Title

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Fuel Effects on PM Emissions from Different Vehicle/Engine Configurations: A Literature Review

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Abstract

Particulate matter (PM) emitted from gasoline combustion continues to be a subject of research and regulatory interest. This is particularly true as new technology gasoline direct injection (GDI) engines can produce significantly higher levels of PM compared to older technology port fuel injection (PFI) engines. The goal of this study was to conduct a comprehensive literature search and subsequent statistical analysis related to the effects of gasoline properties, such as aromatics, octane indices, and fuel volatility, on PM (mass and number) emissions from PFI and GDI vehicles/engines.

The statistical analyses showed a range of positive and negative correlations between different fuel properties and PM mass, total particle number (PN) and solid particle number (SPN) for different engine types (GDI, PFI, and for subdivisions of these engine types), numbers of engine cylinders and driving cycles. For GDI vehicles, total aromatic content, T70, T90 (the temperature when 70% and 90% of a fuel by volume boils away during a distillation test), and distillation end point (EP) [(the highest temperature achieved during a distillation test)] were positively correlated with PM mass emissions, PN emissions, or both. Anti-Knock index (AKI), research octane number (RON), and motor octane number (MON), and T10 (the temperature when 10% of a fuel by volume boils away during a distillation test) were negatively correlated with PM mass emissions, PN emissions, or both. For PFI vehicles for the Federal Test Procedure (FTP), LA92 and US06 cycles, T50, T70, T90, AKI and MON showed more mixed results, with both positive and negative correlations, while distillation EP and RON showed a negative correlation with PM mass emissions. Many of these analyses also showed statistically significant interactions, which indicates that the magnitude and direction of the regression coefficient (slope) estimated between the fuel property and PM emissions component varied as of function of at least one of the categorical variables (i.e., vehicle engine technology or model year, number of cylinders, and/or drive cycle). The presence of such statistical interactions demonstrates the underlying complexity in the data set. The details related to the interactions can provide valuable information to researchers for interpreting data sets that include combinations of different vehicle technologies. The information can also be used in the design of test programs, where a better understanding of how the effects of different fuel properties can vary as a function of different vehicle technologies and drive cycles can aid in study planning.

Introduction

Particulate Matter (PM) emissions are an important contributor to the air quality impacts of transportation sources [1], [2]. Although heavy-duty diesel engines in on-road and off-road applications are the most prevalent sources of PM in mobile source emissions inventories, the contribution of PM emissions from gasoline light-duty vehicles (LDVs) is also significant [3]. The issue of PM emissions from gasoline LDVs is becoming even more relevant as the technology in the marketplace moves from port fuel injection (PFI) vehicles to gasoline direct injection (GDI) vehicles, which inherently produce more PM emissions in the combustion process [4], [5], [6]. The characterization of PM emissions from gasoline LDVs has been studied extensively, especially since the 2000s. In particular, many researchers have been trying to better understand how different parameters, such as fuel properties, engine type, engine operating conditions, and injection processes affect PM characteristics, including mass and number [7], [8], [9], [10].

In 2010, the Honda Motor Company proposed a method for predicting the tendency of a gasoline engine to generate PM during engine combustion based on a Detailed Hydrocarbon Analysis (DHA) of the fuel's composition [11], [12]. For each hydrocarbon component assigned in the DHA of the fuel, a Particulate Matter Index (PMI) value was calculated based on the component's vapor pressure and Double Bond Equivalent (DBE). In general, higher PM emissions from engines appear to correlate with higher PMI values and with higher concentrations of higher boiling point aromatic compounds. Similar results were also observed in other studies conducted on GDI vehicles/engines and PFI vehicles [13], [14], [15].

Recent work has suggested that differences in vehicle hardware can influence the correlation of PM emissions to PMI [16]. Higher concentrations of ethanol in the fuel also appear to enhance the PMI effect [17], such that more PM is produced with ethanol in the fuel for the same PMI value. Recently, PMI has also been correlated with specific distillation values, such as T80 and T90, and End Point (EP) [18]. This is consistent with higher boiling hydrocarbons having a greater influence on PMI values and PM emissions. In general, as these distillation values increase so does the PMI value for the fuel.

According to the PMI method, PM emissions from light duty vehicles are expected to increase with higher PMI values for a fuel. So, the distillation parameters of fuels used in a study should serve as an indicator of the fuel's PMI [11], [12]. The published literature does not always provide PMI data on fuels tested with different vehicle technologies and driving cycles, however. Therefore, the relationship between PMI, vehicle technology and driving cycle is not well defined.

The goal of this study was to collect, review and analyze the available literature to evaluate the impacts that different fuel properties have on PM (mass, total number, and solid particle number [SPN]) emissions as a function of vehicle engine characteristics and driving cycle. This study represents one of the largest and most comprehensive analyses of fuel property impacts on PM emissions. The results could be utilized to better understand fuel design from a standpoint of reducing PM emissions. The information also could be used to better understand experimental designs for major test programs evaluating PM emissions, and in interpreting results from tests programs studying PM emissions that include a range of different vehicles or drive cycles.

Methods

This section discusses the methodology used in carrying out this study, including the characteristics of the data collection and data sets and the methods used for the statistical analysis.

Data Collection

The literature covered a full range of technical reports, peer-reviewed journal articles, as well as information from internal reports by major investigators. A subset of 24 studies included test results that were used for the subsequent statistical analysis. This included some studies where the data were available in the study itself. In most cases, however, data were obtained directly from the authors of different studies. In total, 1841 test results for PFI vehicles and 1325 test results for GDI vehicles were identified for the database. The majority of the data were obtained from published and internal technical reports prepared by environmental and regulatory agencies in the US and Canada (i.e., the Environmental Protection Agency [EPA], California Air Resources Board [CARB], etc.). The balance was drawn from peer-reviewed journal articles. A significant fraction (~42%) of the test results for GDI vehicles was sourced from European and Asian studies.

The literature review was selective and critical. Journals obtained from scientific indices were the preferred choice, although other non-indexed publications, such as Society of Automotive Engineers (SAE) technical papers and some internal and published reports from organizations such as CARB, EPA, and the European Oil Company Organization for Environment, Health and Safety (CONCAWE) were also cited. It is worth noting that a broader range of papers and reports were evaluated in selecting the sources finally used in the statistical analysis. Some papers were excluded from further analysis as they did not include fuel properties, such as distillation parameters, or the actual data was not available for inclusion in the statistical analysis.

For this literature review, the fuels used in individual studies with spark-ignition engines were all treated as gasoline fuels. Although a number of studies used ethanol blends, butanol blends, and other alcohol fuel formulations, further separation of these fuel types was beyond the scope of this analysis. Thus, all fuels were classified as 'gasoline'. The ranges for the primary properties of the test fuels used for the PFI and GDI vehicles are shown in Table 1. The concentrations of ethanol and other alcohols in the test fuels from studies represented in the database ranged primarily from 0% to 20% by volume, with the exception of some which included fuels with an ethanol content as high as 83% by volume [19].

Some of the key variables evaluated in the statistical analysis were the engine technology, the number of engine cylinders, and the driving cycle used for the testing.

