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ANALYSIS AND REVIEW OF DHA METHODS USED IN CRC OXYGENATED GASOLINE EMISSIONS PROJECTS E-94-2, E-94-3, AND E-129

Final Report

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COORDINATING RESEARCH COUNCIL, INC.

5755 NORTH POINT PARKWAY • SUITE 265 • ALPHARETTA, GA 30022

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Final Report:

Analysis and Review of DHA Methods used in CRC Oxygenated Gasoline Emissions Projects E-94-2, E-94-3, and E-129

Date: 9/30/2020

To: Coordinating Research Council (CRC) Emissions Committee

From: Southwest Statistical Consulting, LLC

Tim Coburn and Jack Schuenemeyer

In fulfillment of the contract for CRC Project E-127-1

Executive Summary

Southwest Statistical Consulting, LLC conducted a third-party investigation (meta-analysis) of the results presented in CRC Report No. E-94-2, "Evaluation and Investigation of Fuel Effects on Gaseous and Particulate Emissions on SIDI In-Use Vehicles," CRC Report No. E-94-3, "Impact of Splash-Blending on Particulate Emissions for SIDI Engines," and CRC Report No. E-129, "Alternative Oxygenate Effects on Emissions." The statistical evidence using data provided by CRC pertaining to the impacts of oxygenated fuels on particulate emissions was examined. The project objectives were to determine (1) whether combining data from the previous studies could help resolve conflicting results concerning ethanol enhancement of fuels and (2) whether results from detailed hydrocarbon analysis (DHA) could provide additional explanation.

The principal findings of this investigation are provided here, with additional commentary given in the summary below:

- After combining data sets, the limited number of vehicles on some programs, and test runs associated with the individual studies still constitute too small a dataset to resolve all the differences.
- There are statistically significant differences in average weighted particulate matter (PM) among both fuels and vehicles, but there is also a statistically significant and *persistent* fuel-by-vehicle interaction (subsequently designated as "fuel x vehicle") which negates the ability to make definitive inferences about the fuels.
- DHA results provide strong clues about, but not definitive explanations for, differences among the fuels. From a carbon perspective, the combination of C_9 and C_{10+} (in terms of weight percent, or Wgt%) is most predictive of "average" weighted PM. From a group perspective, Mono-Aromatics, I-Paraffins, Naphtheno/Olefino-Benzs, and Naphthalenes (Wgt%) are all individually strong predictors.
- Disaggregating the DHA results down to the individual constituents within carbons and groups provides additional clues regarding differences in fuels and the associated PM response, particularly with regard to the importance of Mono-Aromatics and I-Paraffins; but due to inconsistencies in the presence of individual constituents across fuels, this resolution of the data is too granular (at least in the existing data set) to be definitively explanatory.

This effort identified and built on common effects observed and reported in the three prior studies and statistically combined (pooled) them to construct a larger body of information from which to develop more precise estimates. As suggested above, there were two major components to the study. Part 1 investigated the relationship between weighted PM and other variables in the E-94-2, E-94-3 and E-129 reports. Part 2 investigated the accompanying DHA data, including the relationship between weighted PM and carbon and group variables, which was not part of the three original studies.

The analysis for these investigations was accomplished using various combinations and forms of regression analysis, analysis of variance (ANOVA), tabular studies, and graphical/visual

presentation, all approaches that are commonly used to study automotive emissions. Other methods including clustering, linear discriminant analysis, mixed (random-fixed effect) models, and several non-parametric analyses were used but did not provide any additional conclusive evidence. Because of the small number of observations relative to the number of variables in the available data, median values of PM were frequently used in the analysis. Also, a transformation to the data was applied where appropriate to satisfy underlying statistical assumptions.

Part 1: Meta-analysis of PM as a function of other variables

In studies such as this one involving multiple explanatory variables, it must be determined which variables are fixed and which are random. In the three previous studies, "fuel" was considered fixed while "vehicle" was considered random. Specifying the vehicle effect to be random implies that the vehicles used in the studies were selected at random (i.e., using a probabilistic sampling approach) from all those available, allowing any model inference to apply to a larger group of vehicles in the sampled population/fleet. As a result of our discussions with CRC concerning this assumption, we concluded that the vehicles used in the three prior studies do not constitute a random sample, and hence, for the current investigation, we designated them as fixed.[1] This decision directly impacted the structure of our analyses and the inferences to be drawn from the results. We emphasize that our investigation was primarily focused on differences in fuels. We note that, collectively, the E-94-2, E-94-3, and E-129 reports devote considerable effort to differences in vehicles, and we accept that prior work without stipulation.

Taking the preceding consideration into account, we used the same statistical procedures and models to analyze the data from each of the three prior studies, as well as the combined set containing the data from all three. In addition to weighted PM, fuel, and vehicle, the other three important variables are antiknock index (AKI), ethanol (EtOH), and the particulate matter index (PMI). For the three latter variables there is only one observation per fuel, which limits the formal statistical analyses that can be undertaken. Tables are presented which show relationships between PM and AKI, EtOH, and PMI.

Relying on the experimental designs of the E-94-2, E-94-3, and E-129 programs and their resulting data structures (217, 36, and 27 observations, respectively), we used ANOVA to investigate the three original data sets, as well as the combined data set, using fuel, vehicle, and fuel x vehicle as prospective explanatory variables. When analyzing the combined data, we also considered program and blending protocol as additional variables. Fuel, vehicle, and fuel x vehicle were found to be statistically significant in all cases, as were program and blend when analyzing the combined data set. The specific forms of all the ANOVA models are presented in the report.

[1]See p. 7 of the E-94-2 report where the authors indicate that "these vehicles were selected because they were available, widely used in the U.S. and were equipped with engines using gasoline direct injection." From a statistical perspective, this statement suggests the vehicles constitute a "convenience sample" rather than a randomly selected sample.

While we pursued this investigation from several different angles, our results show there is no real benefit of pooling information from the three studies, contrary to the original hypothesis of the study. A major complicating factor is the fuel x vehicle interaction. We suggest two ways to address this issue: 1) formally (rather than anecdotally) determine if any of the vehicles are truly outliers and eliminate them and 2) increase the number of vehicles by synthetic means using a simulation procedure (since replicating any of the three original studies is likely impractical). Eliminating any vehicles, however, will further restrict the applicability and extensibility of the analyses, so increasing the number of vehicles through synthetic means seems the most logical and cost-effective approach.

Part 2: Analysis of DHA data

Again, as noted above, the second major component of the study was to determine whether DHA results could explain the conflicting observations about PM attributable to ethanol-enhanced fuels reported in the prior three studies.

Initial data exploration focused on the compositional nature of the DHA data. For each fuel, C_8 was determined to be the largest contributor to total Wgt%. The carbon having the second, third, etc. largest contribution varies from one fuel to the next without much consistency, but the mid-range carbons (say, C_5-C_9) clearly dominate. For all fuels, C_{12} and above add small to miniscule amounts on a Wgt% basis to the overall composition, as do C_2-C_4, except, as expected, in the case of oxygenated fuels where C_2 represents a higher contribution.

Our analysis indicates that there are statistically significant differences among the fuels attributable to various carbon-group combinations. C_9, C_{10}, Mono-Aromatics, and I-Paraffins tend to be predominant. The three E-129 fuels are clearly different from their counterparts due to a preponderance of I-Paraffins, whereas Mono-Aromatics are dominant for all other fuels. In addition, there are statistically significant differences among the fuels based on the ordering of the Wgt% contributions of individual constituents.

To investigate the link between DHA results and PM, the differences we observed among fuels based on analyzing the rank ordering of individual constituents were compared to those we observed when analyzing PM responses separately. On the basis of this simple "yes-no" or "agree-don't agree" basis, we found a close (73.4%), but not perfect, correspondence among the results obtained with the two different analysis methods; i.e., in most cases, the decision as to whether or not a pair of fuels has a statistically significant difference in mean PM is identical to the decision about those same fuels when comparing the means of the ranks assigned to their DHA constituents. This finding is noteworthy in the sense that it suggests that differences among the same fuels can be detected in different ways and by using different data, thereby strengthening the validity of the observed differences. Still, due to the multivariate nature of DHA results and the limited number of observations[2], this finding does not directly explain why the fuels exhibit high or low average values of PM.

[2]There is only one DHA observation per fuel (i.e., only one set of DHA results per fuel).

In total, we conclude there is evidence that differences in mean PM among fuels can be linked to the Wgt% values of C_9 thru C_{11}, and possibly C_{12}, in combination with Mono-Aromatics, I-Paraffins, Naphtheno/Olefin-Benzs, and Naphthalenes. The effects of C_9 thru C_{12} can, perhaps, be better characterized if considered more parsimoniously as C_9 and C_{10+}. Given the number of combinations among this collection of variables, it would be difficult, if not impossible, to parse out the most important ones without additional data (since there would still be more variables than observations).

Again, we emphasize that, because of the nature and limitations of the data set, the evidence we report concerning the link between DHA results and PM is not direct nor conclusive. Further, we believe that the individual DHA constituent data is too granular and too inconsistent from one fuel to the next to produce reliable conclusions about the PM response. As noted in Part 1, these limitations can only potentially be resolved through actual or synthetic (simulated) replication of the DHA study.

Summary

Our overall investigative process, findings, and conclusions are summarized below:

1. We verified the existence of differences in mean PM (as well as median PM) reported by authors of the E-94-2, E-94-3, and E-129 studies, and confirmed the conflicting responses attributable to ethanol-enhancement of fuels.
2. Using multiple statistical modeling approaches, we conducted a meta-analysis of the PM data, pooling together observations from all three programs under the hypothesis that the combined data set would resolve the conflicts noted above. We found this not to be the case. Fuels observed to have statistically significant differences in mean PM in the three original studies still have statistically significant differences based on the meta-analysis we conducted. Contrary to our original hypothesis, our analyses indicate that there was no real benefit to pooling data from the three original studies. Fuels that were determined to have statistically significant differences in mean PM in the three original studies are still determined to have statistically significant differences in all the meta-analytical analyses we conducted.
3. In all our analyses of PM data, we determined the fuel, vehicle, and fuel x vehicle factors to be statistically significant (also noted by the previous authors). The persistence of a fuel x vehicle interaction across all analyses is most problematic because (1) it implies that inferences about fuels cannot be made without first stipulating the vehicle(s) in question and (2) that averaging over vehicles is technically and statistically inappropriate.
4. Since the fuel factor is already statistically significant across all analyses, there is no need to increase the number of vehicles or tests to achieve such significance, but there is a definite need to increase the numbers of vehicles and tests in order to alleviate the fuel x vehicle interaction. As long as the fuel x vehicle interaction persists, no statistically valid statements can be made about fuel differences. Increasing the number of vehicles and tests can only be accomplished through physical replication of the studies (which is likely impractical) or through synthetic (simulation) means.

5. Analysis of the corresponding DHA data suggests that C_9 and C_{10+}, in combination with Mono-Aromatics, I-Paraffins, Naphtheno/Olefin-Benzs, and Naphthalenes, are likely contributors to the differences in PM responses among the fuels. However, because of the limitations of the DHA data set and its multivariate nature, this evidence is not direct or causal. We believe that the DHA data at the level of individual constituents is too granular and inconsistent to be sufficiently explanatory. However, it may be possible to employ more advanced techniques of data analytics and machine learning, such as neural networks, to explore the relationships more thoroughly.
6. Finally, in multiple analyses we observe that PMI has a significant effect on PM, but that AKI and EtOH do not. Further, we observe that PMI is strongly positively correlated with C_9 thru C_{12} (and certainly C_{10+}), suggesting that PMI in combination with carbons and groups may encapsulate the most important predictors of differences in PM responses among the fuels.

Although not directly germane to the findings of our report, in the interest of completeness and added value we have included additional information in an appendix concerning differences in DHA results obtained by Southwest Research Institute (SwRI) and Separation Systems, Inc. (SSI).

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1.0 Introduction

Three CRC sponsored projects, referred to in this report as E-94-2, E-94-2 and E94-129, investigated oxygenated gasoline fuels and their resultant effects on emissions. The present study also focuses on these fuels, including how they differ and if the differences can be more fully explained by data furnished to us by CRC.

Section 2 is an analysis of weighted particulate matter (PM) as a function of fuel, vehicle, fuel x vehicle interaction, antiknock index (AKI), ethanol (EtOH) and the particulate matter index (PMI). Data from each of the reports are analyzed separately and combined. The purpose of the combined analysis was to determine if there was benefit to pooling the data sets. The main tools for these analyses were regression, analysis of variance (ANOVA), graphical displays, and tables.

Section 3 is a detailed hydrocarbon analysis (DHA) data. Major components of this data are constituents within group and carbons. Weighted PM is studied as a function of carbon and groups. This analysis uses regression, ranking, graphics, and tables. This analysis and that in Section 2 provide detailed information on differences in pairs of fuels.

Section 4 is a review of relevant work from a statistical perspective. It includes a summary of statistical procedures used in the E-94-2, E-94-3, E-129 reports.

Section 5 is an overall summary with recommendations for follow up work.

A two-part bibliography follows Section 5. Part 1 contains items related to the statistical analysis of automotive emissions. Part 2 contains items related to the impacts on emissions of adding ethanol to gasoline.

The report concludes with four appendices. Appendix A contains an extended comparison of fuels. Appendix B provides additional analysis of the PM-DHA relationship. Appendix C discusses the evolution of the detailed hydrocarbon analysis. Appendix D briefly describes the DHA master file.

2.0. PM Analysis of E-94-2, E-94-3, E-129, and combined data

This report details the work undertaken by Southwest Statistical Consulting, LLC to conduct a meta-analysis of the tailpipe particulate matter (PM) data collected in the E-94-2, E-94-3, and E-129 studies previously funded by the Coordinating Research Council (CRC).

An analysis of weighted PM and its relationship to other variables in the E-94-2, E-94-3 and E-129 data sets is presented here. Following these introductory remarks and comments about activities leading up to the main analytical effort, the report presents a comparison of differences

between fuels and vehicles[3] and the interaction between fuels and vehicles and concludes with a comparison of the results for all data sets. The major ancillary variables are AKI, EtOH, and PMI. Part of the analysis is exploratory using scatter plots and boxplots. Other analyses use regression and analysis of variance (ANOVA) with weighted PM over all three tailpipe test phases as the response variable. Any reference to PM should be taken to mean the weighted value of PM over the three test phases. The analyses, unless otherwise noted, are performed with R computing routines (r-project.org).

Three factors were identified for formal statistical analysis: Fuel, Vehicle and Fuel x Vehicle. Fuel and vehicle effects can be fixed or random. When an effect is fixed, results only apply to the levels chosen, i.e. the specific fuels or vehicles. When an effect is random, it is assumed that the levels are randomly chosen, and results apply to a larger population. However, in the latter case, an additional error term is added to the model, which may make it more difficult to detect a difference in levels, such as type of fuel. In this study, both fuel and vehicle are fixed effects.

