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Diesel Engine Age and Fine Particulate Matter Concentrations in School Buses

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Abstract: In this study, we examine and assess the potential impact of diesel engine age on the levels of fine particulate matter ($PM_{2.5}$) in school buses. The concentration of air pollutants is influenced by several factors, including the technical characteristics of the bus and its engine, the type of fuel used, the length of the commute, the weather conditions, and the ambient air pollution. The behavior of the bus on the road, during the commute to and from school, is also important. This includes its position in traffic, the number of bus stops, boarding procedures, as well as the opening of doors and windows. Data were collected by accompanying a student during their commute to and from school, with bus commutes serving as the sampling unit. A semi-parametric regression was applied to assess the link between the $PM_{2.5}$ concentration and the bus engine age. It was demonstrated that the bus engine age has a statistically significant positive correlation with the $PM_{2.5}$ concentration inside the bus. The fine particulate matter concentrations during boarding at the school also depend on the engine age, indicating that bus idling affects the $PM_{2.5}$ concentration. In the first two minutes before boarding in front of the school and the first two minutes inside the bus, the $PM_{2.5}$ concentrations were 26.3 and 40.3 $\mu g/m^3$, respectively. The findings of this study highlight the impact of bus engine age on the $PM_{2.5}$ concentration, showing that the $PM_{2.5}$ concentration increases with the engine age. However, the effect becomes less visible as the duration of the bus ride increases.

Keywords: bus ride; concentration; diesel engine age; fine particulate matter

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1. Introduction

In 1892, Rudolph Diesel, a German engineer, invented a new type of engine that differed from the standard gasoline engine developed 30 years earlier. This invention became known as the diesel engine. The engine, operating under high compression and temperature, was capable of spontaneously igniting liquid fuel without the need for spark ignition. Since the 1920s, diesel engines have demonstrated increased efficiency and reliability because they utilize a less volatile and less flammable fuel, leading to a surge in popularity. Today, diesel engines are used in a wide array of applications, including trains, ships, the mining industry, heavy construction machinery, farm equipment, electrical power generators, buses, cars, and other road vehicles.

Diesel emissions constitute a complex mixture of hazardous particles, gases, and vapors. Diesel particulate emissions primarily consist of carbonaceous material, typically comprising 75% elemental carbon, known as “char” or “soot”, and 20% organic carbon. These percentages can vary widely depending on the engine technology. A small portion of particulate matter (PM) mass comprises inorganic compounds, such as sulfate, water bound to sulfate, and various trace elements (metal oxides) originating from diesel oil components and engine materials.

Various governmental and scientific agencies have determined that diesel exhaust is a probable human carcinogen [1]. Recent studies have also indicated a relationship between lung diseases, such as asthma, and exposure to emissions from diesel engines [2]. Evidence suggests that children are particularly vulnerable to these effects [3,4]. School bus rides have been identified as a potentially significant source of exposure to diesel emissions. Clinical studies have indicated that asthmatic reactions to airborne allergens can be intensified by prior exposure to air pollution. Recent results from epidemiological studies have confirmed this relationship [5,6]. An association between airborne allergens and hospitalizations for asthma was found to be stronger on days with higher levels of fine particulate matter. Thus, exposure during commutes to and from school may exacerbate asthmatic reactions, and promote other negative health reactions, including unintentional injuries [7].

The objective of this study is to determine the impact of various factors on fine particulate matter ($PM_{2.5}$) concentrations related to bus commutes. The factors considered include the age of the bus engine, the length of the bus ride, weather variables, and ambient $PM_{2.5}$ concentration levels. Our study focuses solely on $PM_{2.5}$ concentrations and does not estimate any associated health effects.

2. Materials and Methods

A total of 41 different diesel-fueled buses were utilized, following various routes on typical school days. While the measurements were taken throughout the entire day, only the concentration values related to commute times were analyzed in this study. The observation units were the bus rides to and from school. This cross-sectional study was based on data collected on bus commutes in Fredericton and Oromocto, New Brunswick, Canada, in late spring 2003. The study measurements were conducted from mid-April to mid-June 2003, with data collected and analyzed for 86 different commutes (bus rides) [8]. The measurements were taken on randomly selected days. Consequently, the external conditions, including the traffic intensity, weather, and ambient air pollution, varied significantly. Additionally, the conditions on each bus were highly diverse. The number of children on the bus, the number of bus stops, and the opening of doors and windows, all changed significantly during the measurement process. The sampling period, adopted for the statistical approach in this study, was one bus ride. Even measurements on the same day could be conducted on two different buses, one for the journey to school and another for the journey back home.

