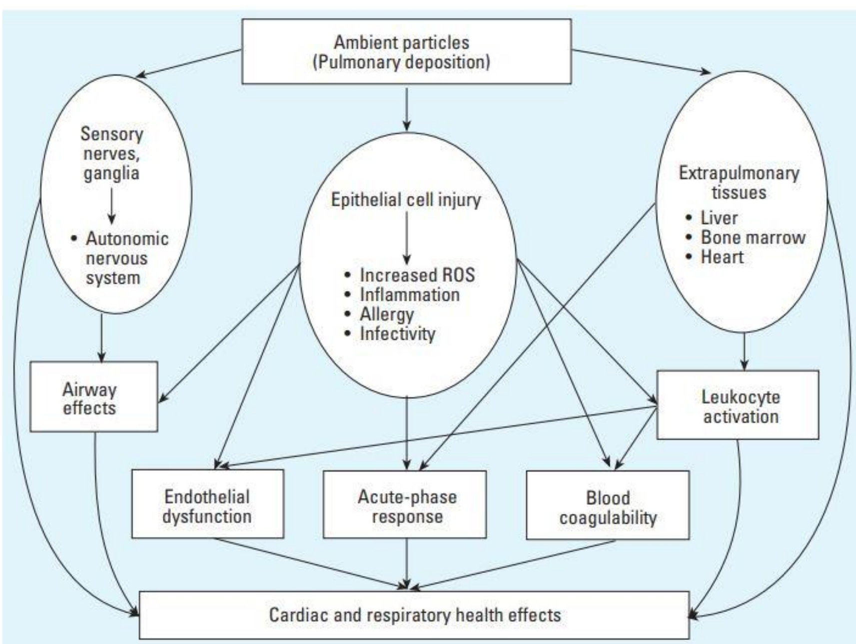

Figure 4. Hypothesis for health effects of particulate matter exposure proposed by the United States Environmental Protection Agency[37].

The US EPA has accomplished acute and chronic studies on particulate matter showing that diesel and gasoline exhaust have a direct influence on inflammation and immunity. It was proven, through studies on animal models, that instillation or inhalation can cause inflammation and epithelial injury at high doses and concentration as well as negative cardiovascular effects[37]. The toxicity of transition metals and organic compounds in exhaust fine particulate matter causes $PM_{2.5}$'s disproportionate effect on mortality. These mobile (traffic) sources of fine particulate matter are significantly more detrimental to human health when compared to natural sources of fine particulate matter. The often quoted "Harvard Six City study"[38] found that a "10 mmg/m^3 increase in $PM_{2.5}$ from mobile sources accounted for a 3.4% increase in daily mortality, and the equivalent increase in fine particles from coal combustion sources accounted for a 1.1% increase. $PM_{2.5}$ crustal particles were not associated with daily mortality".[38] Ultimately indicating that "combustion particles in the fine fraction from mobile and coal combustion sources, but not fine crustal particles, are associated with increased mortality"[38].

Internal combustion engine particulate matter exhaust is the focus of this project. Specifically, pollution that is produced from diesel fuel engines in large vehicles. Diesel engines have had traditionally higher $PM_{2.5}$ emission rates when compared to gasoline engines[12]. Having been at the center of attention of pollution reduction efforts, diesel vehicles have recently caught up to gasoline vehicles, reaching comparable levels of $PM_{2.5}$ emission thanks to diesel particulate filters or DPFs[12]. However, these filters are still an incomplete solution. Local low temperatures within the engine's cylinder and catalytic converters are still sources of incomplete combustion that produces particulate matter that can escape these filters[12]. These spots of low temperature cause incomplete combustion and only partial atomization of fuel, which causes the formation of volatile carbon compounds, commonly referred to as "soot", especially when the fuel is not well oxygenated. These conditions are most common during ignition and acceleration of diesel vehicles, which causes the appearance of the characteristic clouds of black smoke when vehicles start and stop in traffic.

Diesel particulate matter (DPM), also addressed as diesel exhaust particles (DEP) is challenging to monitor because diesel exhaust is a chemically complex mixture. It is made up of thousands of compounds, some of which may be better suited to tracking exhaust than others. Elemental carbon (or black carbon)[14] and nitrogen dioxide[15] have been common markers because studies report significant correlation between these chemical species and DEP levels[16]. For this study, we used fine particulate matter as a marker of DEP because it was less expensive to measure. Fine particulate matter as the marker choice was picked on the basis that it would yield acceptable results for exhaust pollution levels[17], while also retaining human and environmental health significance. However, replacing black carbon with a proxy has an impact in the accuracy and precision of measurements, particularly for spatial measurements. This is because $PM_{2.5}$ displays a weaker concentration gradient. For this reason, this study is presented with the challenge of isolating diesel exhaust from other confounding variables and is limited to presenting descriptive and exploratory findings for the formulated hypothesis.

Recent developments in instrumentation affordability, have allowed for the creation of low cost $PM_{2.5}$ monitors. Such a monitor was used in this study, specifically AirBeam by AirCasting

The advent of public transport: the bus system of Curitiba

The relevancy of DPM pollution from large vehicles in Curitiba arises from its urban planning history. Curitiba is the capital of Parana, one of the southmost states of the country. It has been widely accepted as one of the 20th century most innovative cities, and its greatest success story was its bus rapid transit system (BRT)[18]. Until the late 19th century this European-like city was not very populated, remaining in the shadows of the other two major coastal cities of the area: San Paolo and Rio de Janeiro. When the automotive industry began growing in the region, so did the population, and Curitiba eventually became the fastest growing Brazilian city of the 1960s. When the sparse infrastructure and urban layout became inadequate, the city's transformative period began. By 1968 a Master Plan was already in action, and the cityscape changed forever. The center became closed to automotive traffic, and the city became a bus, rather than car, oriented city. To make a bus system feasible in what would become a city of 2.8 million inhabitants, many aspects of the BRT had to be groundbreaking, and throughout the decades the BRT has transformed into something more appropriately named as RIT: An Integrated Transport Network. This type of bus transit system was the first of its kind, and was adopted by many other cities around the world, including Bogota, Los Angeles, Las Vegas, Jakarta, and even Eugene, Oregon with its Emerald Express.