Fuel is the most important variable. Vehicle is a blocking variable similar to a plot of land in an agricultural experiment, and as such, each vehicle serves as an experimental unit. There are many instances in which vehicles might be considered to be "random;" i.e., a random sample from some population of interest. However, after considerable reflection, study, and consultation with CRC members, the vehicles involved are not a random sample and should not be treated as such. In fact, the E-94-2 reports states clearly that the vehicles are a convenience sample, although the reports for all three programs (E-94-2, E-94-3, E-129) consider them to be random. Treating the Vehicle factor as fixed has the further advantage of simplifying the overall analysis.

In the E-94-2, E-94-3 and E-129 reports, potential or candidate outliers were identified and, in some cases, removed by the authors. We chose not to remove outliers because we did not have credible information indicating that they did not belong to the given population and identification of outliers is arbitrary, especially for small data sets.

In addition, although we refer to and use the mean value of weighted PM in various instances, we more often focus on the median value. We do this because of the observed skewness in various distributions of weighted PM values, the relatively small numbers of values involved, and the difference in variability (uncertainty) of those values from one fuel or vehicle to the next. The arithmetic mean is notoriously sensitive to these factors. Hence, when and where appropriate, we used the median rather than the arithmetic mean; and when and where appropriate, we made a transformation to normalize the data (i.e., make the distribution appear to be more bell-shaped).

2.1 Preliminary Work

In various studies of this type, as much or more time is spent collecting and pre-processing the data as is spent in actual analysis activities. That is certainly true in the case of the E-127 study.

[3] The terms fuel and vehicle are lower case when used generically; they are uppercase when referring to a specific fuel or vehicle or used in a model or analysis of variance table.

Before any actual statistical work could be done, a master data file was constructed, combining all the information available from the prior E-94-2, E-94-3, and E-129 studies. This required us to re-organize, re-configure, and re-structure several large and diverse data sets so that they could be merged into a single file in a format compatible with statistical and computational analysis. In this process we frequently consulted with the CRC Emissions Committee and staff, who also were required to devote additional time to locating and dispensing all the available data. This created a time lag in compiling the master data file, since not all the data were available at the same time. In addition, early in the project, several questions arose concerning the usability of certain fuel data, which required several clarifying conversations with the CRC Emissions Committee and staff. Eventually it was possible to settle on the specific set of data to be used, and from that point construction of the master data file proceeded. The file now consists of a single matrix containing 281 rows and 698 columns. Each column represents an individual variable. This matrix combines vehicle data, fuel data, test data, tailpipe emissions (sample, ambient, net concentration, mass results) for all three phases, plus the respective weighted values), and a large portion of the DHA results (Wgt%, Vol%, Mol%, and Area for individual carbons, groups, and carbon by group combinations).

While this data set is large, many of the matrix cells have 1) no data or 2) have the same value recorded for many variables. For example, there is only one set of DHA measurements for each fuel. Every matrix row associated with a particular fuel contains the same DHA measurements if they are available. Ultimately, among all this data there is only a maximum of four tests expressed as matrix rows for each vehicle combination. However, many variables (matrix columns) could be considered. The data set is overdetermined because there are far more variables (columns) than observations (rows), which is a complicating factor for any statistical analysis.

For the E-94-2 data we conducted a preliminary investigation using regression and correlation analysis of all tailpipe emissions, including and in addition to PM. We found no significant relationships among PM, NOx, CO_2, etc. other than those already reported in the E-94-2 study. Subsequently, in consultation with the CRC Emissions Committee, the decision was made to restrict the E-127 work to an investigation of PM only, since the E-94-2 results comprise most of the available data and PM was deemed to be the primary focus.

In addition, we used the E-94-2 data to investigate the potential relationships between PM and several covariables, such as vehicle mileage and test weight, but found nothing significant to report.

2.2 E-94-2 Analysis

The E-94-2 data set consists of 217 observations (trials), encompassing 8 fuels and 12 vehicles plus other possible covariates. The fuels are match blended. Graphs encompass all fuels, vehicles, and tests in the E-94-2 study. As indicated throughout this report, specific graphs and descriptive statistics involve combining, or pooling, observations over fuels and/or vehicles. However, as demonstrated in the subsequent analyses, there is a statistically significant Fuel x

Vehicle interaction presented in all three reports (E-94-2, E-93-3, E-129). This is a complexity not shown in the graphs.

Figure 1 (top) shows the PM histogram. Figure 1 (center) shows the log(PM) histogram. If the PM distribution was lognormal, Figure 1 (center) would be normally distributed. Clearly it is not. A more symmetric distribution is needed when a statistical test requires a normal distribution. Figure 1 (bottom) shows the histogram of a more symmetric PM distribution obtained using a Box-Cox transformation. Box-Cox is a statistical method to make a skewed distribution as symmetric as possible. The normalization factor for this PM data set is $PM^{0.25}$.

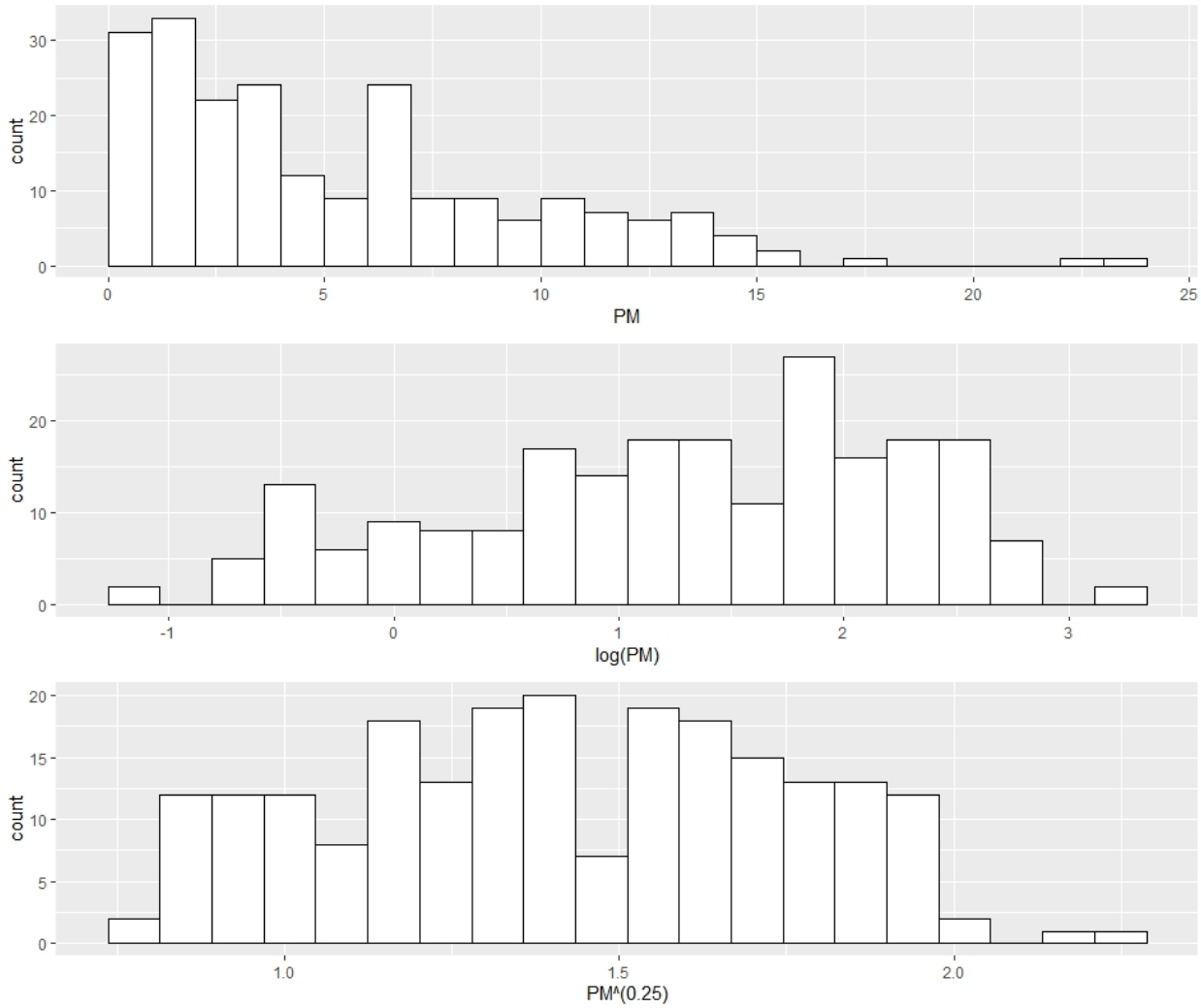


Figure 1. Histograms of PM (top), log((PM) (center) and PM symmetric (bottom). Note the difference in vertical scales.

Figure 2 shows boxplots of variable PM for the individual fuels. The heavy black horizontal line within the box is the PM median. The length of the box is the interquartile range IQR = (Q75 – Q25), where Q75 is the 75th percentile and Q25 is the 25th percentile. The line above Q75 extends to the maximum value of PM or Q75 + 1.5 x IQR, whichever is less.

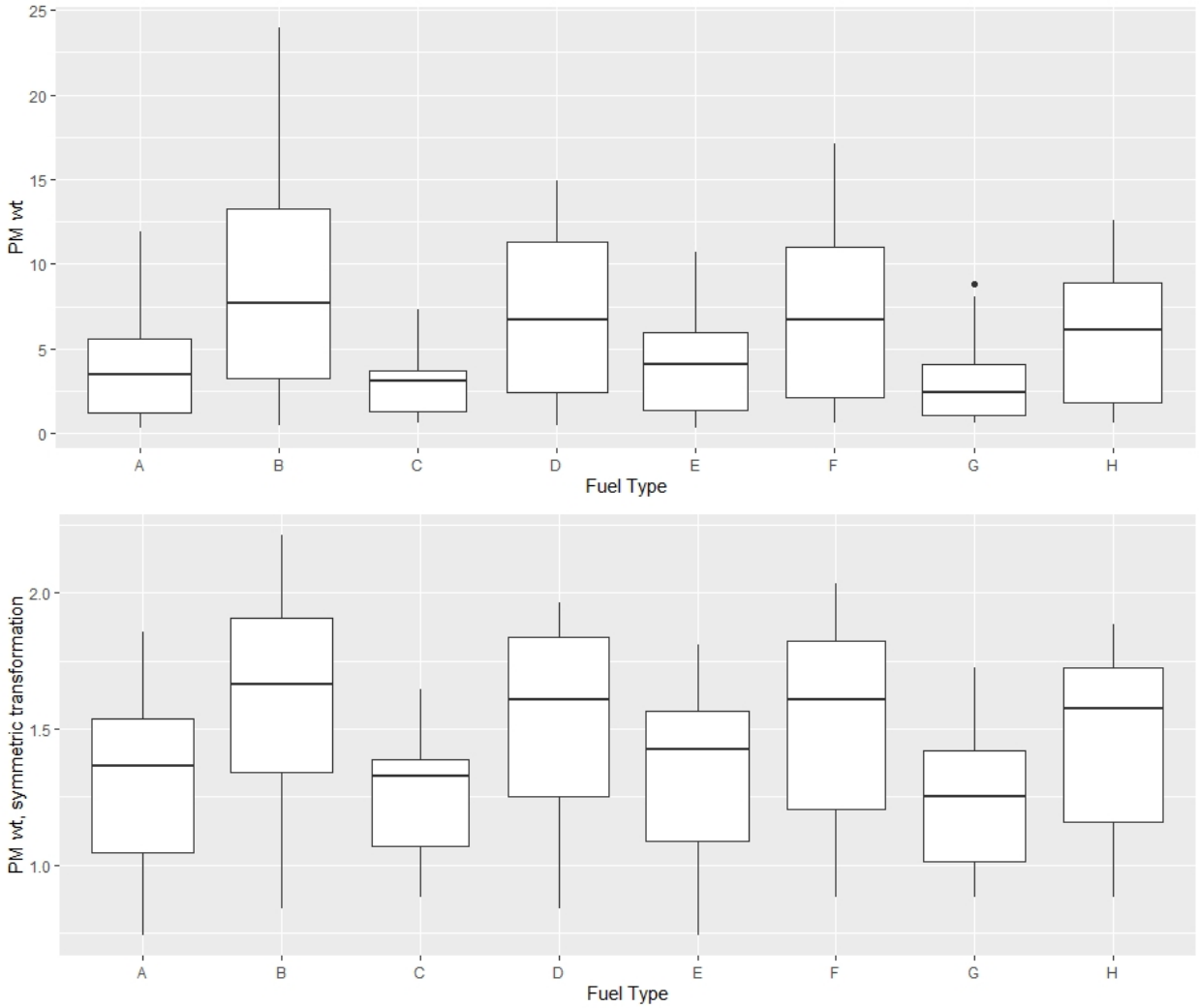


Figure 2. Boxplots of PM by fuel type (top); boxplots of transformed PM (bottom).

The PM distributions (Figure 2, top) vary by fuel from symmetric (Fuel D) to more right skewed (Fuel B and Fuel G). The black dot above Fuel G may be an outlier[4]. Fuels B, D, F, and H have higher and similar PM medians. Fuels A, C, E, and G have lower but similar PM medians. Figure 2 (bottom) shows the boxplots of the PM transformed by $PM^{0.25}$ using the Box-Cox statistical method[5]. Only one transformation was performed on the entire set of PM values. A slightly more symmetric result might have been obtained had each fuel PM data set been transformed, but that would make any type of hypothesis testing difficult. Unless otherwise noted, the untransformed data are used for further analyses.[6] The observed A-C-E-G and B-D-F-H groupings in Figure 2 (top) do not change as a result of using the transformed data in Figure 2 (bottom) but now no possible outlier is indicated for Fuel G.

[4] This outlier represents one data point; however, it could represent multiple outliers in the unlikely event that identical multiple outliers existed.
[5] This transformation makes the resulting distribution as symmetric as possible.
[6] Transformed values of PM are used in all the analyses of variance (ANOVA) shown below.

Table 1 shows the median, mean, standard deviation and coefficient of variation (CV) for PM. CV is the ratio of standard deviation to mean and is a measure of relative variability. The variability is high (CV values are all closer to 1 than they are to 0), which is consistent with the small sample sizes and complex nature of the problem. The values of AKI, EtOH, and PMI are shown for each fuel.

Table 1. Fuel by AKI, EtOH, PMI and PM medians, means, standard deviations, and coefficient of variations (CV). Medians and means are pooled over vehicles and tests.