The particulate mass matter concentration, specifically particles with aerodynamic diameters of less than 2.5 µm, was measured using a DustTrak monitor (DustTrack: [9]). Sampling was typically carried out in the children's breathing zone, with measurement values available every minute. Other pollutants were also measured during the study, but only data from the $PM_{2.5}$ measurements were considered and analyzed.

Meteorological data, including the hourly temperature, relative humidity, wind speed and direction, and cloud cover, were recorded at Fredericton Airport. Ambient air quality data on the levels of $PM_{2.5}$, nitrogen dioxide (NO_2), ozone (O_3), and carbon monoxide (CO) were collected at a single monitoring site in Fredericton. Both sets of data were obtained from Canada's environment agency and were merged with the study measurement data, by date and corresponding hour [10].

The analytical approach used in this study involved generating three series of cumulative exposures. As the bus commute characteristics and concentration measurements varied significantly, it was necessary to introduce a common variable to represent an individual bus ride. This common variable allows for performing statistical analysis. Here, such a variable is defined as the cumulative concentration for a specified time duration of the bus ride. For example, for each bus commute the sum of 10 concentrations during the first 10 min of the bus ride is calculated and used in the analysis. The duration of each bus ride was divided into three parts: first, middle, and last. These parts could overlap for short-duration rides. Cumulative exposure was then calculated for each part, and the corresponding cumulative exposure series was generated for two minute intervals, ranging up to 15 min. For example, for a two minute interval, the sum of two consecutive measurements was calculated for the first two minutes of the bus ride, the two minutes in the middle part of the bus ride, and the last two minutes of the bus ride. The cumulative exposure for nine minutes was emphasized, as it was the shortest recorded duration with available measurement data among all the buses. It is also the longest common duration between the bus rides in this study. Thus, the cumulative concentration can be compared. During each commute, exposure arises from both “vehicle self-pollution” and “second-hand pollution”, which is the pollution trapped by the bus and originating from other polluting sources, including other school buses, particularly in front of the school. This pollution depends on various factors, such as the number of bus stops, open doors, open windows, ventilation, traffic, and ambient $PM_{2.5}$ levels.

The proposed approach involves applying multivariate linear regression to these three generated sequences of cumulative concentrations. The series of cumulative concentrations for the “first–middle–last” minutes in the duration of the bus rides are used. Logarithmic transformation is applied to the values of the calculated cumulative exposure to obtain an approximate normal distribution. As indicated in the technical documentation on the DustTrak apparatus, its measurement values may be affected by humidity. To account for this phenomenon, a semi-parametric approach is applied. This approach can be viewed as linear regression with a non-linear and non-parametric component for the variable related to relative humidity. A smooth function is used to fit the values for relative humidity, while a linear approach is applied to the other parameters in the model [11].

We also investigated the pollution generated by the bus a few minutes before and after boarding, and before and after disembarking. These values showed a marked difference between the concentration of pollution outside the bus and inside the bus. Measurements for one minute and two minutes were used to compare the concentrations. The indoor and outdoor $PM_{2.5}$ concentrations originated from both buses themselves and other sources. It was assumed that the dependence of the $PM_{2.5}$ concentration on the age of the bus engine would be demonstrated.

3. Results

3.1. Statistics on Environmental Factors and Cumulative Concentration of $PM_{2.5}$

The environmental conditions varied significantly during the study period. This variation impacted the measurement quality and, consequently, the results. The results show two main aspects: (i) the associations between the engine age and $PM_{2.5}$ concentration levels, and (ii) the difference between the $PM_{2.5}$ concentration inside and outside of the bus. Table 1 presents a summary of the parameters considered in this study. All variables listed below were tentatively used in the linear regression models. Some of them, such as temperature, visibility, and wind speed, did not show any correlation with the cumulative $PM_{2.5}$ concentrations in the proposed models.

Table 1. The cumulative concentration of $PM_{2.5}$ and the environmental characteristics.