The Parana state capital is comparable in size to Phoenix, AZ. While in this American city only 1% of the inhabitants use public transportation, in Curitiba this number is close to 75%[19.] This highlights the continued relevancy of public transportation systems in large cities, even ones perceived as outdated. The current market for buses is mostly driven by the need of a cheap and fast installment of a public transport service, but it also finds customers in cities where archeological and historical barriers prevent the creation of underground (and above ground) railways. Estimates made from the "Curitiba experiment" indicate that a rapid bus lane costs about fifty times less than a rail route and can be operational in about one tenth of the time[20]. Routes are also non-fixed and suitable to fast-changing cityscapes. Bus transit systems could be easily and widely adopted because of their flexibility, low costs, and short and long-term profitability. Because of the possibility to this technology to spread, the need to choose fuel wisely is augmented, and DPM levels should be kept in consideration as well. It is also important to scale costs of public transport systems to the positive and negative effects they might have on smog and respiratory conditions health care costs. Finally, disproportionate exposure to particulate matter from diesel exhaust might be experienced by low-income citizens who most use public transportation, by citizens concerned with their environmental footprint, and by people living in housing near major roads and bus routes. This may impact the extent by which socio-economic factors are a cause of disease, and only sound evidence on the impact of BRTs can contribute to establishing its implications for environmental and social justice, as well as climatic conditions.

The motivation behind this project is to provide data to elucidate the relationship between ambient fine particulate matter ($PM_{2.5}$) and vehicle exhaust, particularly diesel. It is hypothesized that a correlation exists between traffic density and ambient air fine particulate matter levels. It is also hypothesized that there exists a stronger relationship between diesel vehicle exhaust and $PM_{2.5}$, than between gasoline vehicle exhaust and $PM_{2.5}$.

METHODOLOGY

Sampling Locations

The data collection process for this project was part of a larger study conducted by the Pontifical Catholic University of Paraná in collaboration with the Brazilian Government. The aim of this larger project was to study the relationship between park proximity and their ability to remove localized impacts of traffic-related $PM_{2.5}$. This document describes a portion of this larger study. Specifically, it involves examining the relationship between $PM_{2.5}$ and traffic because it is speculated that the main local source of $PM_{2.5}$ is the bus system. For this preliminary study, four sampling locations were chosen in Curitiba, Brazil: Bosque Alemão, Jardim Botânico, Parque Barigui, and Parque São Lorenço.

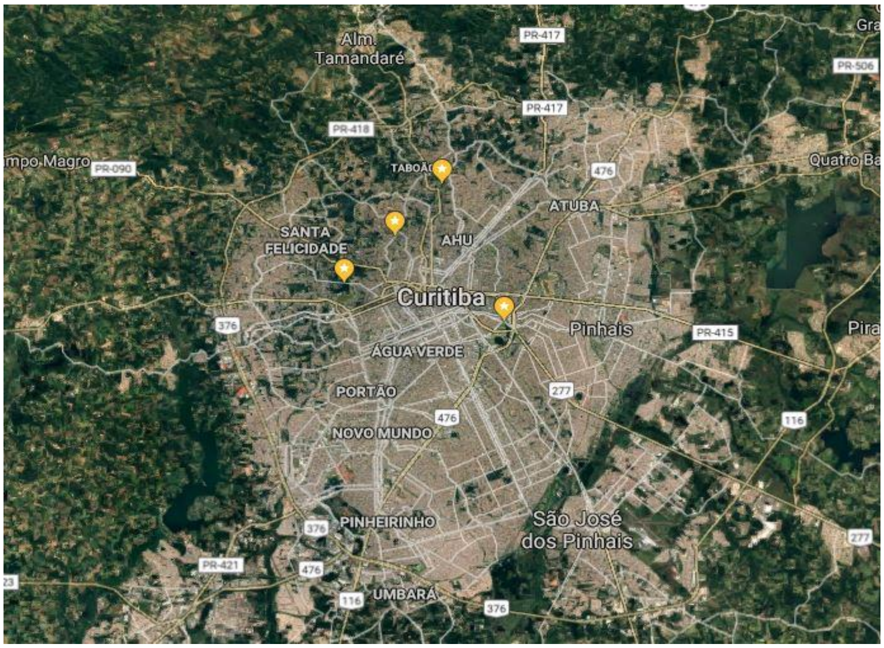

Figure 5. Map of the four sampling locations in the metropolitan area of Curitiba, Parana, Brazil.

These locations are representative of urban parks in Curitiba, which in their collective comprise 154 square miles in the metropolitan area of the city. The sampling locations are located on main artery roads and highly driven byways that are near an urban park. Both directions of traffic on these roads were monitored, and the locations chosen were specifically either a roundabout (Parque Barigui), or the median between the two directions of traffic (Bosque Alemão, Jardim Botânico, Parque São Lorenço).

Figure 6. Street near Bosque Alemao.

Figure 7. Street near Jardim Botanico

Figure 8. Street near Parque Sao Lourenco.

Figure 9. Street near Parque Barigui.

Measurements were made during the local winter season, between July 27th and August 8th, 2018. The night before one of the measuring sessions there were heavy rain showers. This provided an opportunity to examine the effects of rain on particulate matter removal from ambient air in a subset of data from the Jardim Botânico site.

Sampling Equipment

The equipment used to obtain air quality measurements is an instrument manufactured by AirCasting, a digital platform for recording, mapping, and sharing health and environmental data. The air quality sensor used is AirBeam, which is Arduino-powered and uses a light-scattering method to measure fine particulate matter. Air is drawn through a sensing chamber wherein light from a laser scatters off particles in the airstream. This light scatter is registered by a detector and converted into a measurement that estimates the number of particles in the air[21]. The real-time data was sent via Bluetooth to a mobile device operating the AirCasting App, through which data could be observed at time of measurement. The AirCasting program works in a way that at the end of every air quality monitoring session, the collected data is sent to the AirCasting website, where the data is crowdsourced with data from other AirCasters to generate heat maps indicating where particulate matter concentrations are highest and lowest.

Figure 10. AirBeam sampling instrument by AirCasting[21].

Information regarding quality of measurement can be inferred from details provided about this sensor by the US Environmental Protection Agency published Air Sensor Performance Evaluations[22]. This program tests a variety of emerging air-quality sensors by placing the sensors near a regulation-grade monitor and comparing the data collected with both technologies. In this manner, accuracy and reliability can be assessed. AirBeam was tested against a MetOne BAM 1020 FEM PM2.5 Monitor, a more traditional instrument, and the resulting correlation (R^2) value was amongst the highest reported (e.g. 0.65 to 0.66)[23].

Data and analysis

Data monitoring was conducted for one-hour periods, coinciding with local rush hours (between 16:00 and 18:00). Traffic data tabulation was done at five-minute intervals, evenly spaced, and reoccurring throughout the hour. In total, four intervals were used for every location, spaced by 10 minutes, with such a sampling intervals pattern: 16:35-16:40, 16:50-16:55, 17:05-17:10, 17:20-17:25. From AirBeam a minimum and a maximum level of $PM_{2.5}$ are obtained for all time intervals, and they were averaged to yield a median fine particle matter concentration per cubic meter for a specific time period. A geometric mean was operated on the medians across the hour intervals, as well as a standard deviation analysis.