Fuel	AKI	EtOH	PMI	PM Median	PM Mean	PM Std	CV	n
A	87.2	9.55	1.42	3.45	4.12	3.3	0.8	28
B	87.1	9.56	2.64	7.7	8.59	6.3	0.73	28
C	87.9	0	1.42	3.1	3.14	2.04	0.65	25
D	88.2	0	2.65	6.7	7.13	4.6	0.65	27
E	93.6	9.56	1.3	4.1	4.23	3.1	0.73	29
F	93.7	9.51	2.55	6.7	7.01	5.2	0.74	26
G	93.8	0	1.27	2.45	3.05	2.35	0.77	28
H	94.1	0	2.49	6.15	5.92	3.95	0.67	26

A major grouping of PM means and medians are by low and high values of PMI (Table 2). This grouping is consistent with the grouping of fuels based on the box plots shown in Figure 2. The differences in AKI and/or EtOH appear to have no effect, i.e. no consistent observable trend on PM medians or means. Inspection of the pairwise correlations (Table 3) also indicates this.

Table 2. Fuel PM medians and means grouped by PMI where low is rose (top) and high is blue (bottom). Medians and means are pooled over vehicles and tests.

Fuel	AKI	EtOH	PMI	PM median	PM mean	PM std	CV
A	87.2	9.55	1.42	3.45	4.12	3.30	0.80
C	87.9	0	1.42	3.10	3.14	2.04	0.65
E	93.6	9.56	1.30	4.10	4.23	3.10	0.73
G	93.8	0	1.27	2.45	3.05	2.35	0.77
B	87.1	9.56	2.64	7.70	8.59	6.30	0.73
D	88.2	0	2.65	6.70	7.13	4.60	0.65
F	93.7	9.51	2.55	6.70	7.01	5.20	0.74
H	94.1	0	2.49	6.15	5.92	3.95	0.67

Table 3. Pairwise correlations for variables AKI, EtOH, PMI, PM median and PM mean.

	AKI	EtOH	PMI	PM median	PM mean
AKI	1				
EtOH	-0.10	1			
PMI	-0.08	0.02	1		
PM median	-0.10	0.24	0.96	1	
PM mean	-0.19	0.31	0.93	0.98	1

There are positive pairwise correlations between PM median and mean and PMI that suggest a possibility of some PMI effect, however, there are only eight observations so any effect must be interpreted cautiously.[7]

Figure 3 and Figure 4 also show the AKI-EtOH-PMI-PM relationships and illustrate the inconsistent patterns that exist. Figure 3 suggests the following:

- At the low level of EtOH (E0), when PMI is low and AKI increases, median PM increases, but when PMI is high and AKI increases, median PM decreases. Similarly, at the high level of EtOH (E10), when PMI is low and AKI increases, median PM increases; but when PMI is high and AKI increases, media PM decreases.
- At both the low and high levels of AKI, median PM increases when AKI increases whether at low or high levels of EtOH.
- At both the low and high levels of PMI, median PM increases when AKI increases whether at low or high levels of EtOH.

Figure 4 suggests somewhat different patterns indicating additional interaction among AKI, EtOH, and PMI relative to mean PM. Due to the high within-fuel variability (CV values in Table 1), there is no guarantee that these same patterns would persist if the E-94-2 program was replicated.[8]

[7] There are only 8 observations because AKI, PMI, and EtOH do not change from one vehicle/test to the next within the same fuel, and there are only eight fuels (eight rows in Table 1). In this correlation analysis there is one record for each of the eight fuels, although the mean and median values of PM encompass multiple observations.

[8] Since there is no replication of vehicles, there is no direct way to estimate the range of variability that could potentially be observed in similar trials.

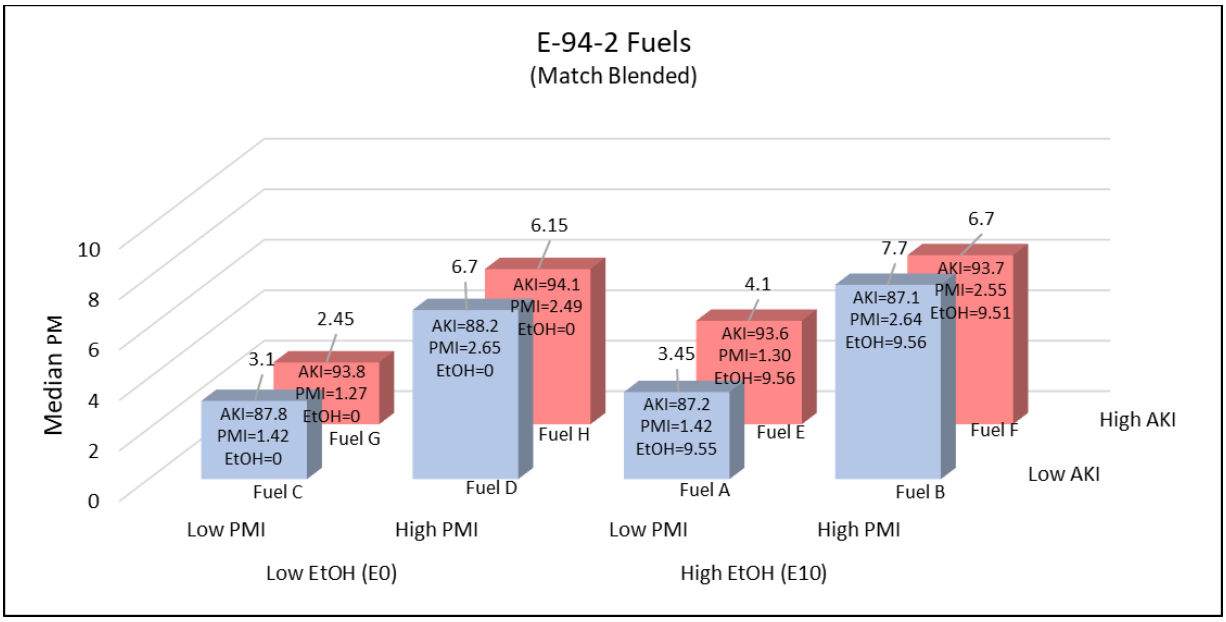


Figure 3. 3-D bar chart illustrating the relationship between AKI, EtOH, and PMI, and their combined impact on median PM. Graphs encompass all vehicles and tests associated with each respective fuel.

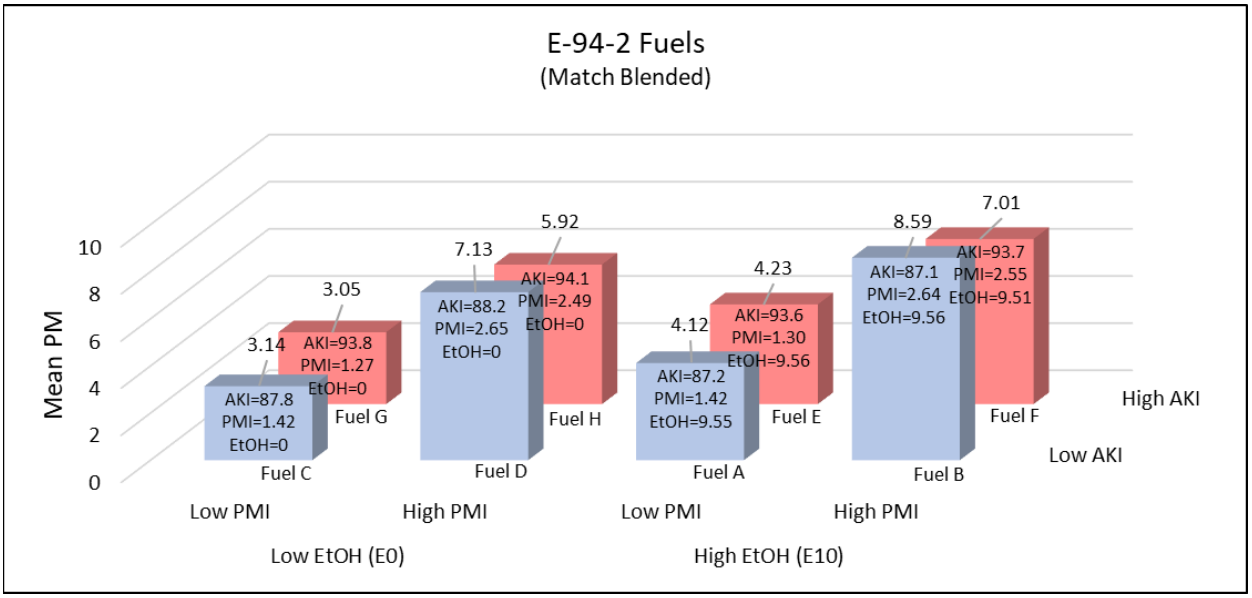


Figure 4. 3-D bar chart illustrating the relationship between AKI, EtOH, and PMI, and their combined impact on mean PM. Graphs encompass all vehicles and tests associated with each respective fuel.

The boxplots of PM by vehicle are shown in Figure 5. Vehicles appear to fall into four groups (Table 4) by PM median and mean. The purpose of this grouping is to consider combining vehicles into more homogeneous parts to create larger sample sizes and for hypothesis testing.

Table 4. Partitioning of vehicles by PM median and mean. Medians and means are pooled over vehicles and tests.

Vehicle	55	78	98	96	71	17	25	29	20	64	51	13
Median	0.60	1.10	1.60	1.80	3.75	4.20	5.00	5.15	6.40	7.90	10.85	11.40
Mean	0.60	1.29	1.85	1.88	4.15	5.89	5.48	4.99	7.88	8.25	10.45	12.85
Group	1	1	1	1	2	2	2	2	3	3	4	4

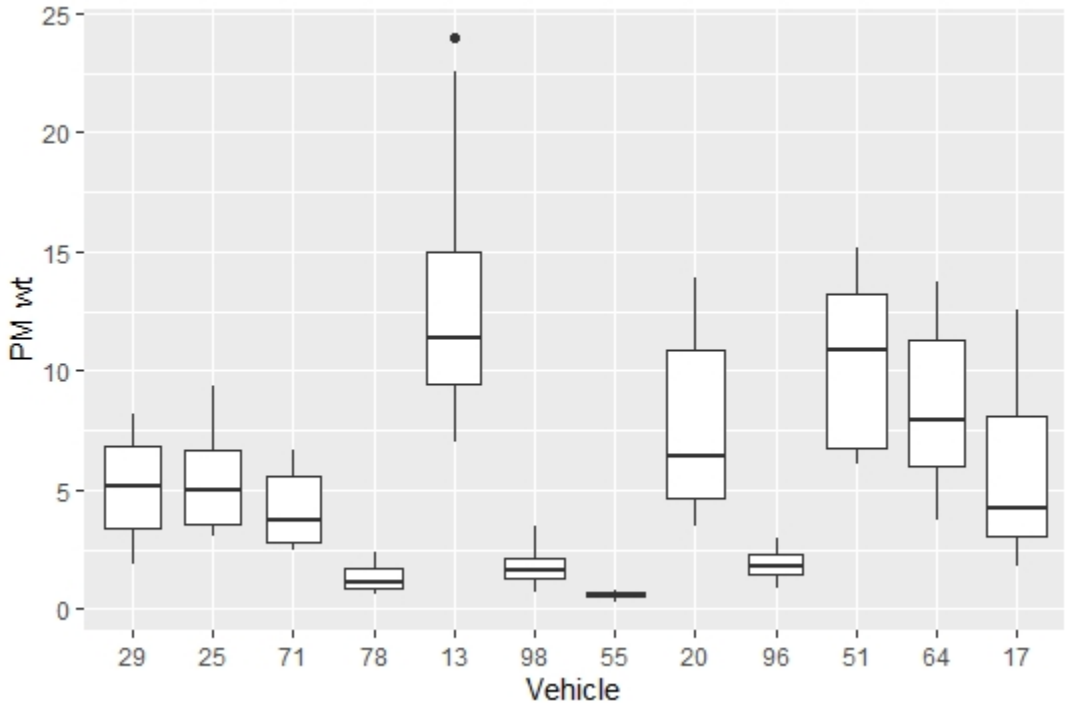


Figure 5. Boxplots of PM by vehicle. Graphs encompass all fuels and tests associated with each respective vehicle.

The 96 Fuel x Vehicle combinations are shown in Table 5. This table is slightly unbalanced because not every fuel x vehicle combination is repeated the same number of times. However, most combinations are repeated two or three times, with one repeated four times.

Table 5. Observations (trials) by Fuel x Vehicle.

	Vehicle												
Fuel	29	25	71	78	13	98	55	20	96	51	64	17	Fuel Totals
A	2	2	4	2	2	2	2	2	2	3	2	3	**28**
B	2	2	2	3	2	2	3	3	3	2	2	2	**28**
C	2	2	2	3	2	2	2	2	2	2	2	2	**25**
D	2	2	2	2	2	2	2	3	2	3	2	3	**27**
E	2	2	2	3	2	2	2	3	3	2	3	3	**29**
F	2	2	2	2	2	3	2	2	3	2	2	2	**26**
G	2	3	3	2	2	2	3	2	2	3	2	2	**28**
H	2	2	2	2	2	2	2	3	2	3	2	2	**26**
Vehicle Totals	**16**	**17**	**19**	**19**	**16**	**17**	**18**	**20**	**19**	**20**	**17**	**19**	**217**

A correction for bias due to imbalance in the Fuel x Vehicle table (Table 1) was not needed because the difference between the least squares means[9] corrected estimate and the arithmetic mean was the same to two decimal places.

Fuel by vehicle PM means are shown in Table 6. The groups, shown in the last row of Table 6, refer to the groups identified from Figure 5, also specified in Table 4. The high fuel PM values correlate with high vehicle PM values. Similarly, low fuel PM values correlate with low vehicle PM values. The median PM values are not shown because they are almost identical to the mean values.

Table 6. Fuel by vehicle PM means and vehicle grouping. Means are pooled over tests.

	Vehicle											
Fuel	29	25	71	78	13	98	55	20	96	51	64	17
A	4.00	4.55	3.05	0.95	10.80	1.20	0.40	5.25	1.65	9.10	6.15	3.37
B	7.47	8.90	6.40	2.30	23.30	3.43	0.67	13.63	2.80	14.90	13.30	10.55
C	3.15	3.45	2.70	0.90	7.15	1.10	0.60	3.70	1.20	6.70	3.95	2.75
D	6.35	7.00	5.60	1.85	14.70	2.30	0.60	11.05	2.65	12.73	12.05	7.87
E	4.15	4.85	2.95	0.95	10.55	1.40	0.43	5.87	1.60	9.15	6.87	3.57
F	7.05	6.80	5.55	1.80	16.25	2.10	0.67	10.90	2.20	14.05	11.40	10.90
G	1.93	3.27	2.70	0.67	8.45	0.95	0.75	4.05	1.00	6.40	4.35	2.05
H	6.15	6.15	4.25	1.55	11.60	1.60	0.70	8.80	1.80	11.57	8.65	7.55
Group	2	2	2	1	4	1	1	3	1	4	3	2

The form of linear model chosen for this analysis is:

$$PM^{0.25} \sim \text{Fuel} + \text{Vehicle} + \text{Fuel x Vehicle} + \text{Error}$$

where Fuel and Vehicle are fixed effects and the error is assumed to be constant, normally distributed. The ANOVA results are shown in Table 7. The response variable PM is transformed because of the skewness in PM distributions. The results for the non-transformed PM data are essentially the same. As Table 5 and Table 6 show, every vehicle is crossed with every fuel with replication.