GDI vehicle data were obtained from 18 studies, including references [13], [14], [16], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35]. The largest sources of data for GDI vehicles included Coordinating Research Council (CRC) programs [20], [21], [22], the European 'PARTICULATES' program [23], the University of California at Riverside (UCR) College of Engineering-Center for Environmental Research and

TABLE 1 Ranges of Selected Properties of Test Fuels Used in PFI and GDI vehicles

	PFI Vehicle	GDI Vehicle
Aromatics, vol %	2.5-52	2.5-45
Research Octane Number (RON)	90.4-106	89.4-106
Motor Octane Number (MON)	81.6-90.5	82.8-90.5
Anti-Knock Index (AKI)	86.8-98.3	86.3-98.3
T10 °F	91-163	94-163
T50 °F	149-237	154-270
T70 °F	172-290	167-395
T90 °F	174-372	173-367
EP °F	189-417	177-436

Note that T10, T50, T70, and T90, respectively, represent the temperatures at which 10%, 50%, 70%, and 90% of a fuel by volume boils off during a ASTM D-86 test, while EP represents the maximum temperature achieved during a ASTM D-86 test when the fuel is essentially entirely vaporized.

Technology (CE-CERT) mixed alcohol program [19], [24], and the European Petroleum Refiners Association program [25], each of which accounted for over 100 test records. These studies represented approximately 900 of the 1325 GDI test results. Other studies that included at least 50 test results included references [14], [16], and [26]. For the GDI vehicles, emissions results were obtained from 38 different model vehicles and 78 different types of fuels.

PFI vehicle data were obtained from 15 studies, including references [13], [14], [16], [17], [19], [23], [24], [25], [26], [27], [28], [29], [36], [37], [38], [39], [40]. The largest sources of data for PFI vehicles included the Energy Policy Act (EPAct)/E-89 program [17], [36] and Sobotowski et al. [16], which included 955 and 270 test records, respectively, or 1235 of the total of 1841 test records. Other test programs that included at least 90 test records included the European PARTICULATES program [23], the CE-CERT mixed alcohol program [19], [24], and the CRC_E-98 program [37], which in total accounted for another 417 test results. The remaining studies accounted for the remaining ~190. For the PFI vehicles, emissions results were obtained from 42 different model vehicles and 77 different types of fuels.

Test results for PFI and GDI vehicles were classified by engine technology, fuel injection system, and intake air. The vast majority of tests on PFI vehicles were done with stoichiometric naturally aspirated (NA) engines (1832). Only a few PFI vehicle tests were obtained for hybrid technologies. The majority of tests for the GDI vehicles were for stoichiometric naturally aspirated engines using wall-guided (side-mounted) injection technology, followed by lean-burn naturally aspirated engines using wall-guided injection systems (313). A total of 97 tests were obtained from GDI vehicles equipped with stoichiometric turbocharged engines and wall-guided injection systems, and 57 of the tests were obtained from GDI vehicles equipped with stoichiometric naturally aspirated engines and spray-guided (centrally-mounted) injection systems.

The literature data for the PFI vehicles included 1087 vehicles equipped with 4 cylinder engines, 24 vehicles with 5 cylinder engines, 560 with 6 cylinder engines, and 170 with 8 cylinder engines. For the GDI vehicles, 924 were equipped with 4 cylinder engines, 43 with 5 cylinder engines, 319 with 6 cylinder engines, and 39 with 8 cylinder engines.

PFI vehicle data predominantly fell into the 2006 to 2010 model year range. On the other hand, the GDI vehicles tended to be somewhat newer (i.e., model year 2011-2015), as this technology has only recently become more widespread.

The driving cycle used for testing was another key difference between studies. The largest number of emissions tests for the GDI vehicles were performed over the LA92 cycle test, followed by the FTP, NEDC, and US06 cycles, respectively. For PFI vehicles, however, the number of tests on different cycles decreased in the following order: LA92, US06, FTP, and NEDC. A large number of tests were classified under the category 'Other Driving Cycles'. This category includes the Common Artemis Driving Cycles (Urban, Rural, and Motorway), the separate segments of the NEDC (i.e., ECE and EUDC), separate phases of the LA92 (i.e., phase 1 or bag 1 and phase 2 or bag 2), the highway fuel economy test (HWFET), the LA-4 test, and steady-state driving conditions at 120 km/hr, 90 km/hr, and 50 km/hr.

Statistical Analyses

Statistical analyses were performed separately for PFI vehicles and GDI vehicles. For each of these two vehicle categories, correlations were made for PM mass, total particle number (PN), and solid particle number (SPN) emissions and selected fuel properties that included distillation characteristics (i.e., T10, T50, T70, T90, and EP), aromatics content, Research Octane Number (RON), Motor Octane Number (MON), and Anti-Knock Index (AKI). Additional parameters were also investigated, which included engine type, injection system, engine breathing strategy, number of engine cylinders, and driving cycle. The driving cycles were categorized as FTP, LA92, US06, NEDC, and 'others'.

A linear mixed model was fit to the compiled literature test data using the SAS Mixed procedure from SAS Institute, Inc [41]. For this model, the studies were considered as a random variable, since the studies were randomly selected from a larger population, and the goal of the study was to make a statement regarding the larger population. Other variables, such as driving cycle, number of cylinders, and turbo vs. NA (only for GDI vehicles) were incorporated in the analysis as fixed factors. A factor is fixed when the levels under study are the only levels of interest. This model included T10, T50, T70, T90, EP, aromatics, RON, MON, and AKI. The model also included interactions between the different fuel parameters and the main variables, including drive cycle, engine type, and number of engine cylinders.

The primary analysis was to estimate the regression parameters for the fuel effects, with the levels of the fuel properties used as continuous variables within the model. In some cases, additional pairwise comparisons were made using a least squares means test to provide a comparison between drive cycles, engine cylinders, engine types, or other properties. These analyses were typically done in a transformed space, as discussed further below.

The normality of residuals was checked in the models for all emissions to determine if a transformation was necessary. Analyses of the data in previous studies have shown that the standard deviation of emissions measurements is relatively constant as a percentage of the emission level [42]. For example, vehicles with higher emission levels will tend to have a higher variability on an absolute basis than those with lower emissions levels. As such, emissions are generally analyzed with some kind of a transformation.

For this study, given the wide range of data being analyzed, different transformations were used for different data sets, which included logarithmic transformations, exponential transformations, as well as square root transformations. PM mass, PN and SPN emissions were transformed according to Equations 1, 2 and 3 for analyses for GDI Vehicles and Equations 4, 2 and 5 for analyses for PFI vehicles, respectively. For emissions components that included zeros, a small constant was added prior to taking the logarithm to allow the analyses to be done in the logarithm scale.

Equation 1 $$y = \ln(x)$$

Equation 2 $$y = x^{0.25}$$

Equation 3 $$y = \log(x+1)$$

Equation 4 $$y = \frac{1}{\sqrt{(x+0.2)}}$$

Equation 5 $$y = \mathrm{sqrt}(x)$$

ANOVA results were considered to be statistically significant for $p \leq 0.05$, or as marginally statistically significant for $0.05 < p \leq 0.1$. Statistically significant effects that did not involve interactions were further analyzed by main effect comparisons, where the levels of the other independent variables were combined. Statistically significant effects involving interactions were discussed by simple effect comparisons, where the effect of one independent variable was compared within one level of a second independent variable. Pairwise comparisons were made using a least squares means test.