Variables	Unit	Mean	SD	Median	Minimum	Maximum
First 9 min: $PM_{2.5}$	$\mu g/m^3$	2.47	0.28	2.47	1.75	3.25
Middle 9 min: $PM_{2.5}$	$\mu g/m^3$	2.55	0.29	2.50	1.79	3.31
Last 9 min: $PM_{2.5}$	$\mu g/m^3$	2.50	0.30	2.52	1.72	3.22
Engine age	years	8.5	4.5	7.0	2.0	16.0
Ride duration	minutes	26.5	12.7	26.0	9.0	67.0
Temperature	°C	12.1	6.9	11.6	−10.7	26.8
Humidity	%	63.2	22.2	67.5	20.0	95.0
Visibility	km	22.5	3.7	24.1	9.7	24.1
Wind speed	km/h	14.4	7.9	13.0	0.0	30.0
Ambient $PM_{2.5}$	$\mu g/m^3$	5.0	4.6	3.6	0.0	21.0

(SD = standard deviation).

Consequently, they were not used in the calculations, but are included here to provide information on the characteristics of the weather conditions. The cumulative concentrations calculated for each of the nine minutes are shown for three periods of the commute. The values calculated for the first period are always smaller than those for the last period of the commute. The cumulative concentration obtained for the last period is smaller than that calculated for the middle time interval. For the first and middle part of the commute, the difference was statistically significant for the entirety of the time intervals, i.e., from 2 to 15 min. Figure 1 shows the relationships between the cumulative $PM_{2.5}$ concentrations.

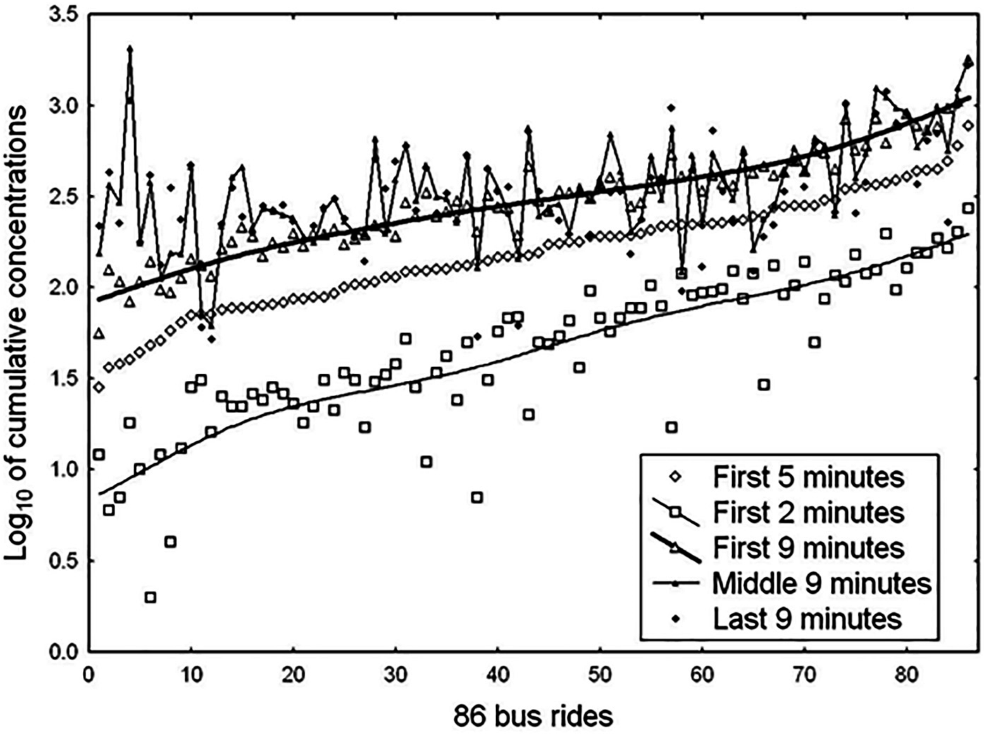

Figure 1. $PM_{2.5}$ concentration for 86 bus rides (in the order of the cumulative concentration for the first 5 min).