Table 7. ANOVA table for $PM^{0.25}$ model.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Fuel	7	3.4592	0.49418	300.0896	2.20E-16
Vehicle	11	19.5363	1.77603	1078.5	2.20E-16
Fuel x Vehicle	77	0.8154	0.01059	6.4303	2.20E-16
Residuals	121	0.1993	0.00165		

The test of statistical significance is the F value. The null hypothesis is that the effect is not significant. For this analysis, the alternative is that it is. The probability of significance is the

[9] Least square means are predicted values or averages over a rectangular grid (see Table 6) using a least squares regression technique. The regression results are not shown here.

likelihood that the null hypothesis is rejected. Table 7 shows that the three effects are highly significant.

To determine which pair of fuels differ by PM (actually $PM^{0.25}$), a Tukey family multiple comparison test was conducted. The word "family" indicates that confidence intervals on pair-wise tests have been widened to account for the comparison of 28 pairs of differences. A 95% confidence interval was used to establish the lower and upper confidence limits. A small p adj (p-adjusted) value indicates a statistically significant difference (Diff in Table 8). The null hypothesis is that the difference between population means is zero. The alternative is that it is not. The only fuel pairs that did not differ at the 0.10 p adj level and greater were (A,E), (C,G), and (D,F). These results are consistent with the fuel boxplots (Figure 2).

Table 8. Pairwise fuel differences for E-94-2 fuels.

Fuel	Diff	Lower	Upper	p adj		Fuel	Diff	Lower	Upper	p adj
B-A	0.273	0.239	0.306	0		E-D	-0.201	-0.235	-0.168	0
D-A	0.216	0.183	0.250	0		G-D	-0.300	-0.333	-0.266	0
F-A	0.186	0.151	0.220	0		H-D	-0.075	-0.109	-0.040	0
G-A	-0.083	-0.117	-0.050	0		F-E	0.170	0.137	0.204	0
H-A	0.142	0.108	0.176	0		G-E	-0.098	-0.131	-0.065	0
C-B	-0.332	-0.367	-0.298	0		H-E	0.127	0.093	0.161	0
E-B	-0.258	-0.291	-0.225	0		G-F	-0.269	-0.303	-0.235	0
F-B	-0.087	-0.121	-0.053	0		H-G	0.225	0.191	0.259	0
G-B	-0.356	-0.390	-0.323	0		C-A	-0.059	-0.094	-0.025	0.00001
H-B	-0.131	-0.165	-0.097	0		D-B	-0.056	-0.090	-0.023	0.00003
D-C	0.276	0.241	0.311	0		H-F	-0.044	-0.078	-0.009	0.00401
E-C	0.075	0.040	0.109	0		F-D	-0.031	-0.065	0.004	0.11276
F-C	0.245	0.210	0.280	0		G-C	-0.024	-0.058	0.011	0.40284
H-C	0.201	0.166	0.236	0		E-A	0.015	-0.018	0.048	0.85449

Some of the pairwise differences contained in Table 8 may seem difficult to reconcile with the patterns observed in the box plots shown in Figure 2. The explanation lies in the differing variability and shape of the distributions of the transformed values of PM, both attributable to small numbers of observations. The focus should not be placed solely on the graphed medians.

A comment on fuel difference related to statistical significance

A practical difference, say between two fuels, is not the same as a statistically significant difference. If a sufficiently large sample is taken, it may be possible to determine a statistically significant difference between two populations that are quite similar but not identical. However, gaining a knowledge of such a small difference may be of no practical value. In the past, a *p*-value less than 0.05 was almost always the rule for deciding a statistically significant difference.

Now a *p*-value is viewed as an indicator of statistical significance, but it should not be considered the only determining factor in decision making.

2.3 E-94-3 Analysis

There are 36 observations encompassing 4 fuels and 4 vehicles, for a total of 16 combinations. The fuels are splash blended, in contrast to the fuels in Program E-94-2, which are match blended. The E-94-3 analysis is similar to that of E-94-2.

Figure 6 (top) shows the PM histogram; Figure 6 (bottom) shows the transformed PM histogram. Because this PM data set only has 36 observations, where a transformation to symmetry is required, the one for the E-94-2 data set, namely $PM^{0.25}$, will be used. Note the difference in vertical scales from Figure 1.

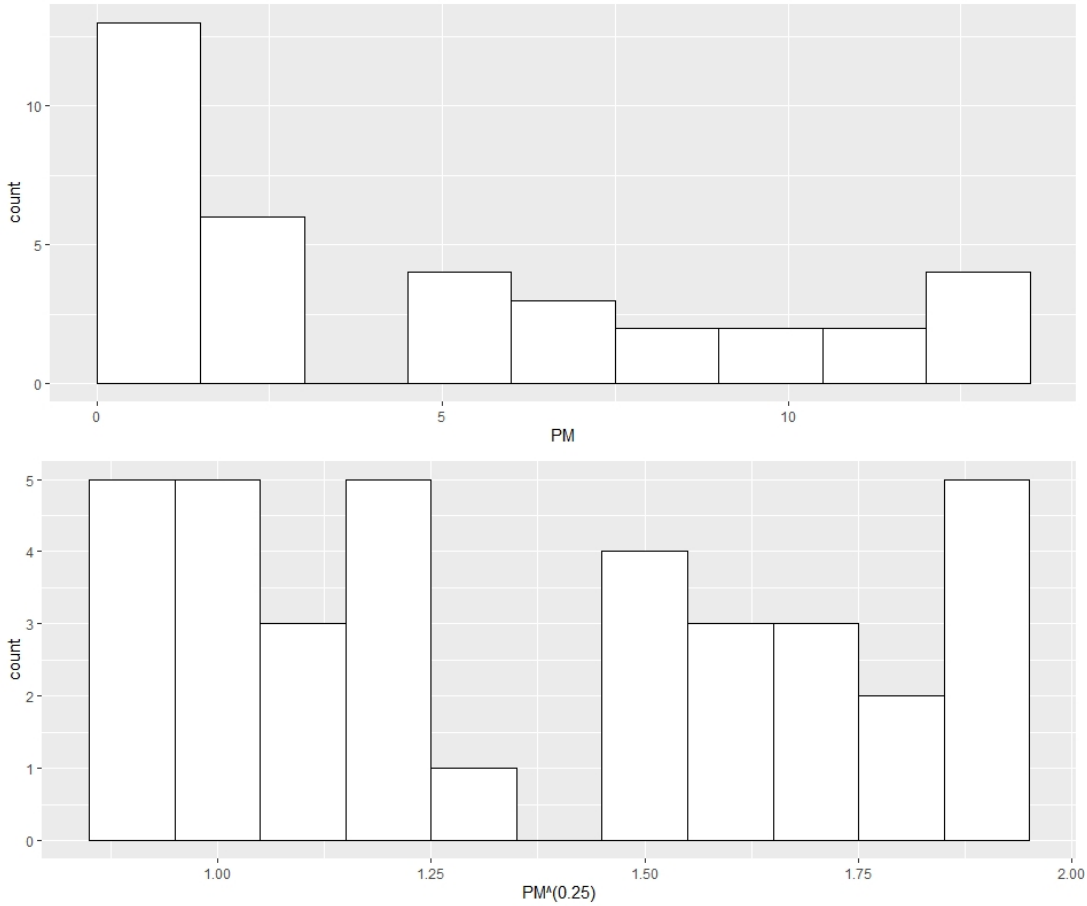


Figure 6. Histogram of PM (top) and normalized histogram of PM (bottom). $PM^{0.25}$ is the symmetric transformation. Graphs encompass all fuels, vehicles, and tests in the E-94-3 study.

Figure 7 shows boxplots of PM by fuel (top) and by $PM^{0.25}$ transformed (bottom). Note the difference in vertical scales from Figure 2.

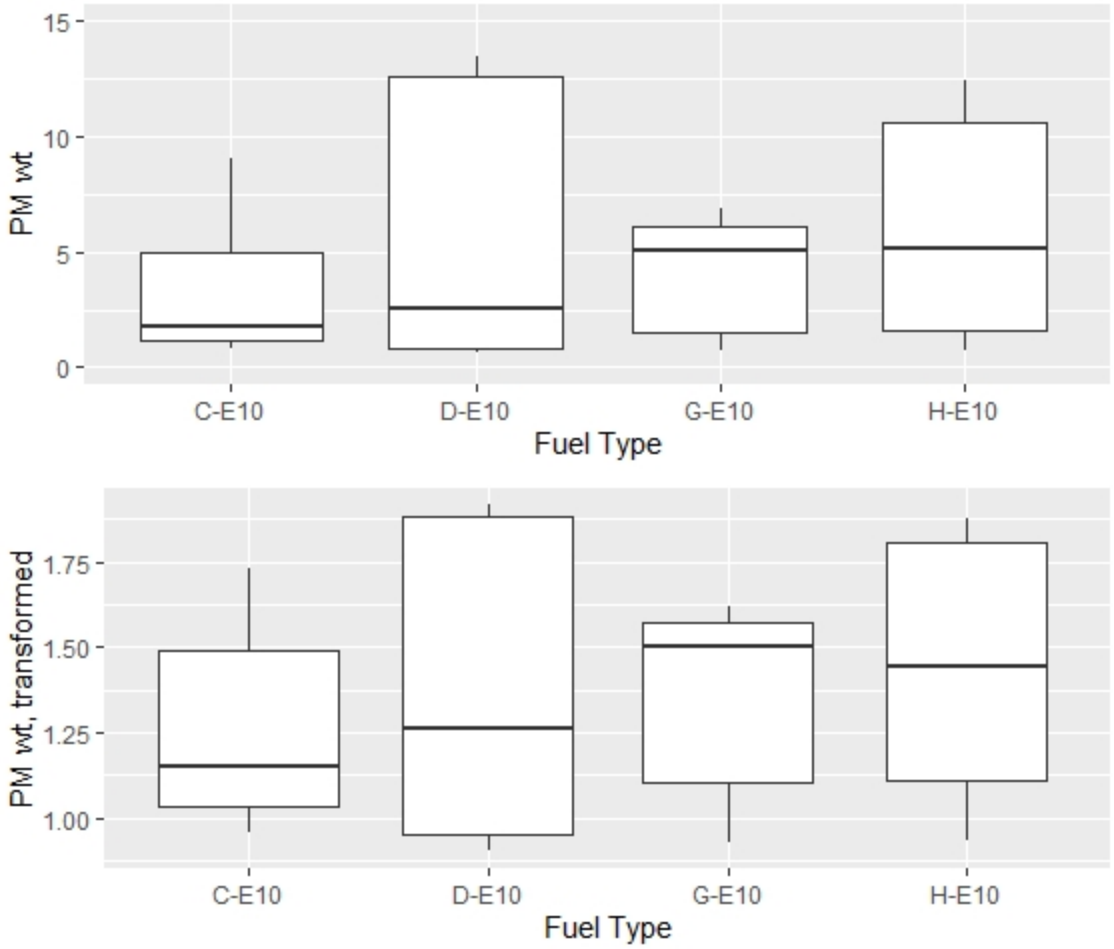


Figure 7. Boxplots of PM by fuel, E-94-3 program. Graphs encompass all vehicles and tests associated with each respective fuel.

Table 9 is a summary of the median and mean values of PM by fuel and factors AKI, EtOH and PMI. Since the numbers of observations are small, there is little basis for interpretation. There are too few samples to make an inference on the impact of the three factors on median and mean PM. Also, there are too few observations with which to construct a reliable pairwise correlation matrix to further assess the AKI-EtOH-PMI-PM relationship.

Table 9. Fuel by AKI, EtOH, PMI and PM mean, median, standard deviation and coefficient of variation (CV). Medians and means are pooled over vehicles and tests. n = number of observations (all tests, all vehicles) per fuel.

Fuel	AKI	EtOH	PMI	PM median	PM mean	Std Dev	CV	n
C-E10	91.50	9.44	1.28	1.77	3.50	3.17	0.91	10
D-E10	91.10	9.71	2.45	2.51	6.43	6.03	0.94	9
G-E10	96.40	9.75	1.17	5.09	3.84	2.52	0.66	9
H-E10	96.00	9.88	2.32	5.17	5.99	5.12	0.86	8

Figure 8 shows a 3-D bar chart illustrating the relationship between AKI and PMI and their combined impact on median PM when EtOH is approximately 10%. Graphs encompass all vehicles and tests associated with each respective fuel. Note the change in vertical scale from Figure 3 and Figure 4. The figure illustrates the dual relationship of AKI and PMI on median PM. At both the lower and higher levels of AKI, median PM increases as PMI increases. Similarly, at both the lower and higher levels of PMI, median PM increases as AKI is increased. However, the E-93-4 fuels are splash blended, so AKI and PMI do not move up or down in concert with one another, and Figure 8 illustrates their interacting effect.

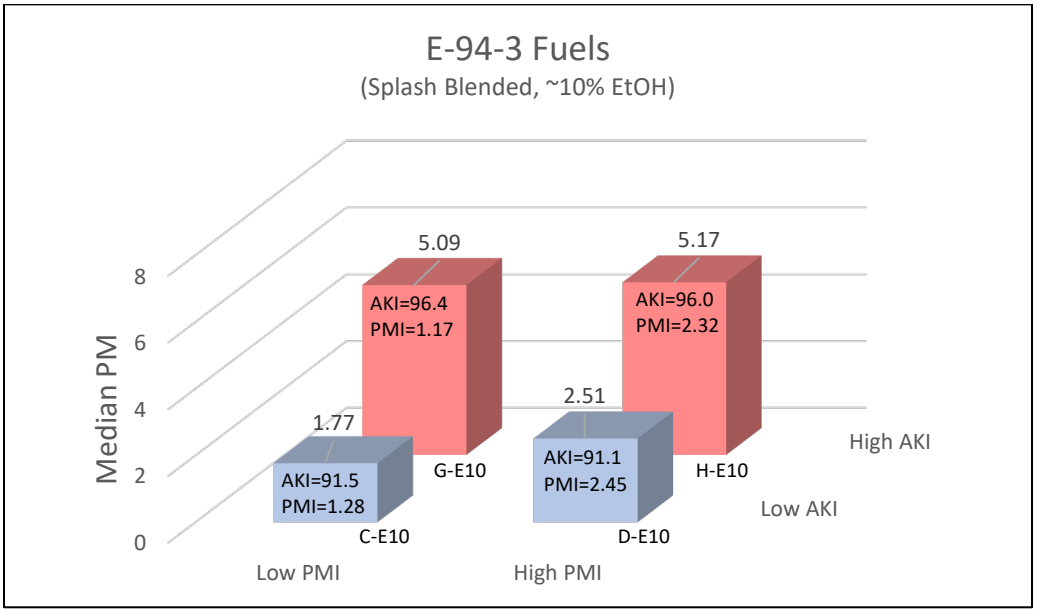


Figure 8. 3-D bar chart illustrating the relationship between AKI and PMI and their combined impact on median PM. EtOH is approximately 10% for all fuels.