It is important to note that because separate statistical models were built for different engine and pollutant types, quantitative comparisons cannot be made between the fuel impacts for engine type, engine cylinders, and drive cycle. Instead, the results provide a qualitative and directional assessment of the impacts of different fuel properties on PM-related pollutants for different engine types, engine cylinder configurations, and driving cycles. It is also important to note that because the analyses were done in a transformed space, the results could not readily be transformed back to provide quantitative % increases or decreases in arithmetic space. Finally, it is important to note that as the fuels are all generically treated as "gasoline" fuels, without accounting for oxygen/oxygenate effects, some of the underlying fuel property impacts attributed to distillation properties may in fact be due to the presence of oxygenates.

Results and Discussion

Statistical analyses were performed for GDI vehicles and PFI vehicles, and the results for these two vehicle types are discussed separately in this section. For each of these vehicle types, PM mass, PN and SPN emissions were individually correlated with the selected fuel properties.

Fuel Properties Influence on PM Mass, PN, and SPN Emissions from GDI Vehicles

The results of the statistical analysis for the overall data set are provided in Table 2 for each of the fuel properties for PM mass, PN and SPN for GDI vehicles. For these analyses, drive cycle, engine type, and engine cylinders were the categorical variables utilized in the statistical analysis. The tables include the number of observations used in the analysis for each fuel property, the directionality of how the fuel property impacts different PM emissions, i.e., is it positively or negatively correlated with different PM emissions, and whether a statistically significant interaction was identified in the analyses. Statistically significant interactions indicate that the slope of the regression between the fuel property and PM emissions component varied as of function of at least one of the categorical variables (i.e., vehicle engine technology or model year, number of cylinders, and/or drive cycle).

The results (Table 2) indicate that T10, T70, EP, aromatics, RON, MON, and AKI showed statistically significant impacts on PM mass emissions. EP and aromatics were positively correlated with PM mass emissions, indicating PM mass emissions increased as the value of these variables increased. EP also showed statistically significant interactions with engine cylinders and engine type, while aromatics showed statistically significant interactions for drive cycle. T10, AKI, RON, and MON were negatively correlated with PM mass emissions, indicating PM mass emissions decreased as the value of these variables increased. Statistically significant interactions for engine cylinder number were also found for T10, AKI, RON, and MON. T70 showed both positive and negative correlations with PM mass emissions, as well as statistically significant interactions, depending on the specific engine type, number of cylinders, and driving cycle. T50 and T90 did not have statistically significant impacts on PM mass emissions. T90 did show statistically significant interactions, however, and showed positive correlations with PM mass emissions for many of the larger data set categories in terms of engine type and number of cylinders, as discussed in the Appendix. This suggests that T90 remains an important property in terms of PM mass emissions.

The GDI vehicle PM mass results showed trends that are consistent with those seen in the literature. Increases in EP or aromatics have both been found to increase PM mass emissions [13], [14], [31]. Higher EP values can be attributed to compounds with higher distillation values, which is consistent with PM emissions trending higher for fuels with higher PMI values. The distillation properties of a fuel, particularly at the high end, play an important role in mixing during the combustion process. To the extent that fuels with higher T90 and EP values produce more heterogeneous mixtures in the combustion chamber, with more zones of rich combustion or liquid fuel films, the greater the propensity of these fuels to form PM.

Aromatics are key precursors to soot formation, which can occur via addition reactions and condensation of the aromatic rings into carbonaceous structures or through slower fragmentation polymerization reactions [43]. Aromatic compounds can also act as seed molecules for molecular growth and polymerization to form larger hydrogen-deficient polyaromatic hydrocarbons (PAHs) that produce soot [18], [43]. Particulate emissions can also be correlated with higher DBE values for different chemical species in the fuel [11], [12]. Differences in molecular structure and DBE between paraffins and aromatic hydrocarbons contribute to greater particulate emissions for aromatics.

Other variables such as AKI, RON, and MON were all found to be negatively correlated with PM mass emissions. Karavalakis et al. [13] have previously noted that increasing octane number can lead to a reduction in PM emissions. They hypothesized that the reduction of PM mass with AKI could be attributed to differences in the fuel composition, as the lower octane fuel in that study had greater levels of high molecular weight isoparaffins with higher boiling points. Other studies, such as the CRC Report E-94-2 [22], on the

TABLE 2 Statistical analysis for each one of the fuel properties for PM mass, PN and SPN emissions for GDI vehicles, whereas drive cycle, engine type, and engine cylinders.

Emissions	Effect	T10	T50	T70	T90	EP	Aromatic	AKI	RON	MON
PM Mass (Equation 1)	N	609	831	432	829	1124	1111	1048	1050	1048
	Fuel property	**0.0101**	0.9185	**0.0022**	0.7005	**0.0159**	**<.0001**	**0.0111**	**0.0242**	**0.0043**
		↓	NS	↑ & ↓	NS	↑	↑	↓	↓	↓
	Fuel property (Driving cycle)	----	----	**0.0086**	----	----	0.0731	----	----	----
	Fuel property (Engine cylinder)	**0.0016**	0.0910	0.6734	**0.0174**	**0.0149**	----	0.0836	0.0724	0.0685
	Fuel property (Engine type)	----	**0.0126**	**0.0187**	**<.0001**	**<.0001**	----	----	----	----
PN (Equation 2)	N	314	533	313	525	949	892	912	916	913
	Fuel property	**0.0144**	0.9874	**<.0001**	**0.0298**	**0.0079**	**<.0001**	NS	NS	0.0689
		↓	NS	↑	↑	↑	↑	NS	NS	↓
	Fuel property (Driving cycle)	----	**0.0377**	----	**0.0118**	----	**0.0025**	----	----	----
	Fuel property (Engine cylinder)	----	----	----	0.0751	----	----	----	----	----
	Fuel property (Engine type)	----	----	----	0.0962	----	----	----	----	----
SPN (Equation 3)	N	55	56	44	59	476	472	468	468	468
	Fuel property	**0.0311**	**<.0001**	**0.0008**	**<.0001**	NS	NS	NS	NS	NS
		↑ & ↓	↑	↑	↑	NS	NS	NS	NS	NS
	Fuel property (Driving cycle)	**<.0001**	**0.0118**	**0.0254**	----	NS	NS	NS	NS	NS
	Fuel property (Engine cylinder)	**0.0392**	**<.0001**	----	**<.0001**	NS	NS	NS	NS	NS
	Fuel property (Engine type)	**0.0434**	----	----	----	NS	NS	NS	NS	NS

Note: N represents the number of data points for each analysis. The other values represent p-values from the statistical analysis. Bold p-values values denote statistically significant results. Underlined p-values denote marginally statistically significant results; 'NS' denotes 'not significant', '---' indicates there were no results to evaluate; ↑ positive correlation and ↓ negative correlation.

other hand, did not show significant changes in PM emissions for increases in AKI from 87 to 94.