The values of the cumulative concentration are presented according to the first five minutes (close to half of a nine minute bus ride). As illustrated in Figure 1, the values calculated for the first two minutes already follow the pattern of the bus rides: from lower to higher $PM_{2.5}$ concentrations. This may indicate that a bus that is already "polluted" remains so for the entire period of the commute. The same is true for the cumulative concentration for the first nine minutes. For the middle nine minutes, a strong fluctuation in the cumulative concentration values were observed. These values represent the influence of "second-hand exposure". For all time intervals, from 2 to 15 min, the average series of cumulative concentrations for the three periods of commutes consistently have the pattern: first < last < middle. Figure 1, the analyzed data, presents the statistical tests that support this observation. The results from the applied linear and semi-parametric models are presented in Table 2.

It is anticipated that during the first (residential area) and last minutes (school area) of a commute, the bus is less affected by external pollution compared to the middle of the bus ride, primarily due to the impact of traffic and bus stops. This characteristic is likely even more pronounced for longer bus rides, such as boarding/disembarking in rural areas with less traffic and no open doors in high-traffic areas near the school. Therefore, the exposure in the first part of a commute is more related to the properties of the bus than at other times during the bus ride. The exposure in the middle part of the travel time is more influenced by other air pollution sources, particularly in non-rural commutes.

Consequently, the cumulative exposure calculated for an entire bus ride is a combination of two sources of exposure: from the bus and from outside.

Table 2. A linear regression model (N = 86) and semi-parametric model (relative humidity in a non-linear and non-parametric form) applied to the cumulative concentration of $PM_{2.5}$ for the first nine minutes of the bus ride. (SE = standard error; * see Wand [11] for details).

Model	**Beta**	**SE**	***p*-Value**
Linear:			
Engine age	0.01	0.012	0.08
Duration of the bus ride	−0.01	0.009	0.01
Ambient $PM_{2.5}$	0.01	0.017	0.13
Humidity	−0.00	0.009	0.20
Semi-parametric:			
Engine age	0.01	0.011	0.05
Duration of the bus ride	−0.01	0.007	0.01
Ambient $PM_{2.5}$	0.01	0.018	0.09
f(Humidity) *	df = 2.24	spar = 78.48	N = 86

3.2. The Dependence of the $PM_{2.5}$ Concentration on Engine Age

The dependent variable is the logarithm of the cumulative exposure for the first nine minutes. The positive association of the $PM_{2.5}$ concentration with engine age is statistically significant (*p*-value = 0.05) and the duration of the bus ride reduces this dependence. We also observe a slight connection with the ambient fine particulate matter concentration. The semi-parametric model is used to represent the linear dependency on the engine age, commute duration, ambient pollution, and non-parametric dependency on the relative humidity. The degree of freedom (df) for the non-parametric part, df = 2.24, indicates the level of non-linearity. Other characteristics describing non-parametric smoothing are also shown [11].

The size of the sample was 101 bus rides, but the measurement data ($PM_{2.5}$) available for the analysis only concerned N = 86 rides [8]. In this study there were 41 different buses. Among the buses for which the measurement data were available (N = 86), the frequency of use was as follows (shown as engine age × times of use): 2 × 6, 3 × 7, 4 × 3, 5 × 12, 6 × 9, 7 × 10, 9 × 8, 11 × 7, 12 × 1, 13 × 7, 14 × 4, 15 × 2, 16 × 10. The engine age was calculated as: engine year—2003 + 1. The duration of the bus ride (often different from the number of available measurements for the bus ride, as some were missing) always affects the results. The duration of a commute reflects the difference between rural bus rides (longer) and urban bus rides (shorter). Some urban bus rides may take longer due to more stops and higher traffic intensity. Figure 2 summarizes the results obtained from the applied semi-parametric model.

The results are provided for the first time interval only, namely the cumulative concentration for 2, 3, . . ., 15 min. For the other two periods (middle and last), the obtained values of the considered coefficients were not statistically significant. Figure 2, which presents the values of the coefficients for the age of the bus and for the ambient $PM_{2.5}$ concentration, reveals that with an increasing commute time, the association between the engine age and $PM_{2.5}$ concentration in the bus decreases (smaller values of the coefficients). During the commute, the technical properties of the bus, such as the engine age, are influenced by the impact of pollution from outside sources. The relationship with the engine age exists, but is obscured by other factors.