Figure 9 shows a 3-D bar chart illustrating the relationship between AKI and PMI and their combined impact on mean PM when EtOH is approximately 10%. Graphs encompass all vehicles and tests associated with each respective fuel. Note the change in vertical scale from Figure 3 and Figure 4. The figure illustrates the dual relationship of AKI and PMI on mean PM. At both the lower and higher levels of AKI, mean PM increases as PMI increases. On the other hand, at the lower level of PMI, mean PM increases as AKI is increased; but at the higher level of PMI, the opposite is true. Again, note that the E-93-4 fuels are splash blended, so AKI and

PMI do not necessarily move up or down in concert with one another. Figure 9 illustrates their interacting effect.

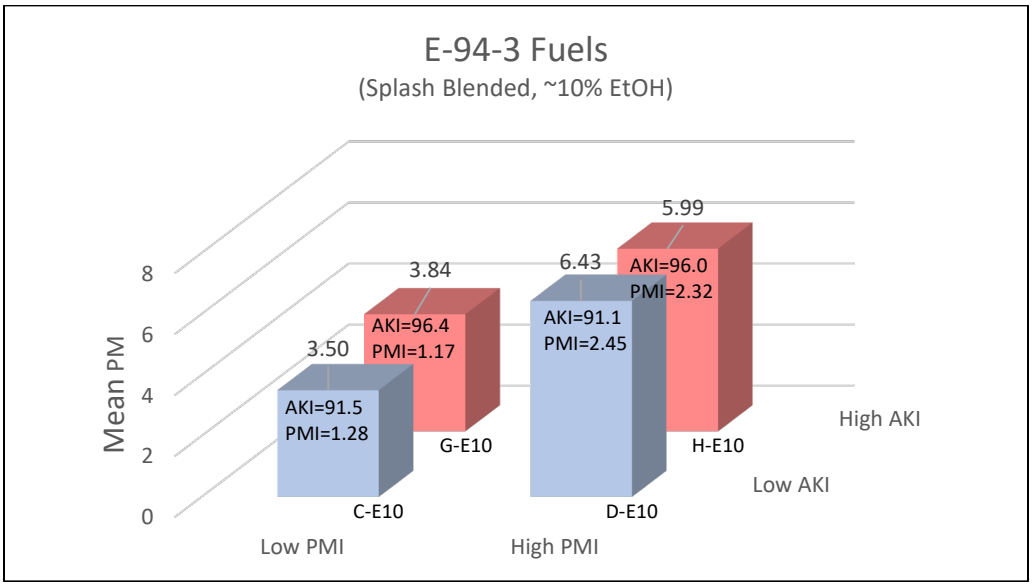


Figure 9. 3-D bar chart illustrating the relationship between AKI and PMI and their combined impact on mean PM. EtOH is approximately 10% for all fuels.

The PM boxplots by vehicle are shown in Figure 10. Boxplots based on the transformed values of PM are not shown because they are essentially the same. Vehicles 98 and 55 clearly seem to be different from vehicles 51 and 64, but the reason is unclear. The same difference and relative ordering of the four vehicles can also be observed in Figure 5 (E-94-2 program). An inspection of the certification data reveals nothing out of order for Vehicles 98 and 55. Figure 10 show boxplots of PM by vehicle. Note the difference in vertical scale from Figure 3 (top).

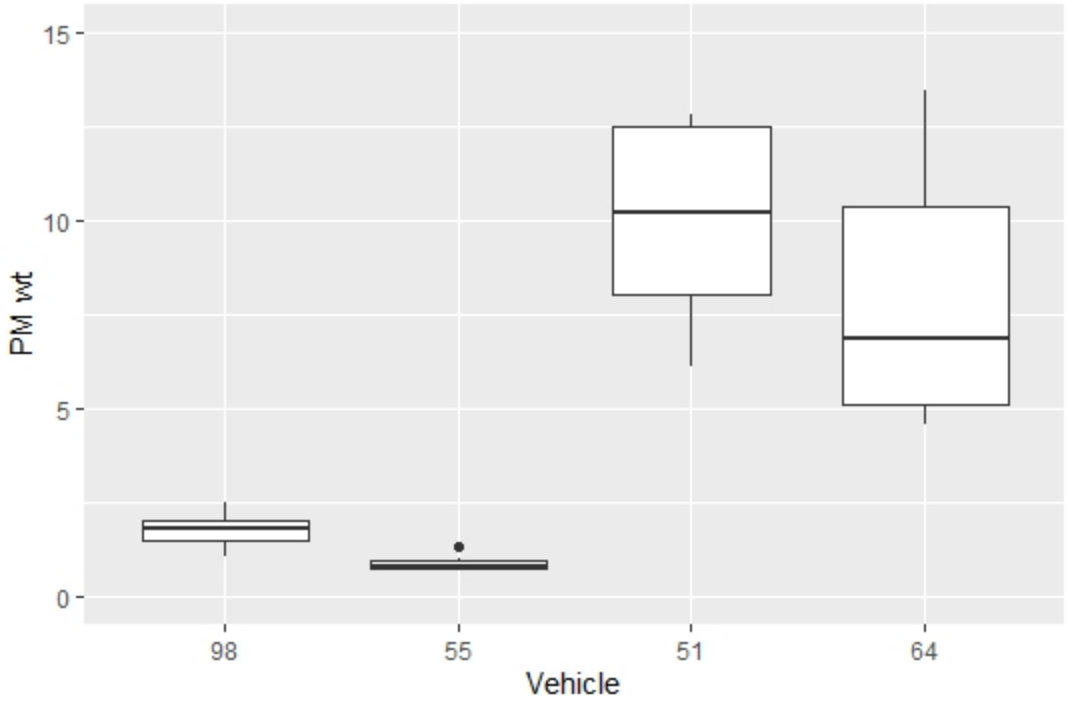


Figure 10. Boxplots of PM by vehicle. Graphs encompass all fuels and tests associated with each respective vehicle.

The number of observations by fuel and vehicle are shown in Table 10. All combinations are replicated at least twice.

Table 10. Observations (trials) by Fuel x Vehicle.

	Vehicle				Fuel
Fuel	98	55	51	64	Totals
C-E10	3	3	2	2	10
D-E10	2	3	2	2	9
G-E10	2	2	2	3	9
H-E10	2	2	2	2	8
Vehicle Totals	9	10	8	9	36

Analysis of variance results for the model

$$PM^{0.25} \sim \text{Fuel} + \text{Vehicle} + \text{Fuel x Vehicle} + \text{Error}$$

are shown in

Table 11. Every vehicle is tested on every fuel with replication (Table 10).

Table 11. ANOVA table for the $PM^{0.25}$ model.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Fuel	3	0.153	0.051	21.76	1.65E-06
Vehicle	3	4.055	1.3517	576.41	< 2e-16
Fuel x Vehicle	9	0.219	0.0243	10.37	8.68E-06
Residuals	20	0.047	0.0023		

The three effects (

Table 11) are highly significant. The Tukey family multiple comparison is used to determine which pairs of fuels are statistically significantly different (Table 12). A 95% confidence interval was used to establish the lower and upper confidence limits. Fuel pair D-E10 and H-E10 are similar. Fuel pair C-E10 and G-E10 are marginally different. The other four pairs clearly differ. A small p adj (p adjusted) values indicates a significant difference.

Some of the pairwise differences may seem difficult to reconcile with the patterns observed in the box plots shown in Figure 5, particularly with regard to the C-E10/D-E10 and G-E10/H-E10 pairs. The explanation lies in the differing variability and shape of the distributions of the transformed values of PM, both attributable to a small number of observations. Again, focus should not be placed solely on the graphed medians.

Table 12. Pairwise fuel differences for E-94-3 fuels.

Fuel	Diff	Lower	Upper	p adj
H-E10-C-E10	0.155	0.090	0.219	0.00001
D-E10-C-E10	0.147	0.085	0.209	0.00001
H-E10-G-E10	0.098	0.033	0.164	0.00237
G-E10-D-E10	-0.091	-0.155	-0.027	0.00377
G-E10-C-E10	0.056	-0.006	0.118	0.08684
H-E10-D-E10	0.008	-0.058	0.073	0.98804

Table 13 is a comparison of paired differences in mean PM (transformed) and their p-values among the four E-94-3 splash blended fuels and their counterpart E-94-2 match blended fuels. Apart from blending differences, the table underscores the difficulty in interpreting the p-values in the face of progressively smaller numbers of observations.

Table 13. Comparison of splash and match blend pairs for Program E-93-2.

Program E-94-3 (Splash Blend)				Program E-94-2 (Match Blend)			
Pair		Difference	p-value	Pair		Difference	p-value
D-E10 (n=9)	C-E10 (n=10)	0.147	0.00001	D (n=27)	C (n=25)	0.276	0.311
G-E10 (n=9)	C-E10 (n=10)	0.056	0.08684	G (n=28)	C (n=25)	-0.024	0.403
H-E10 (n=8)	C-E10 (n=10)	0.155	0.00001	H (n=26)	C (n=25)	0.201	0.236
G-E10 (n=9)	D-E10 (n=9)	-0.091	0.00377	G (n=28)	D (n=27)	-0.300	0
H-E10 (n=8)	D-E10 (n=9)	0.008	0.98804	H (n=26)	D (n=27)	-0.075	0
H-E10 (n=8)	G-E10 (n=9)	0.098	0.00237	H (n=26)	G (n=28)	0.225	0

2.4 E-129 Analysis

There are 27 observations encompassing 3 fuels and 4 vehicles, for a total of 12 combinations. One of the fuels (CRC-FUELC) is match blended, while the other two (CRC-ETOH10, CRC-ETOH15) are splash blended. The analysis is similar to that of E-94-2 and E-94-3.

Figure 11 (top) shows the PM histogram; Figure 11 (bottom) shows the transformed PM histogram. Because this PM data set only has 27 observations, a transformation to symmetry for the E-94-2 data set, namely $PM^{0.25}$, will be used. Note the changes in vertical scale from Figures 1 and 6.

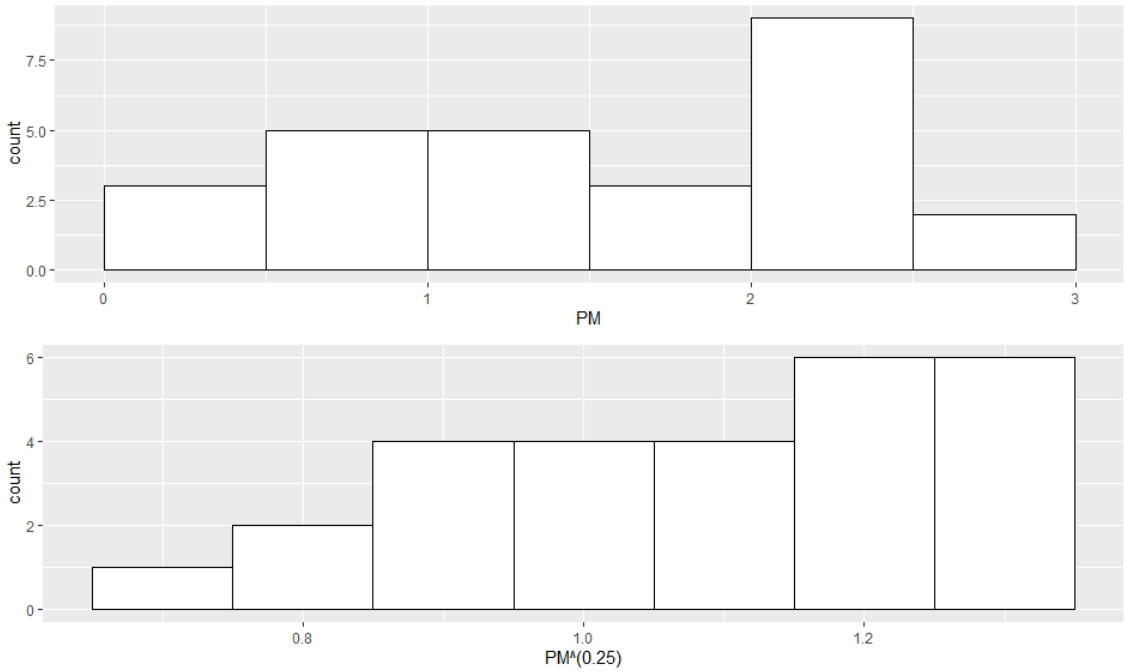


Figure 11. Histogram of PM (top) and normalized histogram of PM (bottom). $PM^{0.25}$ is the transformation. Graphs encompass all fuels, vehicles, and tests in the E-129 study.

Figure 12 shows boxplots of PM by fuel. Table 10 shows a summary of PM by fuel, AKI, EtOH and PMI. In both cases, the median values for all three fuels are essentially identical, but the variabilities and distribution shapes are different. Note the change in vertical scale from Figures 2 and 7.