During these sampling periods, traffic data was tabulated. This was achieved by manually counting cars, motorcycles, buses and trucks. One person per direction of traffic was tasked with counting vehicles. Traffic data included distinct counts of cars, motorcycles, and buses/trucks. The rationale for this categorization among vehicle types was based on fuel-type. Buses and trucks were counted separately, as they operate on diesel rather than gasoline. A total transit count for every 5-minute interval was tabulated, as well as an overall total transit count for the hour monitoring period, representative of the daily's traffic influx.

Statistical Methods

A geometric mean was chosen instead of an average to calculate the average particulate matter level for the overall particulate matter level for a sampling location and measurement event. Performing this operation entails taking the fourth root of the 4-way product (generally the n^{th} root of the product of n numbers)[24]. Due to the skewed nature of ambient air pollution data, which may have extreme lows and highs caused by wind gusts, spike in traffic, etc., the geometric mean can correctly describe the central tendency. Using Geomean functions instead of average also carries an advantage for studies with small data sets which occurred in this study.

Two linear regressions were calculated for four different data set combinations. An excel function was run for this linear approach to a predictive model, with x being the independent variable (traffic density and type), and y the dependent variable being fine particulate matter concentration. In Office Excel this linear model is obtained from a least-sum-of-squares approach,[24] and is essentially the straight line that fits the collection of data points.

Standard deviations were used to quantify the amount of variation for a chosen set of data. Along with the standard deviation, another estimate of variability is the correlation coefficient (R^2) or the coefficient of determination. If R^2 results to be 0.789, it can be interpreted as 78.9% of the variation in y ($PM_{2.5}$) is due to the variation in x[24] (traffic density).

All the above statistical components were used to test if there exists a positive correlation (high R^2 value) between fine particulate matter and traffic density. They were also used to observe the correlation between rain showers and fine particulate matter, and to examine the different correlations between $PM_{2.5}$ and diesel and gasoline fuel vehicles.

<table>
<tr><th>Time interval</th><th>Cars, motorcy. (Gasoline)</th><th>Buses, Trucks (Diesel)</th><th>Total Gasoline Vehicles</th><th>Total Diesel Vehicles</th><th>Total Vehicles</th><th>$PM_{2.5}$ min (ug/m³)</th><th>$PM_{2.5}$ max (ug/m³)</th><th>$PM_{2.5}$ average (ug/m³)</th><th colspan="3">$PM_{2.5}$ (ug/m³)</th><th>°C</th></tr>
<tr><td rowspan="2">16:35 - 16:40</td><td>35</td><td>3</td><td rowspan="2">90</td><td rowspan="2">14</td><td rowspan="2">104</td><td rowspan="2">2</td><td rowspan="2">3</td><td rowspan="2">2.5</td><td rowspan="4">3.33</td><td rowspan="4">±</td><td rowspan="4">1.3</td><td rowspan="2">16</td></tr>
<tr><td>55</td><td>11</td></tr>
<tr><td rowspan="2">16:50 - 16:55</td><td>30</td><td>1</td><td rowspan="2">101</td><td rowspan="2">4</td><td rowspan="2">105</td><td rowspan="2">2</td><td rowspan="2">4</td><td rowspan="2">3</td><td rowspan="2">13</td></tr>
<tr><td>71</td><td>3</td></tr>
</table>

17:05 - 17:10	37	3	80	4	84	2	4	3				13
	43	1										
17:20 - 17:25	33	1	78	5	83	2	9	5.5				12
	45	4										

RESULTS

Table 1. Data summary for the Bosque Alemão sampling location.

Time interval	Cars, motorcy. (Gasoline)	Buses, Trucks (Diesel)	Total Gasoline Vehicles	Total Diesel Vehicles	Total Vehicles	$PM_{2.5}$ min (ug/m³)	$PM_{2.5}$ max (ug/m³)	$PM_{2.5}$ average (ug/m³)	$PM_{2.5}$ (ug/m³)			°C
16:35 - 16:40	60	2	226	15	241	11	18	14.5	14.2	±	4.1	16
	166	13										
16:50 - 16:55	65	6	205	28	233	8	12	10.0				16
	140	22										
17:05 - 17:10	82	9	291	26	317	11	29	20.0				16
	209	17										
17:20 - 17:25	73	12	276	31	307	11	17	14.0				16
	203	19										

Table 2. Data summary for the Jardim Botânico sampling location.

Time interval	Cars, motorcy. (Gasoline)	Buses, Trucks (Diesel)	Total Gasoline Vehicles	Total Diesel Vehicles	Total Vehicles	$PM_{2.5}$ min (ug/m³)	$PM_{2.5}$ max (ug/m³)	$PM_{2.5}$ average (ug/m³)	$PM_{2.5}$ (ug/m³)			°C
17:05 - 17:10	101	5	214	7	221	77	78	77.5	57.5	±	29	21
	113	2										
17:20 - 17:25	79	9	182	12	194	20	24	22.0				20
	103	3										
17:35 - 17:40	89	7	182	8	190	80	80	80.0				18
	93	1										
17:50 - 17:55	87	6	220	8	228	80	80	80.0				17
	133	2										

Table 3. Data summary for the Parque Barigui sampling location.

Time interval	Cars, motorcy. (Gasoline)	Buses, Trucks (Diesel)	Total Gasoline Vehicles	Total Diesel Vehicles	Total Vehicles	$PM_{2.5}$ min (ug/m³)	$PM_{2.5}$ max (ug/m³)	$PM_{2.5}$ average (ug/m³)	$PM_{2.5}$ (ug/m³)			°C
16:35 - 16:40	55	9	127	22	149	4	7	5.5	9.9	±	7.8	16
	72	13										
16:50 - 16:55	41	5	110	19	129	4	7	5.5				14
	69	14										
17:05 - 17:10	40	6	113	15	128	5	25	15.0				14
	73	9										
17:20 - 17:25	53	6	132	15	147	7	36	21.5				14
	79	9										

Table 4. Data summary for the Parque São Lourençо sampling location.

For every 5-minute time interval, the number of vehicles was tabulated separately for each direction of traffic. Cars and motorcycles are grouped together, comprising the subcategory of gasoline vehicles; a subtotal is reported for every time interval. The same procedure is observed for the tabulation of trucks and buses, vehicles running on Diesel. A maximum and minimum levels of particulate matter are reported, as presented by the AirBeam sampling instrument. An average of the minimum and maximum is calculated for each time interval, and an overall Geomean of the four average $PM_{2.5}$ points is obtained in Office Excel by using the Geomean function. Temperature at time of sampling was also measured and is reported above.

Sampling location	Total Gasoline Vehicles	Total Diesel Vehicles	Total Vehicles	$PM_{2.5}$ min (ug/m³)	$PM_{2.5}$ max (ug/m³)	$PM_{2.5}$ geomean (ug/m³) and st.dev.	
Bosque Alemão	349	27	376	2	5	3.33	± 1.3
Jardim Botânico	998	100	1098	10.25	19	14.2	± 4.1
Parque Barigui	798	35	833	61.25	65.6	57.5	± 29
Parque São Lorenço	482	71	553	5	18.75	9.94	± 7.8

Table 5. Summary of data from all sampling locations. Traffic data is condensed in subtotals of gasoline vehicles (cars and motorcycles) and of diesel vehicles (bus and trucks).