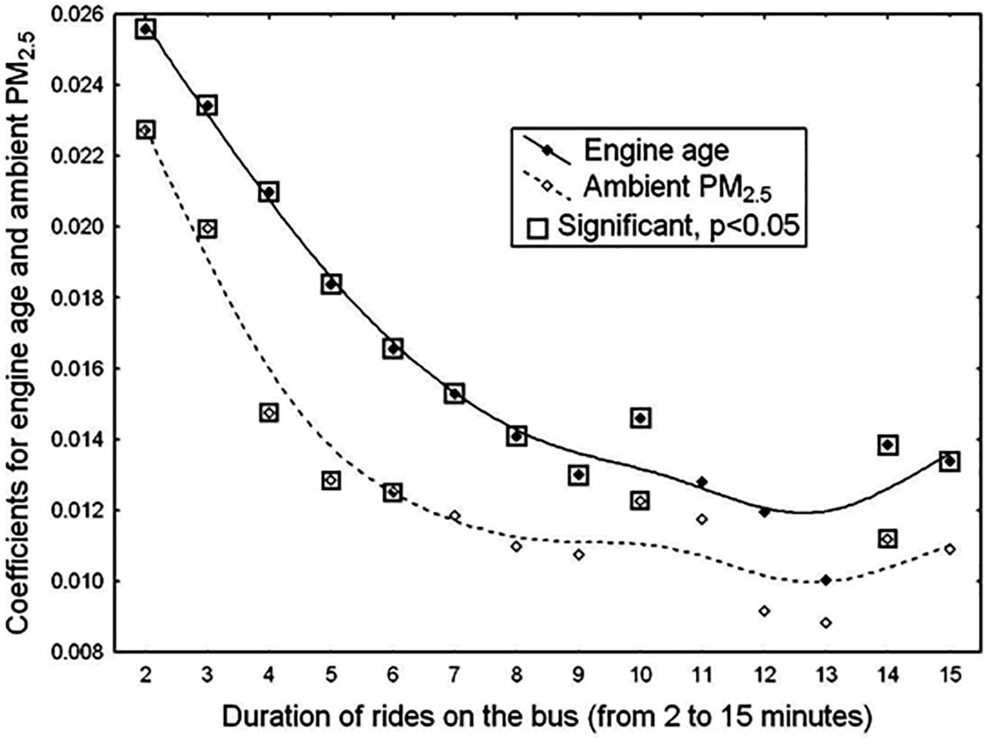

Figure 2. The coefficients for the engine age and ambient $PM_{2.5}$ concentration for the first 2, 3, up to 15 min of the bus ride. Statistical significance is indicated (p-value < 0.05).

3.3. Concentration of $PM_{2.5}$ during Boarding and Disembarking

Another noteworthy aspect of the results is the comparison between the $PM_{2.5}$ concentration during the period when a child boards and leaves the bus. Table 3 contains the mean values of the $PM_{2.5}$ levels measured at 16 different points during the commute to school.

Table 3. Mean level of $PM_{2.5}$ concentration ($\mu g/m^3$) at four time points in the commute: 1 and 2 min on and off the bus.

Location	Mean	Mean	Mean	Mean
Boarding	2 min off bus	1 min off bus	1 min on bus	2 min on bus
a.m. (at stop)	18.4	24.5	25.9	33.5
p.m. (at school)	26.3	32.6	35.3	40.3
Leaving	2 min on bus	1 min on bus	1 min off bus	2 min off bus
a.m. (at school)	46.9	44.9	39.5	26.5
p.m. (at stop)	41.6	36.3	33.4	28.1

The $PM_{2.5}$ values demonstrate a difference between the $PM_{2.5}$ concentration at two pairs of points: on and off the bus. These are: one and two minutes outside the bus and one and two minutes inside the bus. A paired t-test was used to compare the mean of the concentration at two minutes (2 min inside and 2 min outside the bus). In general, the average in-bus level of $PM_{2.5}$ was 32.1 $\mu g/m^3$ (95% CI 28.2–36.5), while the concentration level during walking was 9.7 $\mu g/m^3$ (95% CI 7.4–12.7). Here, the abbreviation CI denotes the confidence interval. Thus, the contrast is large, but smaller at bus stops. The most notable moment is afternoon bus boarding at school. In this situation, a group of buses is usually waiting and probably idling in front of the school. All four considered concentration values (at specific times) for this scenario may be affected by bus-generated pollution.