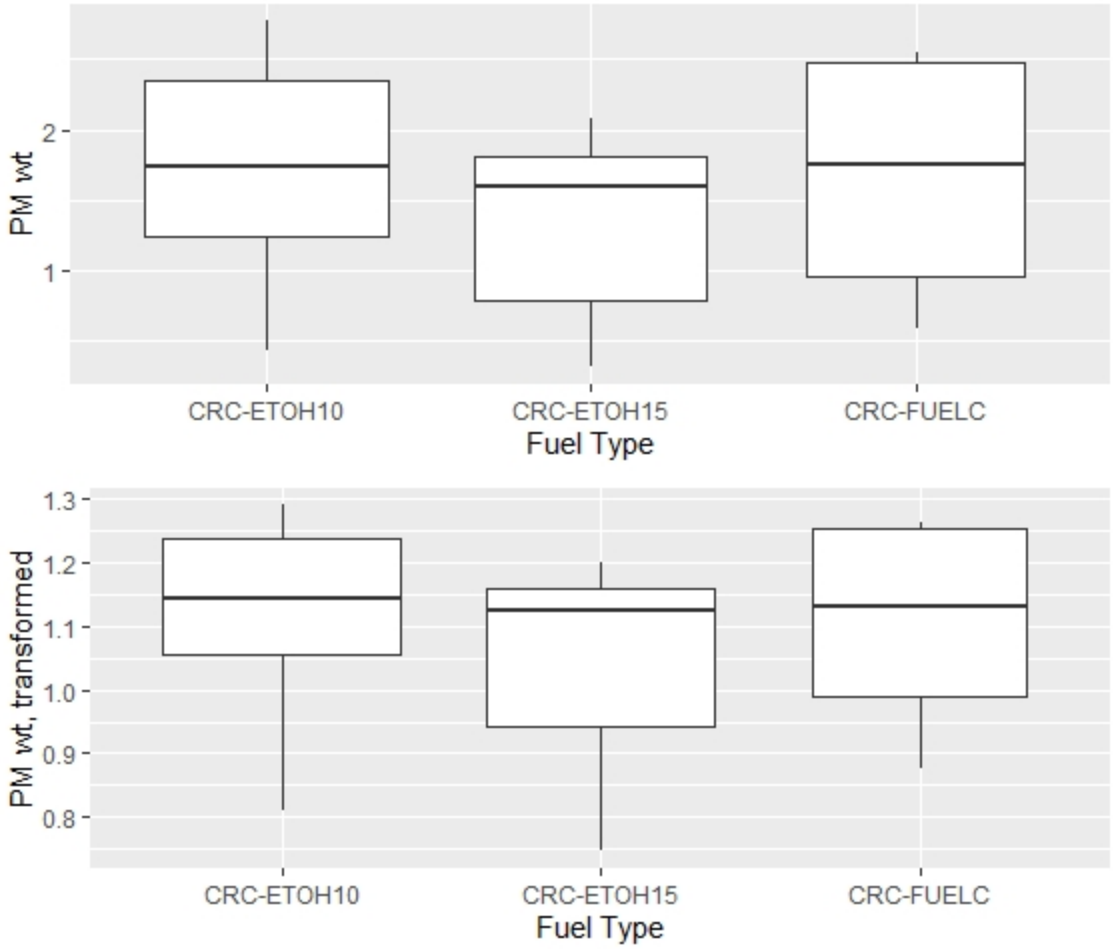


Figure 12. Boxplots of PM by fuel (top) and transformed PM by fuel (bottom). Graphs encompass all vehicles and tests associated with each respective fuel.

Table 14 is a summary of the median and mean values of PM by fuel, AKI, EtOH and PMI. It is presented for the sake of completeness. Since the number of observations are small,[10] there is little basis for interpretation, i.e. there are too few observations with which to make an inference about the impact of the three factors on median and mean PM. The values of relative variability (CV) are all similar. Also, there are too few observations with which to construct a reliable pairwise correlation matrix to further assess the AKI-EtOH-PMI-PM relationship.

[10] There are only three rows in Table 14. Hence each pairwise correlation would only be based on three values.

Table 14. Fuel by AKI, EtOH, PMI and PM mean, median, standard deviation and coefficient of variation (CV). Medians and means are pooled over vehicles and tests.

Fuel	Blend	AKI	EtOH	PMI	PM Median	PM Mean	Std Dev	CV	n
CRC-FUELC	Match	88.20	0.00	1.30	1.75	1.67	0.889	0.532	8
CRC-ETOH10	Splash	91.70	9.97	1.16	1.74	1.70	0.797	0.469	10
CRC-ETOH15	Splash	92.80	14.85	1.08	1.60	1.30	0.711	0.547	9

Figure 13 illustrates the inconsistent effect on mean and median PM of changing AKI, EtOH, and PMI. Note the change in vertical scale from Figure 3 and Figure 4.

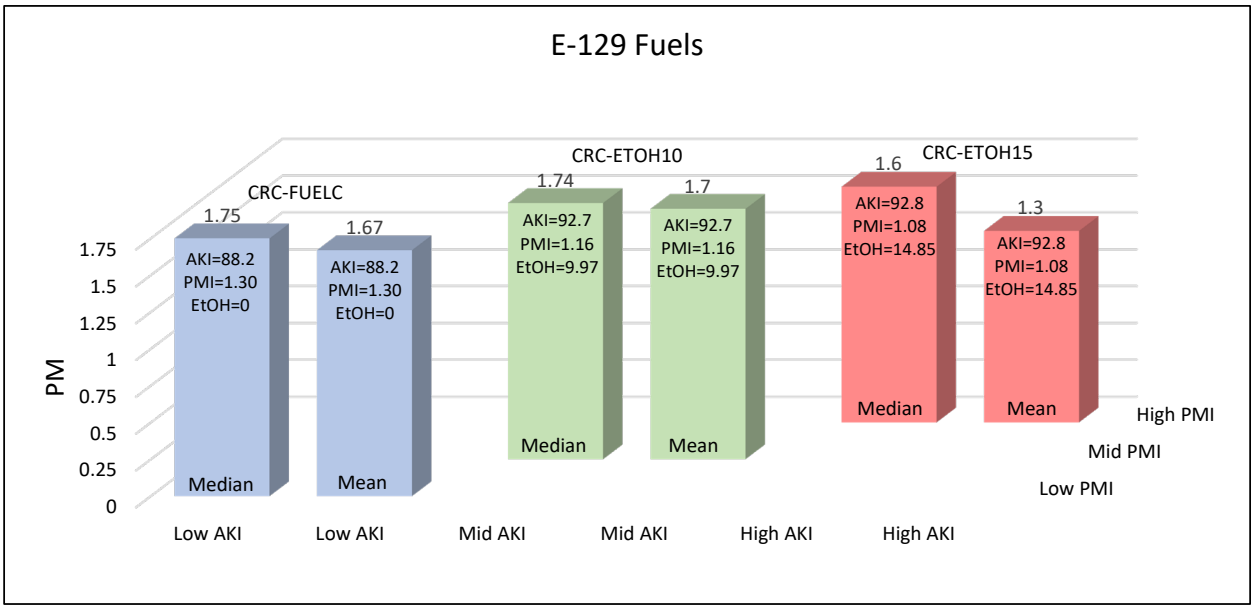


Figure 13. 3-D bar chart illustrating the relationship between AKI, PMI, and EtOH, and their combined impact on median and mean PM. Graphs encompass all vehicles and tests associated with each respective fuel.

The PM boxplots by vehicle are shown in Figure 14. The respective box plots for transformed values of PM are not shown here because they are essentially the same. Note that the relative positioning of the four vehicles in Figure 14 is essentially the same as the relative positioning of these same vehicles in Figure 5 (E-94-2 program). Again, there is no apparent reason why Vehicle 96 should have a much lower median value of PM than the other vehicles.

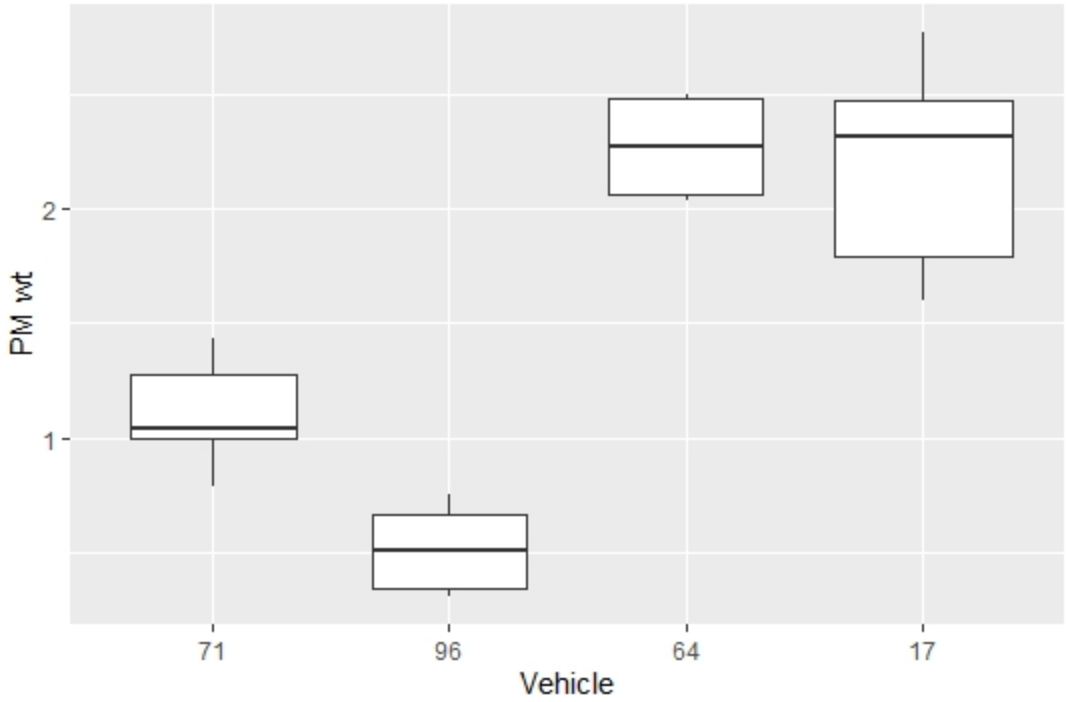


Figure 14. Boxplots of PM by vehicle. Note the change of scale from Figures 5 and 10. The graphs encompass all fuels and tests associated with each respective vehicle.

The number of observations by fuel and vehicle are shown in Table 15. All combinations are replicated at least twice.

Table 15. Observations (trials) by Fuel x Vehicle.

	Vehicle				Fuel
Fuel	71	96	64	17	Totals
CRC-ETOH10	3	2	2	3	10
CRC-ETOH15	2	2	2	3	9
CRC-FUELC	2	2	2	2	9
Vehicle Totals	7	6	6	8	27

Analysis of variance results for the model

$$PM^{0.25} \sim \text{Fuel} + \text{Vehicle} + \text{Fuel x Vehicle} + \text{Error}$$

is shown in Table 16.

Table 16. ANOVA table for the $PM^{0.25}$ model.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Fuel	2	0.041	0.020	22.145	3.34E-05
Vehicle	3	0.655	0.218	238.592	7.07E-13
Fuel x Vehicle	6	0.014	0.002	2.594	0.06283
Residuals	15	0.014	0.001		

Factors Fuel and Vehicle are highly significantly different. Fuel x Vehicle is marginally significantly different. Given the small samples, these *p*-values should be interpreted cautiously. However, the p-values (p adj) are consistent with the boxplots (Figure 12).

Table 17 shows a statistically significant difference between pair CRC-EtOH15 and CRC-EtOH10 and pair CRC-C and CRC-E15. Pair CRC-C and CRC-EtOH10 do not show a statistically significant difference.

Table 17. Pairwise fuel differences for E-129 fuels.

Fuel	Diff	Lower	Upper	p adj
CRC-E15 - CRC-E10	-0.086	-0.122	-0.050	5.07E-05
CRC-C - CRC-E15	0.077	0.039	0.115	0.000277
CRC-C - CRC-E10	-0.009	-0.046	0.029	0.81942

By way of comparison, the difference in mean PM for Fuel C (E-94-2) and Fuel C-E10 (E-94-3) is 1.33 whereas the same difference for CRC-C and CRC-EtOH10 (both in E-129) is -0.009 (see Table 18). Note that, based on this comparison, Fuel C and Fuel CRC-C appear to be different fuels when they are supposed to be essentially the same.

Table 18. Median and mean values of PM for the five "C" fuels. Values are pooled over vehicles and tests.

Fuel	Median PM	Mean PM	n
C	3.1	3.14	25
CRC-Fuel C	1.75	1.67	8
C-E10	1.77	3.5	10
CRC-EtOH10	1.74	1.7	10
CEC-EtOH15	1.6	1.3	9

2.5 Analysis of the Combined E-94-2, E-94-3 and E-129 Data Sets

Figure 15 (top) shows PM boxplots by fuel for all 15 fuels in order of E-129, E-94-3 and E-94-2 data sets. The symmetric transformed PM boxplots are shown in Figure 15 (bottom). A comparison of these two figures suggests that for hypotheses testing, the data should be transformed as $PM^{0.25}$. The width of the boxplots is proportional to the square root of the sample size (number of observations) to reflect less information.

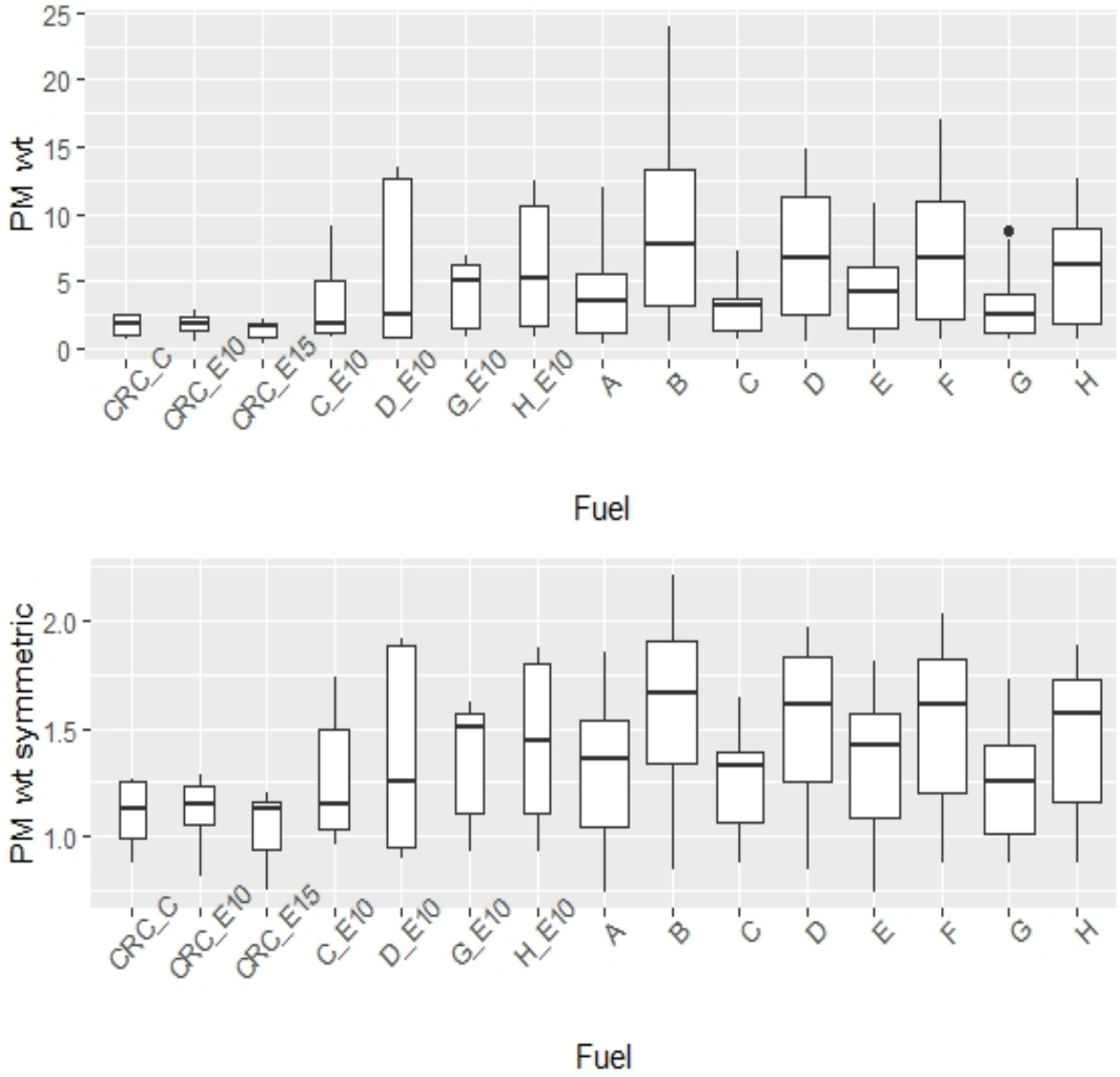


Figure 15. Boxplots of PM by fuel for all 15 fuels (top). Symmetric transformed PM fuels (bottom). The graphs encompass all vehicles and tests associated with each respective fuel.