For PN emissions, the fuel properties that showed statistically significant or marginally statistically significant effects (Table 2) were T10, T70, T90, EP, aromatics and MON. T70, T90, EP and aromatics were each positively correlated with PN emissions, while T10 and MON were negatively correlated with PN emissions. T50, T90 and aromatics also showed statistically significant interactions.

The positive correlations of aromatics, T90, and EP, with PN are consistent with the results of other studies [13], [14], [30], [31]. A recent study has also shown a correlation between increasing PN and increasing PMI [22]. The negative correlation for MON with PN is consistent with the results of Karavalakis et al. [13]. AKI and RON, on the other hand, did not show statistically significant impacts, which is more consistent with the results from the CRC E-94-2 study, where significant AKI impacts on PN were not found [22].

For SPN emissions, T10, T50, T70, and T90 demonstrated statistically significant impacts (Table 2). T50, T70 and T90 were each positively correlated with SPN, although interactions were seen for each of these fuel properties. Previous studies have also found that higher volatility fuels tend to produce high SPN emissions, consistent with the statistical analysis results [31]. T10 showed both positive and negative correlations, as well as statistically significant interactions. It should be noted that for other fuel properties, such as EP, aromatics, AKI, RON, and MON, no statistically significant fuel impacts were found, despite having over 400 test results. The lack of strong fuel trends can probably be attributed in part to the fact that for these fuel properties the SPN data were largely drawn from the European "PARTICULATES" program, where the gasoline fuels used had relatively similar properties, which would make it more difficult to identify potential impacts of fuel properties [23].

More detailed information on the statistically significant interactions with engine cylinder and driving cycle are provided in Table 3 and Table 4, respectively. These interactions were discussed here because they are relatively straight forward, since they involve only an interaction with one of the categorical variables. There were also a number of cases where statistically significant interaction were found for two or all three of these categorical variables, indicating more complicated relationships between fuel properties and the underlying testing variables. These interactions are discussed in greater detail in the Appendix.

TABLE 3 Statistical analysis for distillation characteristics, AKI, RON and MON on PM mass and SPN emissions for GDI Vehicles for engine cylinder

Emissions	PM mass (Equation 1)												SPN (Equation 3)		
Fuel property	AKI			RON			MON			T10			T90		
Effect	N	Slope	P-Value	N	Slope	P-Value	N	Slope	P-Value	N	Slope	P-Value	N	Slope	P-Value
Cylinder = 4	844	−0.0151	0.3944	846	−0.0053	0.7190	844	−0.0325	0.1235	277	0.0006	0.9109	28	0.0133	**<.0001**
Cylinder = 5	---	---	---	---	---	---	---	---	---	38	−0.0863	**0.0083**	8	0.0109	0.5322
Cylinder = 6	182	−0.0085	0.6303	182	−0.0047	0.7443	182	−0.0151	0.4901	259	−0.0299	**0.0014**	26	0.0124	0.1587
Cylinder = 8	21	−0.1233	**<.0001**	21	−0.0856	**<.0001**	21	−0.2152	**<.0001**	34	−0.0454	**0.0002**	---	----	---

Note: N represents the number of data points for each analysis. Bold p-values values denote statistically significant results, and '---' indicates there were no results to evaluate.

TABLE 4 Statistical analysis for distillation characteristics and aromatics contents on PM mass, PN and SPN emissions for GDI Vehicles for driving cycle

Emissions	PM mass (Equation 1)			PN (Equation 2)						SPN (Equation 3)		
Fuel properties	Aromatics			Aromatics			T50			T70		
Effect	N	Slope	P-Value	N	Slope	P-Value	N	Slope	P-Value	N	Slope	P-Value
Driving cycle = FTP	102	0.0528	**0.0005**	77	14.9288	**<.0001**	79	2.1544	**0.0175**	3	0.0269	0.2308
Driving cycle = LA92	386	0.0739	**<.0001**	385	23.2270	**<.0001**	---	---	**---**	---	---	---
Driving cycle = NEDC	90	0.0310	**0.0256**	27	44.5253	0.1665	397	−0.7762	0.4286	39	0.0084	**0.0194**
Driving cycle = Others	500	0.0400	**0.0005**	404	87.2734	**0.0032**	3	4.7574	0.5385	3	0.0079	0.6443
Driving cycle = US06	36	0.0363	**<.0001**	**---**	**----**	**---**	33	3.342	0.1932	5	0.0320	**0.0209**

Note: N represents the number of data points for each analysis. Bold p-values values denote statistically significant results, and '---' indicates there were no results to evaluate.

Statistically significant interactions with the number of engine cylinders were found for T10, AKI, RON, and MON for PM mass emissions, and T90 for SPN emissions (Table 3). The results showed that T10 had a statistically significant impact on PM emissions for the 5, 6, and 8-cylinder data sets, but not for the 4-cylinder data. For 5, 6, and 8-cylinder vehicle, the slope was negative, indicating that there was a negative correlation between T10 and PM emissions, or that PM emissions decreased with increasing T10. This suggests that T10 has a more significant impact on PM mass emissions for larger engines. T90 demonstrated an opposite trend, where only 4 cylinder showed a statistically significant effect, and the slope was positive, indicating that there was a positive correlation between T90 and SPN emissions. This trend was found for relatively small subsets of data, however, suggesting that this trend may be more specific to the data sets from the specific studies that were included in the analysis.

AKI, RON and MON had a statistically significant impact on PM mass emissions for the test results that included vehicles equipped with 8-cylinder, but not for those equipped with 4 and 6-cylinder engines. In each case for the 8-cylinder data, the slope was negative, indicating that there was an anti-correlation between these properties and PM emissions. The fact that the 8-cylinder engine category had a relatively small number of test results suggests that octane number may only have an impact on PM mass emissions for larger engines for some specific studies in the dataset.

Statistically significant interactions with driving cycles were found for aromatics for PM mass and PN emissions, T50 for PN emissions, and T70 for SPN emissions (Table 4). Aromatics had a statistically significant impact on PM mass and PN emissions for all the different driving cycles, except the NEDC cycle for PN emissions. In these cases, the slope was positive, indicating that emissions increased with increasing aromatics. The lack of impacts for aromatics for the NEDC for PN emissions could be due to the fact that the European "PARTICULATES" program, where a majority of the NEDC results are drawn from, used gasoline fuels that had relatively similar properties [23]. T50 was found to have a statistically significant impact on PN emissions for the FTP cycle, but not for the other cycles. For T70, a positive correlation was seen for the NEDC and US06 cycles with SPN, but not for the FTP and other cycles.

Fuel Properties Influence on PM Mass, PN, and SPN Emissions from PFI Vehicles

The results of the statistical analysis for the overall data set for each of the fuel properties for PM mass, PN and SPN emissions for PFI vehicles are provided in Table 5 for the FTP, LA92, and US06 cycles, and in Table 6 for the NEDC and other cycles. The results were treated separately for these two sets of driving cycles because many of the observations for the NEDC and other driving cycles did not include the vehicle model year.

For the PFI vehicles, the trends for PM mass were not as strong and consistent as those seen for the GDI vehicles. The statistical analysis results for aromatics, and AKI and MON showed mixed trends, with both positive and negative correlations for the FTP, LA92, and US06 cycles, in contrast to the mainly positive and negative correlations seen for aromatics and AKI and MON, respectively, for the GDIs. T50, T70, and

TABLE 5 Statistical analysis for each one of the fuel properties for PM mass, PN and SPN emissions for PFI Vehicles for the FTP, LA92, and US06.