Bosque Alemão displayed the lowest $PM_{2.5}$ levels of all sampling locations (geomean: 3ug/m^3, min 2ug/m^3, max 5ug/m^3). Jardim Botânico (geomean: 14ug/m^3, min 10.5ug/m^3, max 19ug/m^3) and Parque São Lorenço (geomean: 10ug/m^3, min 5ug/m^3, max 18.75ug/m^3) have comparable levels, while at Parque Barigui particulate matter concentration in ambient air was almost 5 times greater than was measured anywhere else (geomean: 57ug/m^3, 61.25 5ug/m^3, max 65.6ug/m^3). The sampling location that had the most diesel traffic was Jardim Botânico (100 vehicles), which also had the most gasoline traffic (998 vehicles). However, the location where $PM_{2.5}$ concentration was highest was Parque Barigui, the

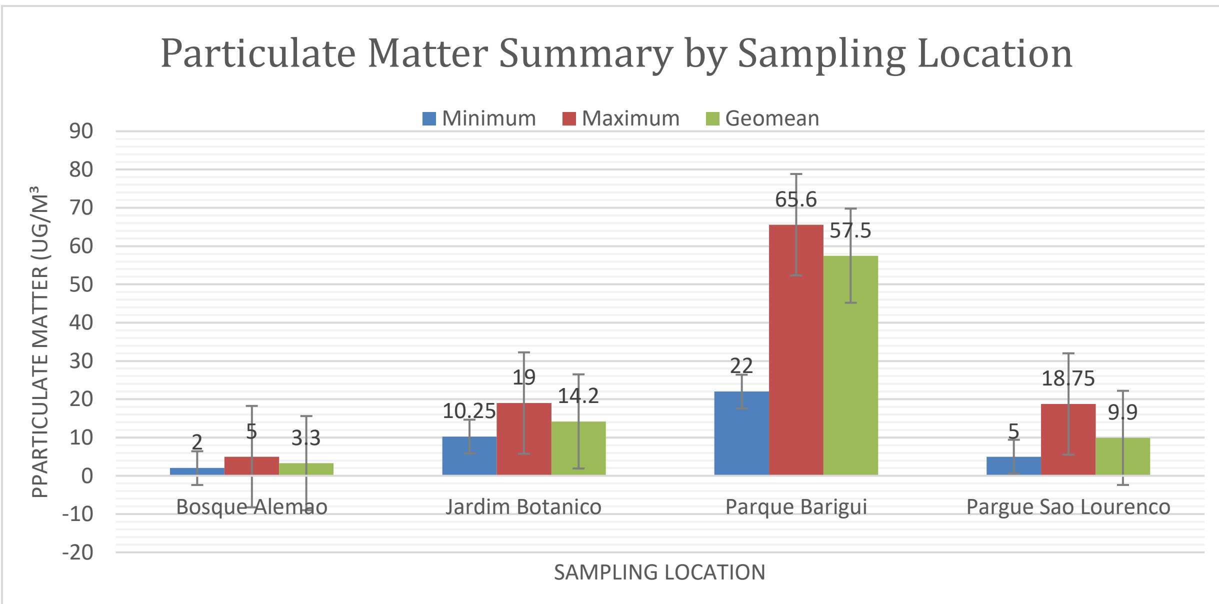

Figure 11. Bar plot of average minimum, average maximum, and geomean of averages for all sampling locations. Variation in overall geomean of particulate matter concentration at a site is also reported.

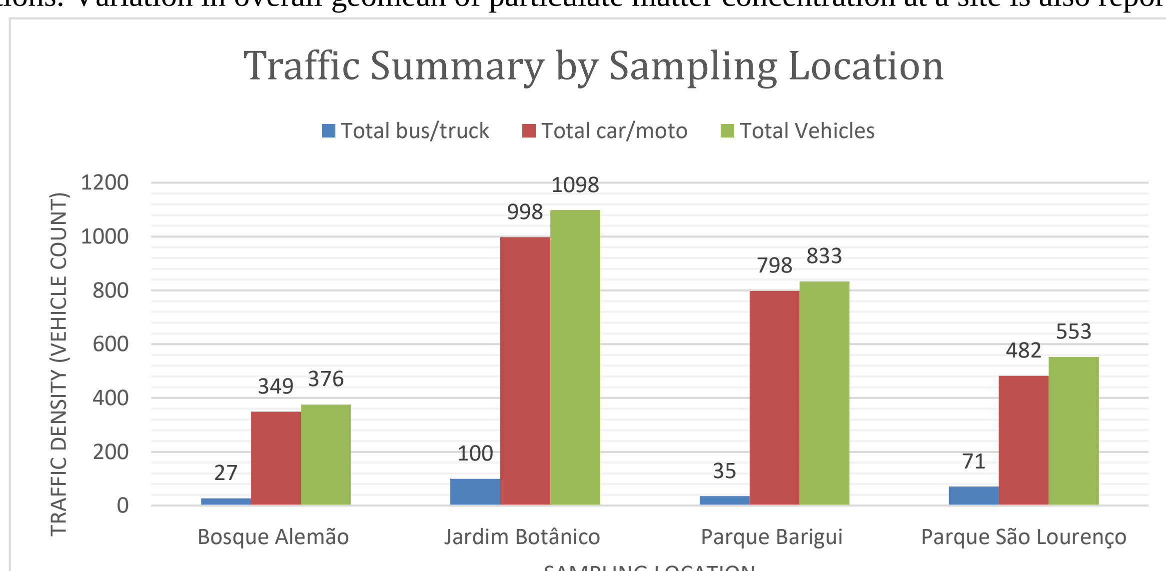

Figure 12. Bar plot of diesel and gasoline vehicles total counts, and total vehicle count for all sampling locations.

second location in the ranking for maximum total traffic (833 vehicles, 798 gasoline, 35 diesel). The lowest levels of particulate pollution at Bosque Alemão, coinciding with the smallest traffic counts of both gasoline (349 vehicles) and diesel vehicles (27 vehicles).

The locations were chosen so that similar traffic density would be observed during all measuring events. For this reason, no distinct anomaly is visible in this data summary. Bus and truck routes were equally distributed, and a small data interval for averages across locations follows: (35,100), with a standard deviation of 29.3. Gasoline vehicles were more numerous, allowing for greater variation in total counts, which yields an interval of (349,998) with a standard deviation of 255. Total vehicle count are a combination of diesel and gasoline, and the variation is a combination of the lesser and greater variation for the subgroups, yielding a data interval of (553,1098) with a standard deviation of 274.