Figure 16 is the same as Figure 15 except the fuels are in increasing order of PM medians.

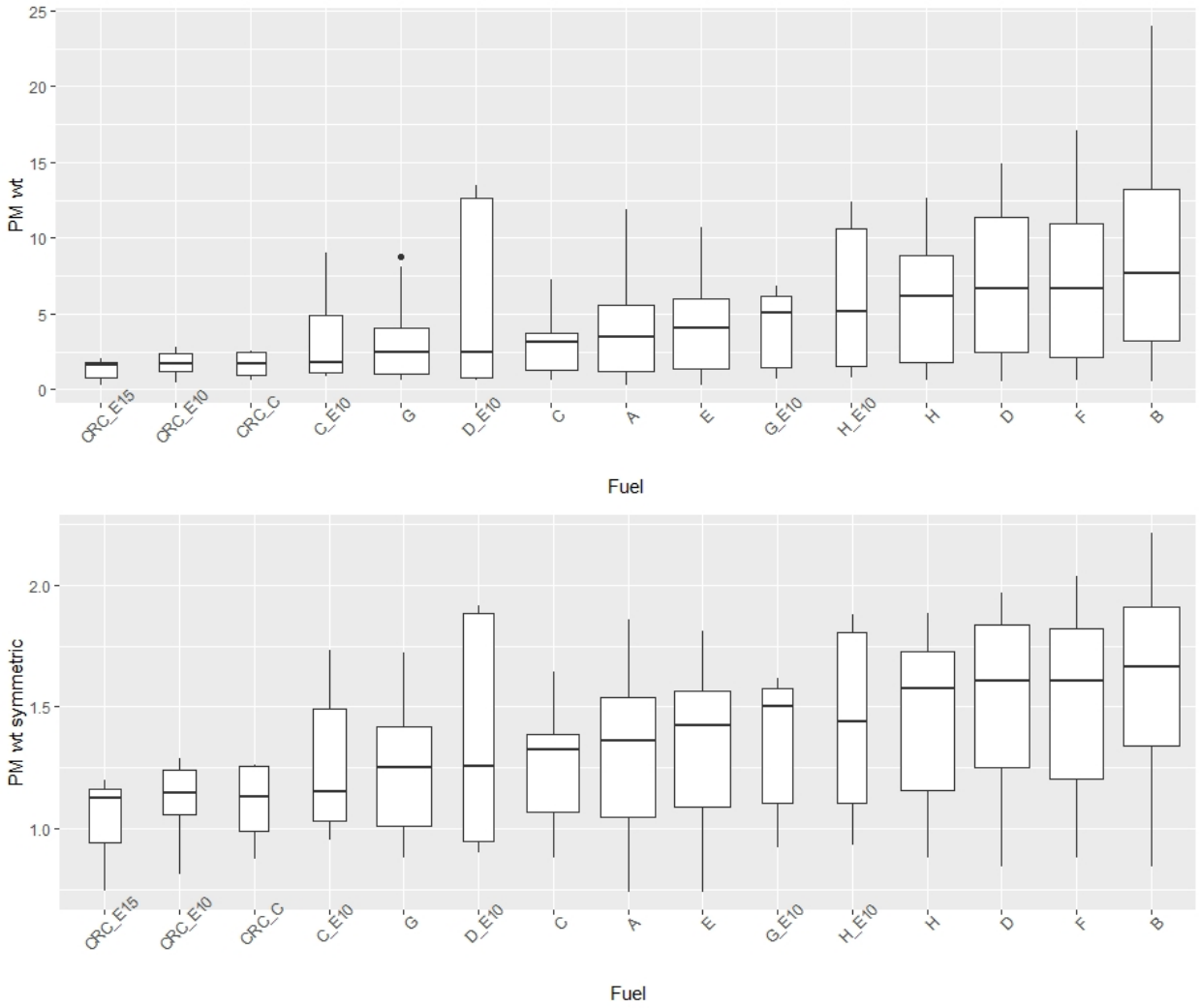


Figure 16. Boxplots of PM by fuel for all 15 fuels (top) by PM medians. Symmetric transformed PM fuels (bottom). The graphs encompass all vehicles and tests associated with each respective fuel.

Figure 17 is a comparison of Fuels C, D, G and H with their ethanol added counterparts (the E-94-3 data). The medians for fuels C, D, and H are lower after adding ethanol, which was to be expected, namely that adding ethanol through splash blending presumably reduces emissions. However, Fuel G-E10 does not behave that way.

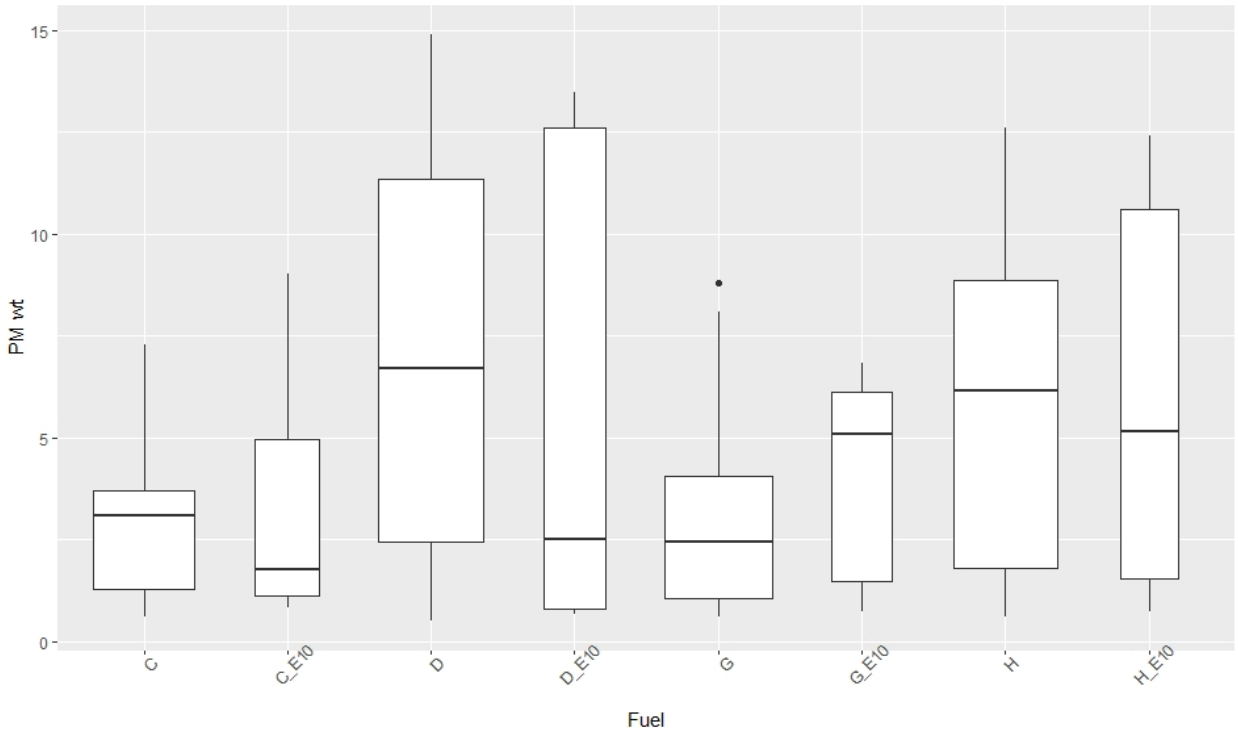


Figure 17. PM boxplot comparison of Fuels C, D, G, and H with their ethanol added counterparts. The graphs encompass all fuels and tests associated with each respective vehicle.

Table 19 is another presentation of all fuels sorted in ascending order by PM median. The results are similar to those shown in Figure 16, and the misbehavior of Fuel G-E10 is again apparent. Note that Fuels H and H-E10 are similar, with the median PM of Fuel H being slightly higher, but the reverse holds when comparing the respective means. This same phenomenon is observed when comparing Fuels CRC-C and CRC-EtOH10. These observations further underscore the importance of considering the median PM rather than mean PM when the relative number of observations is small.

Table 20 shows weak correlations between PM and AKI, EtOH and PMI for the 15 fuels. Table 21 gives the mean and standard deviation of 14 PM medians shown in Table 19 for EtOH = 0 and EtOH $\cong$ 10 fuels. Fuel EtOH15 was excluded from the means and standard deviations shown in Table 21 because it represents a somewhat different fuel formulation.

Table 19. All fuels sorted in ascending order by PM median; n is the sample size.

Fuel	AKI	EtOH	PMI	PM median	PM mean	Std Dev	CV	n
CRC-ETOH15	92.80	14.85	1.08	1.600	1.297	0.797	0.615	9
CRC-ETOH10	91.70	9.97	1.16	1.735	1.704	0.889	0.522	10
CRC-FUELC	88.20	0.00	1.30	1.745	1.673	0.711	0.425	8
C-E10	91.50	9.44	1.28	1.770	3.500	3.169	0.905	10
G	93.80	0.00	1.27	2.450	3.050	2.352	0.771	28
D-E10	91.10	9.71	2.45	2.510	6.430	6.029	0.938	9
C	87.90	0.00	1.42	3.100	3.140	2.044	0.651	25
A	87.20	9.55	1.42	3.450	4.120	3.296	0.800	28
E	93.60	9.56	1.30	4.100	4.230	3.101	0.733	29
G-E10	96.40	9.75	1.17	5.090	3.840	2.522	0.657	9
H-E10	96.00	9.88	2.32	5.170	5.990	5.120	0.855	8
H	94.10	0.00	2.49	6.150	5.920	3.951	0.667	26
D	88.20	0.00	2.65	6.700	7.130	4.603	0.646	27
F	93.70	9.51	2.55	6.700	7.010	5.200	0.742	26
B	87.10	9.56	2.64	7.700	8.590	6.302	0.734	28

Table 20. Correlation of PM, AKI, EtOH and PMI for the 15 fuels shown in Table 19.

	PM	AKI	EtOH	PMI
PM	1			
AKI	-0.090	1		
EtOH	0.035	0.089	1	
PMI	0.443	-0.138	-0.108	1

Table 21. Weighted mean and standard deviation of the PM medians shown in Table 19, excluding Fuel CRC-EtOH15.

	Weighted mean of medians	Weighted standard deviation of medians
EtOH = 0	4.394	1.945
EtOH > 9	4.778	2.002

The distributions of PM medians for EtOH = 0 and EtOH $\cong$ 10 are shown in Figure 18. Normal distributions are assumed. There appears not to be a statistically significant difference given the available data, however, there is a detectable shift in the distributions. This suggests the mean PM for fuels containing approximately 10% ethanol is marginally higher than the mean PM for fuels that do not contain ethanol. This is counter to what would be expected under the assumption that adding ethanol reduces PM emissions, on average.

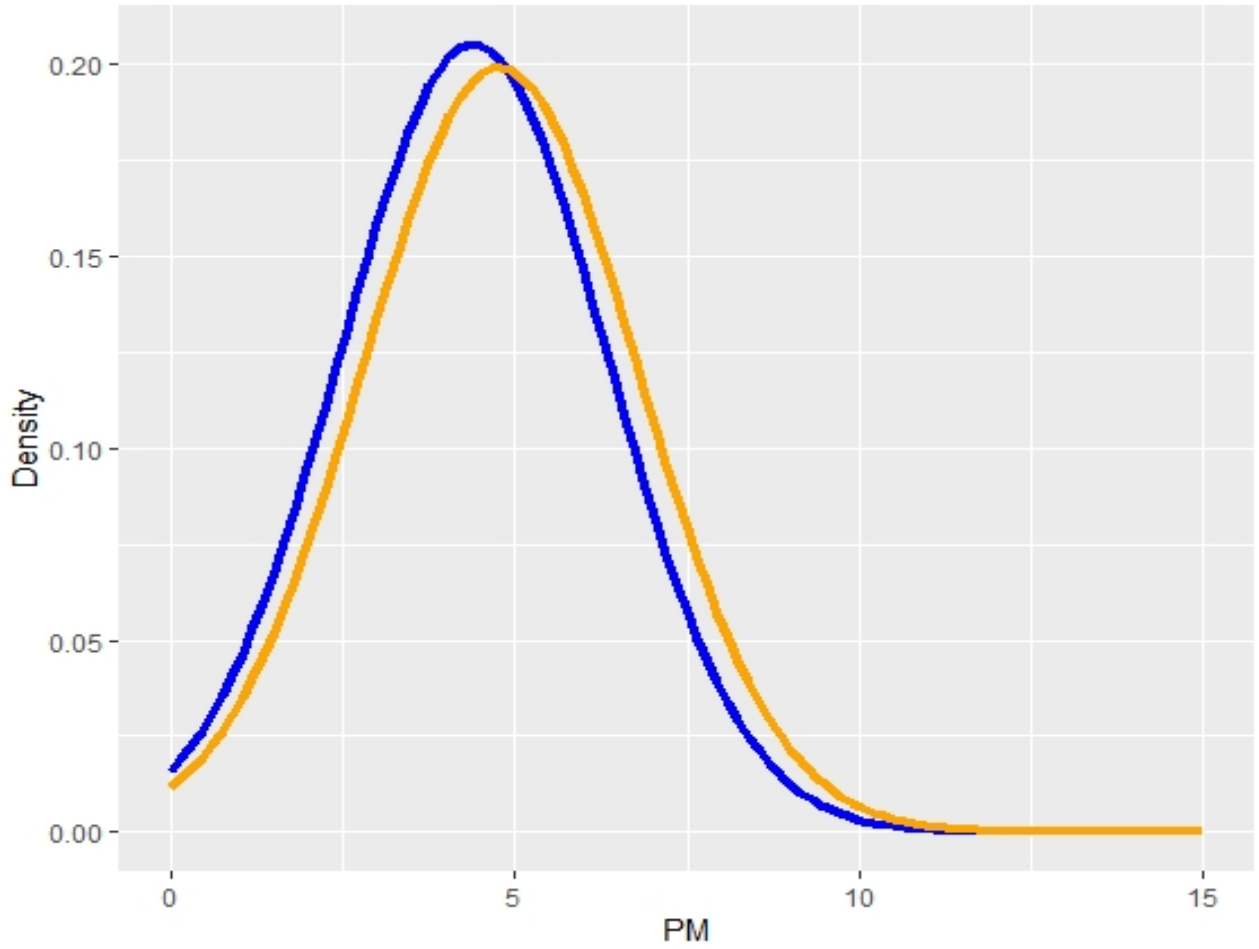


Figure 18. A comparison of the EtOH = 0 distribution (blue) with the EtOH $\cong$ 10 distribution (orange), pooled over all observations. Fuel CRC-EtOH15 excluded.