Emissions	Effect	T10	T50	T70	T90	EP	Aromatics	AKI	RON	MON
PM mass (Equation 4)	N	1250	1238	1107	1241	1208	1197	1104	1102	1104
	Fuel property	NS	NS	NS	**0.0016**	NS	**0.0121**	**0.0001**	**0.0007**	**<.0001**
		NS	↑ & ↓	↑ & ↓	↑ & ↓	↓	↑ & ↓	↑ & ↓	↓	↑ & ↓
	Fuel property (Driving cycle)	NS	NS	**<.0001**	**0.0099**	----	**0.0039**	**<.0001**	**0.0012**	**<.0001**
	Fuel property (Engine cylinder)	NS	**0.0047**	NS	**<.0001**	----	NS	**<.0001**	**<.0001**	**0.0016**
	Fuel property (Model year)	NS	0.0562	----	**0.0009**	**0.0003**	----	----	NS	----
PN (Equation 2)	N	108	108	111	110	108	105	108	108	108
	Fuel property	0.6254	**0.0073**	**0.0112**	**<.0001**	0.0637	**0.0014**	**0.0004**	**0.001**	**0.0002**
		↓	↑	↑	↑	↓	↑	↓	↓	↓
	Fuel property (Engine cylinder)	**0.0083**	**0.0109**	----	----	**0.0308**	----	----	----	----
SPN (Equation 5)	N	17	17	6	17	259	259	255	255	255
	Fuel property	NS	NS	NS	NS	NS	NS	NS	NS	NS

Note: N represents the number of data points for each analysis. The other values represent p-values from the statistical analysis. Bold p-values values denote statistically significant results. Underlined p-values denote marginally statistically significant results; 'NS' denotes 'not significant', '---' indicates there were no results to evaluate; ↑ positive correlation and ↓ negative correlation.

TABLE 6 Statistical analysis for each one of the fuel properties for PM mass and PN emissions for PFI Vehicles for the NEDC and Other Cycles.

Emissions	Effect	T10	T50	T70	T90	EP	Aromatics	AKI	RON	MON
PM mass (Equation 2)	N	232	211	1125	232	463	475	286	286	286
	Fuel property	NS	NS	NS	**<.0001**	NS	**0.0098**	NS	NS	NS
		NS	NS	NS	↓	NS	↓	NS	NS	NS
PN (Equation 5)	N	14	14	12	14	266	256	262	262	262
	Fuel property	NS	NS	NS	NS	NS	NS	NS	NS	NS

Note: N represents the number of data points for each analysis. The other values represent p-values from the statistical analysis. Bold p-values values denote statistically significant results. Underlined p-values denote marginally statistically significant results; 'NS' denotes 'not significant', '---' indicates there were no results to evaluate; ↑ positive correlation and ↓ negative correlation.

T90 also showed mixed trends for the PFI vehicles over the FTP/LA92/US06 cycles, which is more similar to the mixed or lack of trends seen with the GDI vehicles. For T70, T90, AKI and MON, the majority of the data combinations showed a negative correlation with PM mass emissions. RON and EP both showed a negative correlation over the FTP/LA92/US06 cycles, consistent with the results for the GDI RON analysis, but opposite to the results for the GDI EP analysis. In addition, there were statistically significant interactions for all of the fuel properties for the PFI vehicles over the FTP/LA92/US06 cycles. The PFI vehicles showed negative correlations with T90 and aromatics for the NEDC and other cycles, while the other fuel properties did not show statistically significant impacts. The negative correlation for aromatics for the PFI vehicles over the NEDC and other cycles is opposite to the trends seen for the GDI vehicles.

The lack of trends, or in some cases trends opposite to those seen typically in the literature, for the PFI vehicles was somewhat unexpected. The EPACT study, for example, which represented approximately half of the data utilized in the analysis, showed positive correlations for both aromatics and T90 [36]. It is possible that this could be due to underlying correlations with other fuel properties that were not included in this analysis. Ethanol or other alcohols, for example, were critical properties in a number of the studies included in the statistical analysis [16], [24], [36]. The European "PARTICULATES" also did not utilize fuels with strong fuel differences, which could have had an important impact on the NEDC cycles.

For PN emissions for the FTP, LA92, and US06 cycles, T50, T70, T90, EP aromatics, AKI, RON, and MON exhibited statistically significant or marginally significant effects (Table 5). T50, T70, T90 and aromatics showed positive correlations with PN emissions. This is generally consistent with the results for the GDI vehicles, as well as some other studies in the literature [13]. T10, EP, AKI, RON, and MON showed negative correlations. The negative correlations for AKI, MON, and RON are consistent with the results for the GDI vehicles, as well as some other studies in the literature [13]. The negative correlation for EP is interesting, because a higher

TABLE 7 Statistical analysis for distillation characteristics on PM mass and PN emissions for PFI Vehicles for FTP, LA92 and US06 for interactions with interactions with a single categorical variable

Vehicle Year	EP			Distillation characteristics	T10			T50			EP		
Fuel properties	**PM mass (Equation 4)**				**PN (Equation 2)**								
Effect	**N**	**Slope**	**P-Value**	**Effect**	**N**	**Slope**	**P-Value**	**N**	**Slope**	**P-Value**	**N**	**Slope**	**P-Value**
MY = 2005-2010	1137	−0.0033	**0.0039**	Cylinder = 4	67	6.0464	0.105	67	−0.9241	0.4826	67	1.9965	0.2582
MY = After 2010	72	0.0011	0.3242	Cylinder = 6	26	−7.6646	**0.0089**	26	3.9961	**0.0009**	26	0.3557	0.4324
				Cylinder = 8	17	7.0663	0.4055	17	3.1268	**0.0044**	17	−13.2239	**0.0003**

Note: Bold values denote statistically significant results

EP would suggest greater numbers of high distillation point compounds that generally lead to higher PN emissions, as characterized in the PMI index [17]. A statistically significant interaction with engine cylinder was also found for T10, T50 and EP for PN emissions. For the NEDC and 'others' cycles, however (see Table 6), no fuel properties showed statistically significant impacts on PN emissions.

For the SPN data, there were 275 observations, but there were only 18 out of 275 observations without missing data on vehicle year, therefore year wasn't included in the data analysis for SPN. The results did not show any statistically significant effects over the available data for any of the fuel parameters. Similar to the findings for the GDI vehicles, the lack of strong fuel trends for SPN emissions from PFI vehicles can probably be attributed to the fact that the SPN data were largely drawn from the European "PARTICULATES" program, where the gasoline fuels used had relatively similar properties [23]. This would make it more difficult to identify potential impacts of fuel properties.

For PFI vehicles, some properties also showed interactions for one categorical variable, but not the others, as shown in Table 7. EP did not have a statistically significant impact on PM mass emissions for the full set of data, but there still was a statistically significant interaction between EP and model year for the FTP, LA92, and US06 cycle grouping. The results showed a statistically significant negative correlation for EP with PM mass emissions for vehicles with model years between 2005 and 2010, which included a majority of the data, but not for vehicles with model years after 2010. The observation of stronger trends for EP for older model year vehicles could be attributed to the fact that newer vehicles with more advanced combustion and emission control systems can be less sensitive to fuel impacts, although the data set for the 2010 and newer vehicles was also much smaller than that for the 2005-2010 model year vehicles.