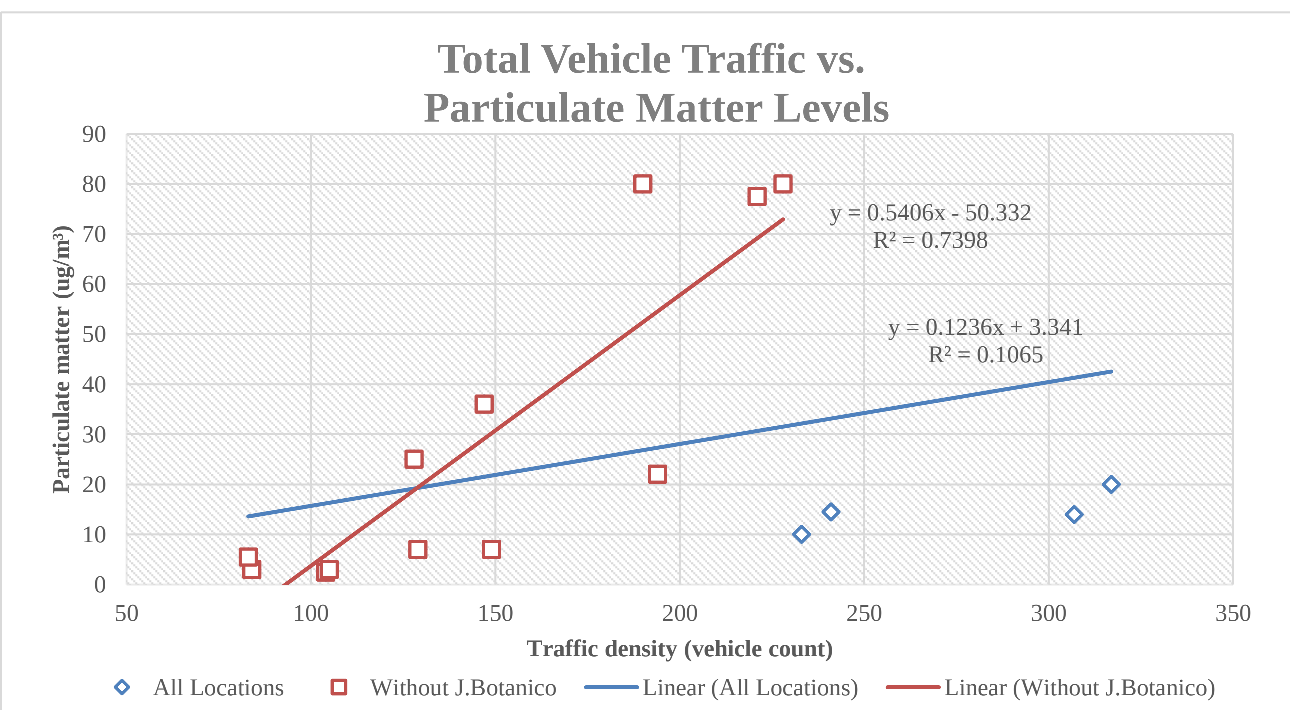

Figure 13. Linear regression of total traffic counts for every sampling location vs. $PM_{2.5}$ levels (in blue), and linear regression of total traffic counts for every sampling location excluding Jardim Botânico.

The unadjusted complete data set linear regression line is y=0.1236x+3.341 and has an R^2=0.1065. The adjusted data set, which excludes Jardim Botânico's sampling location has a linear regression line y=0.5406x-50.332, with R^2=0.7398. Both relationships show strongly upwards trends, with intercepts of differing magnitude and sign.

LINEST Function output for All Sampling Locations			
Slope	0.124	3.341	Intercept
Error	0.096	18.44	Error
R-squared	0.107	27.58	St.dev. of y
F-statistic	1.669	14.00	Deg. of freedom
Regr. sum of squares	1269	10650	Res. Sum of squares

Table 6. Uncertainty estimates for the fitted linear regression values, obtained with LINEST function in OfficeExcel on the line generated from all data points.

In Figure 13, the viability of hypothesizing a correlation between traffic density and fine particulate matter is explored. When the complete data set is used, the linear regression model displays weak evidence of correlation between the variables, with the coefficient of determination being

R^2=0.1065. The resulting linear regression is Y = 0.1236x + 3.341, indicating that for every one unit of increase in traffic, fine particulate matter levels increase by 0.1236 ug/m³ and have a background level of 3.341 ug/m³. Error estimates were calculated using the LINEST function, which yielded an error of 0.096% for the slope, and of 18.44% for the y intercept (Table 6). Because a heavy rainfall event occurred on July 29th, 2018 in Curitiba, the night before Jardim Botânico's sampling event, it is thought that $PM_{2.5}$ concentration levels are artificially low for this subset of data. It is speculated that the rain shower cleaned the lower atmosphere, while traffic density remained within the same order of magnitude of the other locations, and actually displayed the highest levels recorded, as seen in Figure 12. Because of this, Jardim Botânico data is removed from the linear regression generated from total traffic count data vs. concentration of $PM_{2.5}$. The new linear regression line generated displays greater extents of correlation between the two variables, with the coefficient of determination being R^2=0.7398. The resulting regression is Y= 0.5406x - 50.332, indicating that for every one unit of increase in traffic, fine particulate matter levels increase by 0.5406 ug/m³ and have a forecasted background level of -50.332 ug/m³.

This type of background level is physically impossible, especially in a study that doesn't deal with sinks of fine particulate matter and is therefore meaningless for concrete purposes. Error estimates were calculated using the LINEST function, which yielded an error of 0.101% for the slope, and of 15.6 % for the y intercept (Table 7)**.** When the two linear regression lines (Y = 0.1236x + 3.341, R^2=0.1065 and Y= 0.5406x - 50.332, R^2=0.7398) from Figure 13 are compared, it is evident how the removal of a confounding factor increases the strength of correlation between traffic and particulate matter levels. Because R^2 increased seven-fold, this not only displays the extent of the effect of rain on particulate matter suspension in air, but also quantitatively motivates the removal of Jardim Botânico data points from all further analysis. This updated R^2 value shows that there is a moderate to strong correlation between traffic density and $PM_{2.5}$ levels, a result that confirms the initial hypothesis regarding the relationship between traffic density and fine particulate matter pollution.