The difference in the concentration during the two minutes before boarding, and two minutes after, was statistically significant. It is interesting to determine the impact of the bus engine age on pollution levels at these times. To verify this relationship, i.e., the dependency of the $PM_{2.5}$ concentration on engine age, a linear regression model was fitted for each concentration for the 16 considered points: the first and second minutes outside and inside the bus for four situations. Strong, significant results were obtained for the dependency of the $PM_{2.5}$ pollution level on the engine age of the bus and on the ambient $PM_{2.5}$ level for the four points related to afternoon boarding. For the other three groups of four points, there were no such relationships. For morning commutes to school, data from 44 bus rides were available. The average engine age was 8.3 years (SD = 4.7) and, for afternoon commutes (42 bus rides), it was 6.9 years (SD = 4.3). Table 4 shows the results for school bus boarding for the return home.

Table 4. The results (Beta) from the linear regression applied to $PM_{2.5}$ concentration during bus boarding at school at four different moments.

Variable	**Beta**			
Time off/on bus:	2 min off bus	1 min off bus	1 min on bus	2 min on bus
Engine age	0.47	0.43	0.41	0.22
Ambient $PM_{2.5}$	0.45	0.43	0.28	0.32

The *Beta* values represent coefficients of the normalized values, allowing for a comparison using a common regression model. It is evident that the values two minutes before boarding depend on the bus engine age, as do the subsequent two-minute values. Air quality monitors were positioned near the children waiting for their buses. During this waiting period near the school and during boarding, the children were exposed to the emissions from "their" own buses and the combined exhaust emissions from all other buses at the school. Our study shows that this air pollution ($PM_{2.5}$) is influenced by the engine age of the buses.

4. Discussion

The $PM_{2.5}$ concentrations inside the school buses were positively and significantly associated with the age of the bus engine, adjusting for the ambient air pollution ($PM_{2.5}$) concentration, and relative humidity. A recent study on air pollution concentrations in school buses, made the following observations (referenced below in italics) [12–15]:

1. *Self-pollution was detected in all buses, with higher rates observed in older buses.*

This finding is supported by Figure 1 in our study, where cumulative concentrations for the first five minutes follow a similar pattern for nine-minute cumulative concentrations in different periods of the commute. Older buses tend to maintain higher levels of $PM_{2.5}$ throughout the commute.

2. *With windows closed, ventilation was faster inside older buses compared to newer buses.*

As mentioned, our applied semi-parametric model did not yield any significant results related to engine age for the middle and final periods of bus rides. This could be attributed to faster ventilation inside older buses, as noted by Sabin and colleagues [12].

3. *For $PM_{2.5}$, which has both primary emission sources and substantial secondary formation, closing the windows yielded slightly lower mean concentrations inside the cabin, and fewer high-peak concentrations, although the differences between open and closed windows were generally small.*

Similar to engine age effects, the influence of ambient $PM_{2.5}$ is more pronounced at the beginning of a commute and diminishes later, likely due to increased influence from traffic-related pollution. Figure 2 illustrates that the impact of ambient $PM_{2.5}$ decreases with the duration of the commute.

This study is primarily methodological, aimed at investigating the influence of diesel engine age in school buses on fine particulate matter concentrations. Many studies explore the impact of external pollution on pollutants inside buses, often using tracers for this purpose. Here, statistical models are employed to assess the effect of external pollution on indoor bus pollution [16].

The US Environmental Protection Agency (EPA) has recommended four strategies to reduce emissions from buses built between 1998 and 2010 that are still in use. These recommendations include idling reduction, retrofit technologies, engine replacements, and fuel selection [17].

5. Conclusions

This study employs an analytical approach to evaluate the impact of bus engine age on $PM_{2.5}$ concentrations. A more detailed description of the school bus study and additional results can be found in [8]. This study demonstrates that engine age significantly influences the level of air pollution ($PM_{2.5}$) during bus rides, particularly noticeable in the initial minutes of the commute. Engine age also affects $PM_{2.5}$ concentrations during boarding for the return trip home from school. This research primarily focuses on statistical modeling of $PM_{2.5}$ concentrations, underscoring the necessity for further investigations into $PM_{2.5}$ levels in relation to diesel engine age. While recent studies may estimate lower $PM_{2.5}$ levels, the associations observed between engine age and pollutants remain pertinent.

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