T10, T50 and EP exhibited statistically significant interactions between engine cylinders for PN emissions. These interactions were investigated further in Table 7. The results indicated that T10 had a statistically significant impact on PN emissions with a negative correlation for 6-cylinder, but not for 4 and 8-cylinder vehicles. T50 had positive correlations for PN emissions with 6 and 8 cylinder vehicles, but not for 4 cylinder vehicles. EP showed a negative correlation 8 cylinder engines, but not for other combinations of engine cylinders. These particular interactions do not seem to suggest any broader implications, given that they are not consistent across the different fuel properties and that some of the data sets are small. As such, the interactions might be related to some specific conditions within the specific studies that were included in the analyzed dataset.

Summary and Conclusions

A comprehensive literature review and statistical analysis was conducted to identify possible correlations between selected fuel factors, such as the distillation parameters, aromatics and octane indices, and PM mass and Total and Solid PN emissions. A summary of some of the broader results of this study and a discussion of the implications of some of the more complex interactions are provided below.

In terms of broader results for GDI vehicles, aromatics and distillation temperatures had the strongest positive correlations with PM mass and total PN emissions, with increasing levels leading to higher emissions. For distillation temperatures, EP was statistically significant for both PM mass and total PN, while T70 and T90 showed a consistent positive correlation only for total PN. The positive correlation for aromatics and distillation temperatures with PM mass/PN emissions is consistent with trends seen for the PMI index, which is a function of higher double bond equivalent and boiling point species.

Other properties, such as octane indices AKI, RON, and MON, and T10, generally showed more negative correlations with PM and PN for GDI vehicles. AKI, RON, and MON, showed negative correlations for PM mass, while MON showed a negative correlation for total PN emissions. Similar trends have been seen in some other larger studies [13], but not in others [22]. T10 showed negative correlations for both PM mass and total PN. Analysis of statistically significant interactions of T10 with engine cylinder number suggested that T10 may have a more significant impact on PM mass emissions for larger engines.

For PFI vehicles, the strongest fuel effects were seen for PN. T50, T70, T90 and total aromatic content showed positive correlations with PN for the FTP, LA92 and US06 cycles. T10, EP, AKI, RON and MON showed negative correlations with PN emissions for the FTP, LA92, and US06 cycles. These trends were directionally similar to the fuel trends seen for the GDI vehicles, except for EP. Fuel trends were less clear for PM mass emissions for PFI vehicles, with T50, T70, T90, aromatics, AKI, and MON all showing both positive and negative statistically significant correlations with PM mass for the FTP, LA92 and US06 cycles. Only EP and RON showed a consistent negative correlation with PM mass emissions for these driving cycles. For the NEDC and 'other' cycles, the results indicated that T90 and aromatics showed a negative correlation for PM mass emissions, while the other fuel properties did not show statistically significant impacts. For SPN emissions for PFI vehicles, the data set was relatively small, and did not show any statistically significant effects for any of the fuel parameters.

While understanding fuel effects in a universal sense was an important objective of this study, another key finding of this study was that for many fuel properties there were statistically significant interactions between the fuel property and either engine type, number of cylinders, and/or drive cycle in the regression models. This indicates that there was an underlying complexity in the data set, such that the magnitude and direction of the regression coefficient (slope) estimated for a particular fuel property varied as of function of at least one of these categorical variables. It is also important to note that as the fuels are all generically treated as "gasoline" fuels, without accounting for oxygen/oxygenate effects, some of the underlying fuel property impacts attributed to distillation properties may in fact be due to the presence of oxygenates.

In terms of interactions, there were some cases where statistically significant interactions could indicate underlying trends in the data related to particular combinations of engine types/model years, number of engine cylinders and drive cycles. For example, T10 had a more significant impact on PM mass emissions for larger engines for GDI vehicles. For EP, statistically significant effects for PM mass were found to be strongest for vehicles equipped with wall guided GDI naturally aspirated engines, which all showed positive correlations.

In other cases, the nuances of the statistical interactions could suggest cases where there are data limitations. For example, for GDI vehicles, aromatics had a statistically significant impact on PN emissions for all the different driving cycles, except the NEDC cycle for PN emissions. This could be due to the fact that some of the larger European studies used fuels with relatively similar aromatic levels. In another example, statistically significant interactions with all three categorical variables (number of engine cylinders, engine type, and driving cycle) were found for GDI vehicles for T70 for PM mass emissions and T90 for PN emissions, but the majority of those combinations showed positive correlations (see Appendix). This suggests that for other combinations of engine cylinders, engine types, and drive cycles that additional data might be needed to better quantify the effects of T70 for PM mass and T90 for PN for GDI vehicles.

There were also cases where statistically significant effects were found for only a small number of tests results, suggesting that some observed fuel effects may be a specific to a certain study or small subset of studies. The findings of a positive correlation with T90 for SPN emissions for GDI vehicles with 4 cylinder engines and a negative correlation for AKI, RON, and MON for GDI vehicles with 8 cylinder engines are examples of where this might be happening.

While a more detailed discussion of the complexity of all of the different interactions is beyond the scope of this paper, the examples that we have shown may help to serve as a reference guide for other researchers looking to better understand more specific impacts of fuel properties on PM mass, total PN, and SPN emissions. The details related to the interactions could be of use for researchers designing experiments related to PM emissions that involve particular fuel properties, or in selecting vehicles that might be either more or less sensitive to fuel effects. This information could also be of potential value to researchers trying to understand subtleties in larger datasets, where some vehicles or some drive cycles might show fuel effects while others do not.

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Appendix

Fuel Properties as a Function of Engine Type/Model Year, Engine Cylinders and Driving Cycle for PM, PN and SPN Emissions

As discussed in the main section, the effects of different fuel properties on PM emissions are often complicated by multiple interactions between different categorical variables such as the engine type/model year, number of engine cylinders, and driving cycles. In a number of cases, statistically significant interactions were found for two or all three of these categorical variables, indicating a more complicated relationship between the fuel property and the underlying testing variables. These more complicated interactions are further investigated in this Appendix.

It is important to note that due to the complexity of the interactions, the goal of this subsection is not to identify universal trends between different fuel properties and PM emissions, but rather to identify potentially underlying subtleties that might occur in datasets where particular combinations of engine types/model years, number of engine cylinders and drive cycles might be used. Thus, this information is more of a reference for researchers designing experiments or understanding subtleties in larger datasets of emission results.

For this subsection, the analyses were again separated by vehicle type into GDI and PFI vehicles, with each of these different interactions discussed separately for the two vehicle types.

GDI Vehicles This section provides further detail for combinations of different engine types, engine cylinders and driving cycles for PM, PN and SPN emissions for GDI vehicles where two and three way statistically significant interactions were identified.