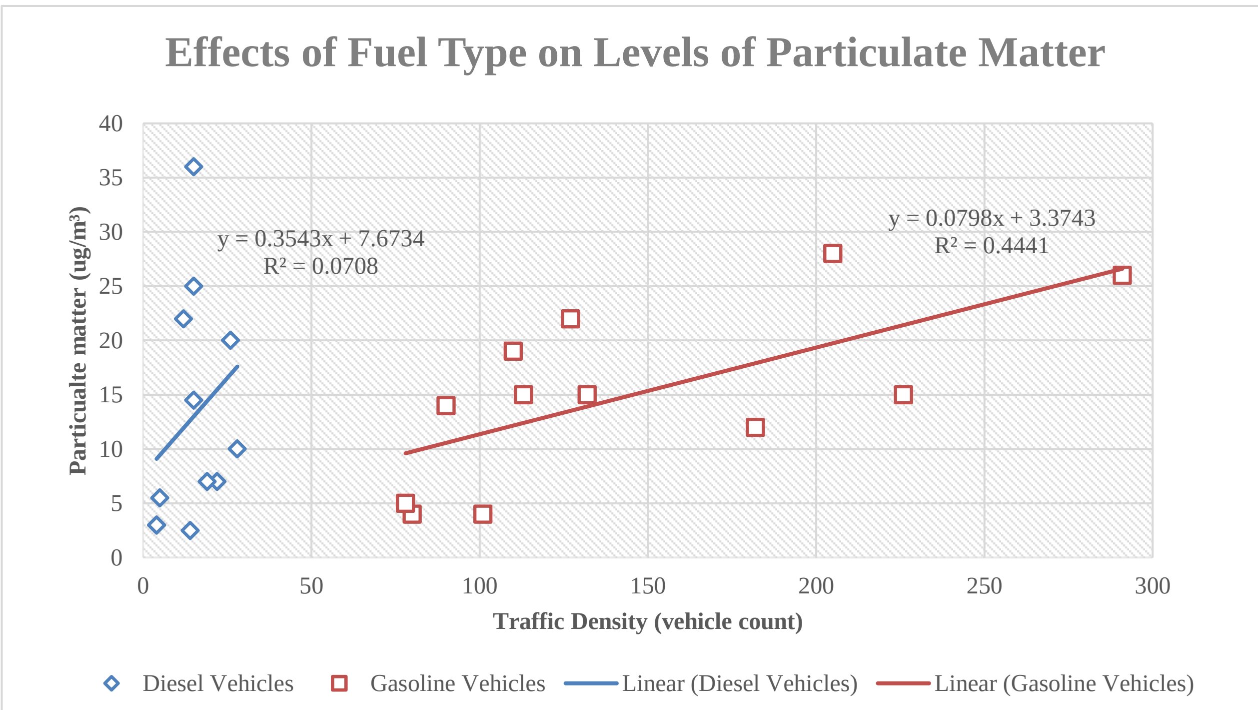

Figure 14. Comparison of influence of Diesel and Gasoline vehicles on levels of $PM_{2.5}$

LINEST Function output for All Sampling Locations excluding Jardim Botânico			
Slope	0.541	-50.33	Intercept
Error	0.101	15.69	Error
R-squared	0.740	17.11	St.dev. of y
F-statistic	28.43	10.00	Deg. of freedom

Regr. sum of squares	8317	2926	Res. Sum of squares

Table 7. Uncertainty estimates for the fitted linear regression values, obtained with LINEST function in OfficeExcel on the line generated from all locations excluding Jardim Botânico.

The linear regression was obtained from plotting the four averages of particulate matter concentration for three sampling locations, one for every time interval during the hour monitoring period and excluding Jardim Botânico, versus diesel vehicle counts for a total of 12 points. In Figure 13 it can be seen how the diesel data is clustered to the left of the graph due to the limited amounts of heavy vehicles counted compared to private passenger ones. In contrast to the linear regressions from Figure 13, the y intercepts resemble each other more, having both a positive value of comparable magnitude. Furthermore, lines in Figure 13 display significantly lower correlation values than the regressions in Figure 13, but for this analysis the relevant statistical values are the slopes of the two lines. The Diesel vehicle regression line Y=0.3543X+7.6734 (R^2=0.0708) indicates a background level of particulate matter of 7.6734 ug/m³ (6.81 % error from LINEST) and infers that for every one additional bus/truck there is a 0.3543 ug/m³ (0.406% error from LINEST) increase in particulate matter. The Gasoline vehicle regression line Y=0.0798X+3.3743 (R^2=0.441) indicates a background of 3.3743 ug/m³ (7.33 % error from LINEST) and infers a 0.0798 ug/m³ (0.446% error from LINEST) increase in particulate matter for every increment in gasoline vehicles. These models confirm the hypothesis that diesel vehicles influence particulate matter pollution more than gasoline vehicles do, because the ratio of the two slopes of the linear regressions (the predictor of fuel-type influence on emission) suggests that diesel vehicle contribution is 4.4 times greater than the contribution from gasoline vehicles. This ratio of slopes translates to 2 buses/trucks having the same impact as almost 9 cars or motorcycles.

DISCUSSION

Traffic density was tabulated, distinguishing vehicles based on their fuel type: diesel or gasoline. Concurrently fine particulate matter ($PM_{2.5}$) ambient air levels were monitored and recorded using AirBeam. By performing linear regression analyses, it was found that there exists a moderate to strong correlation between traffic density and $PM_{2.5}$ concentration (R^2=0.7398), and that a rain event plays a significant role in removing suspended particulates from the air (R^2 increased 0.6333 once the sampling location affected by a rain event from removed from the data set). Modeling the asymmetrical impact that diesel ($y=0.3543x+7.7634$) and gasoline ($y=0.0798x+3.3743$) vehicles have on $PM_{2.5}$ resulted in a slope ratio of 4.4, interpreted as 2 diesel vehicles having a similar impact as 9 gasoline vehicles on the concentration of $PM_{2.5}$. Indicating that out of total traffic, diesel vehicles more strongly contribute to fine particulate matter emission.

Comparing results to other studies is challenging, because traditionally diesel exhaust sampling is performed from diluted and cooled exhaust[25] (i.e. exhaust gas that has exited the tailpipe). This procedure is in accordance with the common $PM_{2.5}$ mass measurement procedures for mobile sources[25]. Another customary method to measure particulate matter, as specified by US EPA procedures, is by gravimetric analysis from a PM sample obtained by filtering diluted engine exhaust at a temperature of 47°C ± 5°C[26]. Both approaches necessitate laboratory settings, whilst this investigation was based in the field using real-world observations and used AirBeam technology. Results from sampling methods that are so different don't allow meaningful comparisons, but nonetheless support the observations made in this study regarding the asymmetric contribution to fine particulate matter by diesel and gasoline vehicles. What is although possible, is comparing findings to other studies that aim at elucidating spatiotemporal characterization of $PM_{2.5}$, studies which usually employ daily $PM_{2.5}$ concentrations obtained at air quality monitoring sites.

Literature confirms that traffic density is related to $PM_{2.5}$.[28] Ultrafine particles, and $PM_{2.5}$ at several sites with significant diesel and gasoline-fueled traffic in Boston, found that concentrations of all pollutants were lower at greater distances from the road, upwind, and at higher wind speeds.[27] Reviews of a variety of recent studies also confirm the positive association between traffic density and PM2.5.[28] An outstanding example is the characterization of traffic-generated particulate matter in Copenhagen, DK[29], which explores the impact that breaking has on the release of $PM_{2.5}$. The literature also supports the finding that fine particulate matter concentration in ambient air is strongly influenced by weather events, which have a large impact on the diffusion, accumulation and transport of air pollutants[30]. When rain falls through the atmosphere, it can attract fine particulate matter, and through the process of coagulation it can remove them from the air[31]. There is no definite extent to which rain cleans the atmosphere of $PM_{2.5}$, as rain's coagulation efficiency depends on altitude of a cloud, the size of its droplets, type of rain event, and the nature of the suspended particulates, for which models are continued to be developed[32] to better understand the likelihood of $PM_{2.5}$ removal from the air during a rain event.

When the focus is shifted to the differential contribution that diesel vehicles and gasoline vehicles have on fine particulate pollution, the data quantifies the impact of an increment in conditional traffic on $PM_{2.5}$. With diesel fuel disproportional contribution being 4.4 times greater than gasoline, on a per vehicle basis according to the generated linear models (Figure 14). These models have low R^2 values, indicating low predictive power. In this specific analysis, assessing correlation is not the goal and the R^2 values just indicate how well a linear relationship fits the observed data. Rather the slopes of the model indicate the contribution of a fuel source to ambient air fine particulate matter levels. The literature confirms the disproportionate contribution to fine particulate matter emission arising from diesel vehicles, as found in this study. Although diesel fuel contains no lead, and emissions of the regulated pollutants (carbon monoxide, hydrocarbons) are lower than those from gasoline cars, they have a much higher emissions of NOx and much higher emissions of particulate matter[33]. This complication is further compounded by the fact that diesel exhaust has a size distribution that mainly consists of fine particulate[34], whilst gasoline exhaust does not (Table 5).

Vehicles	Carbon monoxide	Hydro - carbons	Oxides of nitrogen	Particulate matter	Carbon dioxide
* Gasoline car without a catalyst	100	100	100	---	100
Gasoline cars with a catalyst	42	19	23	---	100
Diesel cars without a catalyst	2	3	31	100	85

Table 5. Emissions for Road Vehicles (per vehicle km)[33].

* Gasoline cars without catalysts have been given a relative value of 100 for comparison

The field results obtained are useful to assess the effectiveness of measures such as diesel particulate filters (DPF) and usage of oxygen-rich diesel fuel mixtures. If DPFs[12] are the main way through which $PM_{2.5}$ is removed from diesel exhaust, then whatever difference found between the results and the pre-filter literature is an estimate of their effectiveness.

It follows that abatement efforts need to be proportionately allocated to sources that constitute a greater threat to human health, like vehicle exhaust. Reduction of fine particulate matter ambient air pollution has a positive impact on more than just human health. It also has a positive impact on the economy of a country. In Canada alone, a country with relatively clean air and small urban centers, public transit saves about $115 million in annual heath care costs related to respiratory illnesses[39]. These numbers become exorbitant when translated and transported to China, India, and other fast developing countries with large, growing populations concentrated in cities. In China about 5% of the GDP is sunk into health care costs related to pollution and pollution prevention and voidance programs and technologies.[39] Considering that China's GDP for 2016 was 11.2 trillion dollars[39], reducing air pollution is nothing short of essential.

In face of having found that on the road two diesel vehicles are equivalent to nine cars for $PM_{2.5}$ concentration purposes, and since it is estimated that one modern and efficient bus replaces about fifty cars[40], switching to public transportation would be a positive tradeoff for fine particulate matter levels would still be lower than under current patterns in automotive traffic. Furthermore, diesel public vehicles would not only reduce overall $PM_{2.5}$ but also reduce the transportation sector's fuel consumption and carbon footprint by at least 40-fold, and up to 50-fold with alternatively fueled buses.[40] In an average sized European city of about one million people, owning about one million cars, traffic could be nulled by running about 200 buses for the entire duration of the day. This would circumvent rush hour traffic, CO_2 and particulate matter emissions, additional complex-chemical-matrix emissions caused by idle traffic, and countless hours spent in vehicles by reducing the traffic congestions of rush hour. Because of this, it is invaluable to increase public transportation on heavy diesel vehicles (diesel is generally preferred for public transportation due to its greater fuel economy and reduced maintenance requirements[33]), as public transportation in Canada reduces the costs of traffic collisions by almost $2.5 billion annually and reduces annual greenhouse gas emission by 2.4 million tons (valued at $110 million), all while Canada remains a private automotive preferential country, so these values could easily be doubled and tripled with low cost BRT system implementation.[40]

If the transition to public transportation was to also entail a transition to alternative fuels (biofuel/diesel mix), fine particulate matter levels would be lowered even further.[41] Switching fuels is the next measure for Curitiba's BRT system, and a "green line" is already underworks. This line will adopt both biofuels and diesel-mix-fuels strategies, as well as introducing an electric component. Incorporating the use of biofuels is the easier transition, and fruition of this measure is scheduled to come quickly, as Brazil is already a leading manufacturer of sugar cane-based biofuel,[42] and a country in which automobiles running on this alternative fuel are not the exception, but rather the norm.[42] Incorporating electric buses is the more challenging component for this specific Brazilian city, but may very well be the fastest, cleanest step towards public transport for other cities around the world. For this reason, when implementing heavy vehicle strategies around the world, they must be tailored to incorporate the renewable resource most available locally, thereby boosting regional economy, innovation in technology, and reducing the environmental footprint of these services most effectively. Evidence that Curitiba, with its use of the BRT system, is a relatively clean from fine particulate matter, is obtained from the comparison of its overall $PM_{2.5}$ levels, to urban centers around the world. For instance, as seen in Figure 15, urban centers in Asia display levels around 60 ug/m^3, while the experimental data obtained for Curitiba is less than 30 ug/m^3.

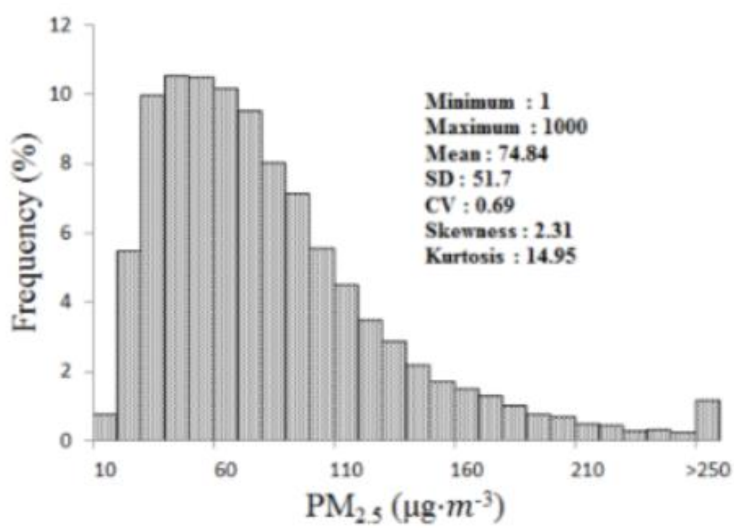

Figure 15. Statistical characterization of $PM_{2.5}$ concentration (ug m^{-3}) in Shandong province during 2014.[43]