For PM mass emissions, T50, T90 and EP all showed statistically significant or marginally statistically significant interactions between engine cylinder and engine type, as shown in Table 2, even though T50 and T90 did not show statistically significant impacts for the full set of data. These statistically significant interactions are presented in greater detail in Table A1. It is worth noting that all the statistically significant effects for T50 and T90 on PM emissions were from wall guided GDI engines. These effects showed a positive correlation for T50 and a mixture of positive and negative correlations for T90. For EP, the statistically significant effects were all associated with vehicles equipped with wall guided GDI naturally aspirated engines and all showed a positive correlation.

Properties that showed interactions with all three categorical variables for GDI vehicles are presented in Table A2. T70 showed statistically significant interactions for PM mass emissions for different engine cylinder, driving cycle and

TABLE A1 Statistical analysis for distillation characteristics on PM mass emissions for GDI Vehicles for the combination engine cylinder and type.

Distillation characteristics	T50			T90			EP		
Effect	N	Slope	P-Value	N	Slope	P-Value	N	Slope	P-Value
Cylinder = 4, Engine = WGDI_NA	392	0.0018	0.5057	392	0.0131	**<.0001**	806	0.0125	**<.0001**
Cylinder = 4, Engine = WGDI_Turbo	68	0.0110	**0.0001**	68	0.0028	<u>0.0688</u>	56	0.0015	0.2208
Cylinder = 5, Engine = WGDI_NA	38	−0.0257	0.3320	38	−0.0062	0.4345	----	----	----
Cylinder = 6, Engine = SGDI	52	0.0033	0.3760	52	−0.0011	0.5893	52	0.0026	0.3128
Cylinder = 6, Engine = WGDI_NA	229	0.0169	0.5085	229	0.0179	**<.0001**	175	0.0128	**<.0001**
Cylinder = 6, Engine = WGDI_Turbo	19	0.0129	**0.0122**	19	−0.0106	0.2773	17	0.0444	0.2631
Cylinder = 8, Engine = WGDI_NA	34	0.0145	**0.0092**	34	0.0088	**<.0001**	21	0.0036	**0.0330**

Note: Bold values denote the statistically significant results, whereas underlined values denote the marginally statistically significant results and '---' do not have results to evaluate.

TABLE A2 Statistical analysis for distillation characteristics on PM mass, PN and SPN emissions for GDI Vehicles for the combination driving cycle, engine cylinder and type

Emissions	PM mass			PN			SPN		
Distillation characteristics	**T70**			**T90**			**T10**		
Effect	**N**	**Slope**	**P-Value**	**N**	**Slope**	**P-Value**	**N**	**Slope**	**P-Value**
Driving cycle = FTP, Cylinder = 4, Engine = WGDI_NA	36	0.0117	0.0994	33	4.4195	**<.0001**	---	----	**---**
Driving cycle = FTP, Cylinder = 4, Engine = WGDI_Turbo	11	0.0203	0.1516	3	5.4696	0.1272	3	0.0331	**0.0112**
Driving cycle = FTP, Cylinder = 5, Engine = WGDI_NA	---	----	**---**	---	----	**---**	6	−0.0272	0.3562
Driving cycle = FTP, Cylinder = 6, Engine = SGDI	18	−0.0159	**0.0410**	17	0.8881	0.0777	---	----	**---**
Driving cycle = FTP, Cylinder = 6, Engine = WGDI_NA	25	0.0050	0.1977	17	2.6622	**0.0002**	---	----	**---**
Driving cycle = FTP, Cylinder = 6, Engine = WGDI_Turbo	---	----	**---**	3	−2.3952	0.1573	---	----	**---**
Driving cycle = FTP, Cylinder = 8, Engine = WGDI_NA	10	0.0089	**0.0283**	11	2.4982	**0.0052**	---	----	**---**
Driving cycle = LA92, Cylinder = 4, Engine = WGDI_NA	96	0.0208	**<.0001**	278	5.1863	**<.0001**	---	----	**---**
Driving cycle = LA92, Cylinder = 6, Engine = SGDI	17	0.0125	0.0658	34	1.8894	**0.0002**	---	----	**---**
Driving cycle = LA92, Cylinder = 6, Engine = WGDI_NA	51	0.0228	**<.0001**	72	5.8284	**<.0001**	---	----	**---**
Driving cycle = LA92, Cylinder = 8, Engine = WGDI_NA	12	0.0140	**0.0011**	11	2.0673	**<.0001**	---	----	**---**
Driving cycle = NEDC, Cylinder = 4, Engine = WGDI_Turbo	20	0.0099	0.1612	---	----	**---**	20	0.0041	0.7209
Driving cycle = NEDC, Cylinder = 6, Engine = WGDI_NA	20	0.0041	0.7574	---	----	**---**	20	−0.0390	0.1108
Driving cycle = Others, Cylinder = 4, Engine = WGDI_NA	50	0.0169	**0.0095**	3	19.6540	0.3276	3	−0.0021	0.9325
Driving cycle = Others, Cylinder = 4, Engine = WGDI_Turbo	18	0.0103	**0.0298**	20	2.8169	0.0518	---	----	**---**
Driving cycle = Others, Cylinder = 6, Engine = WGDI_Turbo	12	0.0068	0.2800	12	2.4269	0.7454	---	----	**---**
Driving cycle = US06, Cylinder = 4, Engine = WGDI_NA	3	0.0630	**0.0352**	---	----	**---**	3	−0.0375	**0.0223**
Driving cycle = US06, Cylinder = 4, Engine = WGDI_Turbo	20	0.0043	0.0520	18	3.4596	**<.0001**	3	0.0425	**0.0131**
Driving cycle = US06, Cylinder = 6, Engine = WGDI_NA	9	−0.0011	0.8946	---	----	**---**	---	----	**---**
Driving cycle = US06, Cylinder = 6, Engine = WGDI_Turbo	6	0.0255	**0.0042**	6	4.3846	**0.0002**	---	----	**---**

Note: Bold values denote the statistically significant results, whereas underlined values denote the marginally statistically significant results and '---' do not have results to evaluate.

engine type combinations, with the majority of those combinations showing positive correlations. T90 for PN emissions and T10 for SPN also showed interactions with all three of the categorical variables. The correlations were positive for almost all combinations for T90 for PN emissions, as well as for the FTP, 4 cylinder, WGDI Turbo combination for T10 for SPN.

There were also statistically significant interactions between T50 and engine cylinder and engine type for SPN emissions, as shown in Table A3. This included statistically significant and marginally statistically significant effects for 6 and 4 cylinder engines over the NEDC that both showed positive correlations.

TABLE A3 Statistical analysis for the combination engine cylinder and driving cycle on SPN emissions for GDI Vehicles on T50

Effect	N	Slope	P-Value
Driving cycle = FTP, Cylinder = 4	3	0.0092	0.7597
Driving cycle = FTP, Cylinder = 5	6	0.0407	0.3562
Driving cycle = NEDC, Cylinder = 4	20	0.0040	0.0767
Driving cycle = NEDC, Cylinder = 6	20	0.0143	**0.0035**
Driving cycle = Others, Cylinder = 4	3	0.0233	0.2076
Driving cycle = US06, Cylinder = 4	5	0.0092	0.6514

Note: Bold values denote the statistically significant results, whereas underlined values denote the marginally statistically significant results.