Much higher R^2 values are found when diesel and gasoline vehicles are kept combined in a correlation analysis, whilst much lower linearity is found in regressions for the separate types of traffic. This indicated that predictive power of models was greatest when total traffic is dealt with, rather than subcategorizing it based on fuel type. Total ambient air pollution is caused by a variety of factors, and even if traffic is the greatest contributor, taking the overall $PM_{2.5}$ concentration and relating it to quantities that asymmetrically contribute to it, inherently causes a reduction in statistical soundness. Furthermore, the ratio of diesel to gasoline vehicles is not always constant which is a limitation of this analysis. Observing extremes from the data set shows how Parque Sao Lorenço had 6 times as many gasoline vehicles than diesel ones, while Parque Barigui had 22 times as many gasoline vehicles than diesel ones. The data cannot be effectively normalized for these differences, and this highlights the challenge that is isolating diesel pollution under field conditions, since other sources of particulate matter are measured simultaneously and act as confounding variables. The merit of this study therefore, is not in providing an absolute, quantitative model for predicting source contribution to fine particulate matter levels but is rather to provide an estimate of real-life urban environments overall levels and their relationship to exhaust sources.

It is also worth noting that small diesel passenger cars and commercial vehicles with capacities below 1000kg do not circulate on Brazilian roads due to a ban placed in 1976.[44] This embargo was placed mainly to reduce the country’s reliance on foreign oil reserves and consequently improve their trade balances on imported petroleum.[44] This embargo is the reason for which diesel vehicles in this study have been identified as “heavy,” and is also the reasoning behind needing caution when applying these results to other locations where Diesel vehicle regulations and frequency patterns may be different. Large and small vehicles do not emit the same amount of fine particulate matter per unit of vehicle, mostly because of their different engine heating patterns and consequent differences in peak-of-release events.[45] If traffic density was tabulated on the basis of engine size, or vehicle weight, this might be different, but traffic was calculated on the basis of “one vehicle, one count.” Notably, in the United States, diesel vehicles make up only a small percentage of the Nation’s fleet of motor vehicles, and most of these are medium and heavy trucks, but diesel passenger vehicles are nonetheless present.[46] It was estimated that in 2014, Diesel-powered cars accounted for about 3 percent of total auto sales,[47] meaning that this study’s results should not be too far off the expected results if the same study was to be performed in the US, under similar urban landscape conditions. The same cannot be said to apply to European cities, where Diesel-powered cars account for about 50 percent of the total fleet.[47]

This study faced many limitations. For instance, traffic was not normalized for either type of fuel-type vehicle; meaning no data was obtained for solely gasoline or solely diesel traffic. When recording overall traffic, it is impossible to discern from where the particulate matter is coming from. It is especially challenging to obtain comparable results among traffic subsets, as proportion of diesel to gasoline vehicles passing is different, and as different types of vehicles for each fuel type are present. This source of confoundment is further exacerbated by grouping buses and trucks together without discerning among these two different types of vehicle. This may be significant for fine particulate matter levels due to the capacity, load, and overall operational characteristics of these different vehicles. Small passenger trucks have unequal contribution to $PM_{2.5}$ levels than large semi-trucks, or articulated buses. Different manufacturing of engines and catalytic converters, designed to perform under different conditions, are also likely to cause disparity in $PM_{2.5}$ emission from these vehicles.

It would also be valuable to record more environmental and climatic data for each sampling event, as wind speed, temporal distance from a rain event, and cloud cover may affect how much particulate matter is being, or has been, removed from the atmosphere, dampening the effect that traffic has on ambient air levels. Information regarding day of the week, duration of street lights nearby, and where in respect to the road data was collected, could also increase the soundness of results. All these tactics could both explain and reduce variability in data. Most notably, a limited number of data points was analyzed in this study, which greatly affect variability of data and reduces the strength of linear predictive models. Knowledge regarding the details of buses and trucks populating the streets of Curitiba could also improve the significance of the results. Specifically information on the types of catalytic converters installed, how many vehicles use DPF or DPT, as well as the age and potential obsoletion of the public transportation fleet.

Seasonality also affects fine particulate matter, and it is worth noting that the obtained results are not applicable across the board. They are specific to the mild climatic period between June-September in southern Brazil, equivalent to the end of the local winter. Different frequency of rain, wind, fires, heavy heating usage, and pollen production are variable based on geography, and can be partially modeled and accounted for when seeking an overall impact on fine particulate matter levels. An absolute contribution to $PM_{2.5}$ concentration from transportation sources can only be obtained if all these other mentioned variables are effectively quantified and accounted for. This was not done in this study, and has not been achieved by any other either, as fine particulate matter sources are complex and variable. Ultimately, all these limitations restrict the study to providing descriptive and exploratory findings only.

CONCLUSION

In recent times, the disproportionate impact of diesel vehicle traffic on fine particulate matter levels has been reduced by implementing regulations, improving catalytic converters, and diesel particulate filters. This study indicated that two diesel vehicles equated to nine gasoline vehicles for measured $PM_{2.5}$ concentrations. Overall, this study and data from other transportation studies show that switching to diesel powered public transportation has a net positive tradeoff on air pollution levels. Meaning that the city of Curitiba ought to display lower levels of $PM_{2.5}$ pollution from transportation sources than urban areas of similar magnitude where citizens rely more heavily on private gasoline vehicles. Further improvements to the public transportation system could be achieved by continuing to make regulations stricter and promoting technological advances in catalytic converters and DPFs. Limiting particulate matter would also likely reduce the concentrations of other compounds in vehicle exhaust and ultimately having a much larger positive effect on air quality. Drastic betterment of air quality by pollution prevention is not only favorable for mitigation of long-term climatic effects and chronic exposure effects, but also for a short-term human health purpose. The infamous smog conditions of China is the poster child for the extent of damage and limitation to human freedom that bad air quality can have.

Further investigation could include monitoring only buses, researching locations where a different percentage of the fleet is diesel, and more extensive weather studies. Fine particulate matter concentration does not have discreet origins, composition matrices, nor removal mechanisms; hence a variety of factors affect the degree and severity of human exposure.

The larger project under which this study falls under, came to fruition in December 2018. This Brazilian micropollutant study was successful at convincing the board of the National Environmental Agency to update Brazil’s air quality standards. The former legislation on air quality (Resolution n.3/1990), which did not include fine particulate matter as a pollutant of concern, was overturned. It was replaced on the 19th of December 2018 with a Health Ministry law that now includes $PM_{2.5}$ as pollution criteria.

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