PFI Vehicles For PFI vehicles, two and three-way interactions were only found for PM mass emissions. Aromatic content was found to have a statistically significant interaction with combinations of driving cycle and engine cylinder for PM mass emissions, as shown in Table A4. The majority of the combinations that showed statistically

TABLE A4 Statistical analysis for aromatics on PM mass emissions for PFI Vehicles for the combination driving cycle and engine cylinder.

Effect	N	Slope	P-Value
FTP, LA92, US06 driving cycles			
Driving cycle = FTP, Cylinder = 4	16	0.1537	0.2288
Driving cycle = FTP, Cylinder = 6	12	0.02113	**0.0037**
Driving cycle = LA92, Cylinder = 4	519	−0.00809	**<.0001**
Driving cycle = LA92, Cylinder = 6	417	−0.00707	**0.0004**
Driving cycle = LA92, Cylinder = 8	144	−0.00684	**0.0069**
Driving cycle = US06, Cylinder = 4	67	−0.01296	**0.0001**
Driving cycle = US06, Cylinder = 6	32	0.00429	0.079
NEDC and other driving cycles			
Driving cycle = NEDC, Cylinder = 4	31	−0.00719	0.3279
Driving cycle = Others, Cylinder = 4	386	−0.01673	**0.0088**
Driving cycle = Others, Cylinder = 6	56	−0.00455	0.5074

Note: Bold values denote the statistically significant results, whereas underlined values denote the marginally statistically significant results.

significant effects had negative slopes, indicating that there was anti-correlation between aromatics content and PM emissions.

T50, T70 and T90, AKI, RON and MON all showed interactions with model year and engine cylinder or driving cycle for PM emissions, as shown in Table A5 and A6. For T50, the majority of the data combinations showed a negative correlation with PM mass emissions, although the largest data subset for 4 cylinder, 2005-2010 vehicles over the LA92 showed a positive correlation with PM emissions. T70 showed

TABLE A5 Statistical analysis for distillation characteristics on PM mass emissions for PFI Vehicles for the combination engine cylinder, model year and FTP, LA92, US06 driving cycles.

Distillation characteristics	T50			T70			T90		
Effect	**N**	**Slope**	**P-Value**	**N**	**Slope**	**P-Value**	**N**	**Slope**	**P-Value**
Driving cycle = FTP, Cylinder = 4, MY = After 2010	16	−0.01108	0.2494	16	0.02972	**0.0028**	16	0.01158	**0.0304**
Driving cycle = FTP, Cylinder = 5, MY = 2005-2010	8	−0.09519	0.0545	---	---	----	8	−0.02538	0.0545
Driving cycle = FTP, Cylinder = 6, MY = 2005-2010	10	0.04189	0.294	---	---	----	10	0.01309	0.294
Driving cycle = FTP, Cylinder = 6, MY = After 2010	12	0.00319	0.3658	12	0.00319	0.0782	12	0.00326	**0.0038**
Driving cycle = LA92, Cylinder = 4, MY = 2005-2010	492	0.00073	0.0914	490	−0.00524	**<.0001**	492	−0.00288	**<.0001**
Driving cycle = LA92, Cylinder = 4, MY = After 2010	30	−0.008	0.0753	30	−0.0032	0.3425	30	0.00687	**0.0075**
Driving cycle = LA92, Cylinder = 5, MY = 2005-2010	7	−0.06417	**0.0008**	---	---	----	7	−0.01711	**0.0008**
Driving cycle = LA92, Cylinder = 6, MY = 2005-2010	408	2.1E-05	0.9765	406	−0.0036	**0.0022**	408	−0.00167	0.1041
Driving cycle = LA92, Cylinder = 6, MY = After 2010	12	−0.00161	0.5742	12	−0.0017	0.2632	12	−0.00105	0.3297
Driving cycle = LA92, Cylinder = 8, MY = 2005-2010	144	0.00112	0.2084	---	---	----	144	−0.00337	**0.0072**
Driving cycle = US06, Cylinder = 4, MY = 2005-2010	67	−0.002	0.2168	3	−0.02181	0.2326	67	−0.0072	**<.0001**
Driving cycle = US06, Cylinder = 5, MY = 2005-2010	9	−0.04153	**0.0004**	---	---	----	9	−0.01108	**0.0004**
Driving cycle = US06, Cylinder = 6, MY = 2005-2010	37	0.00076	0.5459	---	---	----	37	−0.00042	0.657
Driving cycle = US06, Cylinder = 6, MY = After 2010	6	−0.00123	**<.0001**	6	−0.00104	**0.0038**	6	0.00078	0.4428

Note: Bold values denote the statistically significant results, whereas underlined values denote the marginally statistically significant results and '---' do not have results to evaluate.

TABLE A6 Statistical analysis for AKI, RON and MON on PM mass emissions for PFI Vehicles for the combination driving cycle, engine cylinder and model year

Fuel property	AKI			RON			MON		
Effect	**N**	**Slope**	**P-Value**	**N**	**Slope**	**P-Value**	**N**	**Slope**	**P-Value**
FTP, LA92, US06 driving cycles									
Driving cycle = FTP, Cylinder = 4, MY = After 2010	16	−0.337	**0.0155**	16	−0.2545	**0.0099**	16	−0.4514	**0.0406**
Driving cycle = FTP, Cylinder = 6, MY = After 2010	12	−0.02541	**0.0322**	12	−0.06854	**0.0138**	12	−0.03749	**0.0241**
Driving cycle = LA92, Cylinder = 4, MY = 2005-2010	490	−0.01941	**0.0002**	490	−0.0163	**<.0001**	490	−0.01503	0.0536
Driving cycle = LA92, Cylinder = 4, MY = After 2010	30	−0.08035	0.0722	30	−0.06794	**0.0241**	30	−0.02954	0.6497
Driving cycle = LA92, Cylinder = 6, MY = 2005-2010	406	−0.0078	0.3608	406	−0.00851	0.1633	406	0.00179	0.8878
Driving cycle = LA92, Cylinder = 6, MY = After 2010	12	0.01675	0.2515	12	0.01249	0.2232	12	0.02449	0.3328
Driving cycle = LA92, Cylinder = 8, MY = 2005-2010	144	−0.02561	**0.0129**	144	−0.02064	**0.0055**	144	−0.02582	0.0915
NEDC and other driving cycles									
Driving cycle = NEDC, Cylinder = 4	30	0.01816	0.78	---	---	---	30	0.01152	0.8325
Driving cycle = Others, Cylinder = 4	246	−0.00071	0.9966	---	---	---	246	−0.00319	0.9817
Driving cycle = Others, Cylinder = 6	8	0.0583	**0.0004**	---	---	---	8	0.05708	**0.0004**

Note: Bold values denote the statistically significant results, whereas underlined values denote the marginally statistically significant results and '---' do not have results to evaluate.

a mix of positive and negative correlations, but with the largest data subset for 4 cylinder, 2005-2010 vehicles over the LA92 showing a positive correlation, and the second largest data set for 6 cylinder, 2005-2010 vehicles over the LA92 showing a negative correlation. T90 showed a mix of combinations with positive and negative correlations. For AKI, RON and MON, the vast majority of the combinations showed negative correlations with PM mass emissions, with the exception of 6 cylinder vehicles over "other" cycles for AKI and MON.

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