The number of observations by vehicle and program data set is shown in Table 22. The fuel by vehicle PM mean are given in Table 23. Blank spaces occur where fuel x vehicle observations are missing. The PM median values are almost identical to the means and are not shown.

Note that Vehicle 64 is used in all three programs and is tested on all fuels. Also note that inspection of the values of mean PM in Table 23 for ethanol/non-ethanol pairs of fuels (C/C-E10, D/D-E10, G/G-E10, H/H-E10) indicates that the value for the ethanol fuel is higher than for the corresponding non-ethanol fuel in most cases for each of the four vehicles on which both fuels were tested. This observation is contrary to what ordinarily would be expected and indicates the presence of a fuel x vehicle interaction. This also is true for one of the four vehicles on which CRC-Fuel C and CRC-ETOH10 were tested.

Table 22. Number of observations by vehicle and data set.

	Vehicle												Program
Data	29	25	71	78	13	98	55	20	96	51	64	17	Totals
E-94-2	18	17	16	19	16	20	19	19	17	20	17	19	**217**
E-94-3						9	10			8	9		**36**
E-129			7						6		6	8	**27**
Vehicle Totals	**18**	**17**	**23**	**19**	**16**	**29**	**29**	**19**	**23**	**28**	**32**	**27**	**280**

Table 23. Fuel by vehicle PM means. Mean values are pooled over tests.

	Vehicle											
Fuel	29	25	71	78	13	98	55	20	96	51	64	17
A	4.00	4.55	3.05	0.95	10.80	1.20	0.40	5.25	1.65	9.10	6.15	3.37
B	7.47	8.90	6.40	2.30	23.30	3.43	0.67	13.63	2.80	14.90	13.30	10.55
C	3.15	3.45	2.70	0.90	7.15	1.10	0.60	3.70	1.20	6.70	3.95	2.75
C-E10						1.53	1.04			8.81	4.83	
D	6.35	7.00	5.60	1.85	14.70	2.30	0.60	11.05	2.65	12.73	12.05	7.87
D-E10						2.39	0.71			12.73	12.74	
E	4.15	4.85	2.95	0.95	10.55	1.40	0.43	5.87	1.60	9.15	6.87	3.57
F	7.05	6.80	5.55	1.80	16.25	2.10	0.67	10.90	2.20	14.05	11.40	10.90
G	1.93	3.27	2.70	0.67	8.45	0.95	0.75	4.05	1.00	6.40	4.35	2.05
G-E10						1.64	0.88			6.21	5.70	
H	6.15	6.15	4.25	1.55	11.60	1.60	0.70	8.80	1.80	11.57	8.65	7.55
H-E10						1.87	0.79			11.90	9.39	
CRC-ETOH10			1.33						0.56		2.27	2.47
CRC-ETOH15			0.88						0.32		2.07	1.72
CRC-FUELC			1.04						0.67		2.49	2.50

All the foregoing comparative statements about fuels assume it is appropriate to "average over" vehicles. The previous ANOVA results suggest this is not true. Specifically, the PM fuel response was shown to be conditional on individual vehicles (i.e., a significant Fuel x Vehicle interaction).

The next analyses use nested models to combine results from the different programs (meta-analysis):

1. Fuels and vehicles are pooled over programs
2. Fuels and vehicles ae pooled over match blend
3. Fuels and vehicles are pooled over splash blend, and
4. Fuels and vehicles are pooled over blends and programs.

In this process ANOVA results show overall statistical significance of all factors. All the factors are considered to be fixed effects. All the F values (see for example Table 25) are the ratio of the factor mean square (Mean Sq) to the Residuals mean square. The smaller the residual mean square, the more likely statistically significant results will be obtained. Following each ANOVA, pairwise comparisons between fuels are presented using a Tukey family multiple comparison[11].

[11] The Tukey HSD procedure generates p-values that account for the number of comparisons made when determining statistical significance.

The results shown in the following tables appear to be consistent with graphical results (Figure 16). The number of fuels by program and blend is shown in Table 24.

Table 24. Number of fuels by program and blend.

	Blend	
Program	Match	Splash
E94-2	8	0
E94-3	0	4
E129	1	2

2.6 Pooled over Programs

The linear model is:

$$PM^{0.25} \sim \text{Program} + \text{Fuel within Program} + \text{Vehicle within Program} + (\text{Fuel \& Vehicle}) \text{ within Program}$$

The ANOVA results are shown in Table 25[12]. All factors/results are highly significant. There are statistically significant differences among the three programs, statistically significant differences among fuels within programs, statistically significant differences among vehicles within programs, and a statistically significant Fuel x Vehicle interaction, all of which align with, and confirm, the ANOVA results shown in Tables 7, 11, and 16.

Table 25. ANOVA results for pooled over programs model.

ANOVA	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Program	2	2.692	1.346	807.935	2.20E-16
Program:Fuel	12	3.653	0.304	182.719	2.20E-16
Program:Vehicle	17	24.247	1.426	856.120	2.20E-16
Program:Fuel:Vehicle	92	1.049	0.011	6.841	2.20E-16
Residuals	156	0.260	0.002		

[12] The transformed values of weighted PM are used in this and all subsequent analyses of variance. In the discussion of results, references to differences in mean PM imply that the transformed values have been used.

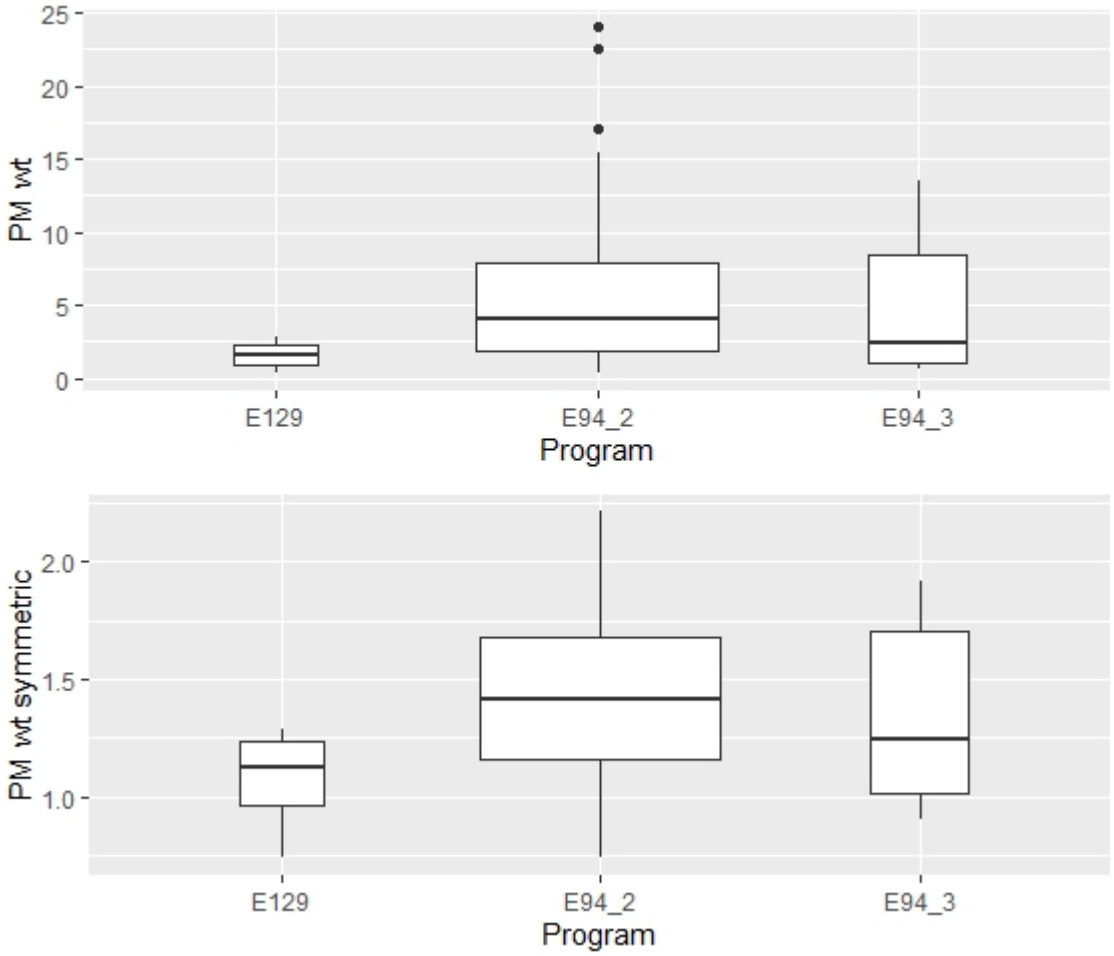


Figure 19. Boxplot of PM within Program (top) and PM transformed within Program (bottom). Graphs encompass all fuels, vehicles, and tests associated with each respective program.

Figure 19 shows a distribution of PM withing Program. E129 is different than the other two programs because its median is slightly lower, and its variability is much lower.

Table 26 shows the fuel paired differences in mean PM within a program. A low value of the adjusted p-value (p adj) indicates a statistically significant difference. In Table 26 fuel differences for p-values less than 0.10 (colored orange) are considered to be statistically different, while those above this level (colored green) are considered not to be statistically different. The choice of 0.10 is somewhat arbitrary. An alternative way to view statistical significance is to view the lower (lwr) and upper (upr) confidence bounds in Table 26 and subsequent similar tables. For the pairs to be considered different, the 95% confidence interval[13] fails to include zero. The 95% confidence interval is used for all subsequent pairwise differences.

For the same pair of fuels, differences remain the same across models, however, confidence bounds and adjusted p-values may be different. For example, in the analysis of E-94-2 data (Table 8) fuel difference F-D = -0.031. In Table 26, the fuel pairs F-D for the within program, is the same, however confidence bounds and adjusted p-values differ. In the Table 8 data the F-D lower confidence limit (lwr), upper confidence limit (upr) and p-adj are respectively (-0.065, 0.004, and 0.113). The corresponding values for F-D within program (Table 26) are (-0.076, 0.014, and 0.771). The wider interval for the differences within programs is due to the multiple comparison adjustments caused by the addition of E-94-3 and E-129 data.

[13] For this and subsequent similar tables, the confidence level is 95 %.

Table 26. Fuel differences within program.

Fuel pairs/Program	diff	lwr	upr	p adj
E94_2:B-E94_2:A	0.2728	0.2289	0.3168	0
E94_2:C-E94_2:B	-0.3323	-0.3775	-0.2871	0
E94_2:D-E94_2:A	0.2164	0.1721	0.2608	0
E94_2:D-E94_2:C	0.2759	0.2303	0.3215	0
E94_2:E-E94_2:B	-0.2578	-0.3013	-0.2142	0
E94_2:E-E94_2:D	-0.2014	-0.2453	-0.1574	0
E94_2:F-E94_2:A	0.1856	0.1408	0.2303	0
E94_2:F-E94_2:B	-0.0873	-0.1320	-0.0425	0
E94_2:F-E94_2:C	0.2450	0.1990	0.2910	0
E94_2:F-E94_2:E	0.1705	0.1261	0.2149	0
E94_2:G-E94_2:A	-0.0832	-0.1271	-0.0393	0
E94_2:G-E94_2:B	-0.3561	-0.4000	-0.3122	0
E94_2:G-E94_2:D	-0.2997	-0.3440	-0.2553	0
E94_2:G-E94_2:E	-0.0983	-0.1418	-0.0548	0
E94_2:G-E94_2:F	-0.2688	-0.3135	-0.2240	0
E94_2:H-E94_2:A	0.1418	0.0970	0.1865	0
E94_2:H-E94_2:B	-0.1310	-0.1758	-0.0863	0
E94_2:H-E94_2:C	0.2013	0.1552	0.2473	0
E94_2:H-E94_2:E	0.1267	0.0823	0.1711	0
E94_2:H-E94_2:G	0.2250	0.1803	0.2698	0
E94_3:D-E10-E94_3:C-E10	0.1470	0.0715	0.2225	0
E94_3:H-E10-E94_3:C-E10	0.1546	0.0766	0.2325	0
E94_2:E-E94_2:C	0.0745	0.0297	0.1194	4.00E-07
E94_2:H-E94_2:D	-0.0746	-0.1198	-0.0295	4.00E-07
E94_2:C-E94_2:A	-0.0595	-0.1047	-0.0142	0.0003483
E94_2:D-E94_2:B	-0.0564	-0.1007	-0.0121	0.0007367
E94_3:H-E10-E94_3:G-E10	0.0985	0.0186	0.1783	0.0014543
E94_3:G-E10-E94_3:D-E10	-0.0909	-0.1683	-0.0134	0.0039343
E129:CRC-E15-E129:CRC-E10	-0.0857	-0.1612	-0.0102	0.007158
E129:CRC-E15-E129:CRC-C	-0.0771	-0.1569	0.0028	0.0776151
E94_2:H-E94_2:F	-0.0438	-0.0893	0.0018	0.0822403
E94_3:G-E10-E94_3:C-E10	0.0561	-0.0194	0.1316	0.587003
E94_2:F-E94_2:D	-0.0309	-0.0760	0.0143	0.7708419
E94_2:G-E94_2:C	-0.0238	-0.0690	0.0214	0.9914385
E94_2:E-E94_2:A	0.0151	-0.0285	0.0586	0.9999995
E129:CRC-E10-E129:CRC-C	0.0087	-0.0692	0.0866	1
E94_3:H-E10-E94_3:D-E10	0.0076	-0.0722	0.0874	1

2.7 Pooled Over Programs Involving Match Blending

The linear model is:

$$PM^{0.25} \sim \text{Program} + \text{Fuel within Program} + \text{Vehicle within Program} + (\text{Fuel \& Vehicle}) \text{ within Program}$$

where the data is associated with match blending. The two programs involved are E-94-2 and E-129. ANOVA results are shown in Table 27. All results/factors are highly significant. There is a statistically significant difference between the two programs, there are statistically significant differences among fuels within the two programs, statistically significant differences among vehicles within the two programs, and a statistically significant Fuel x Vehicle interaction.

Table 27. ANOVA results for pooled over programs model for match blending.

ANOVA	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Program	1	0.7485	0.74854	465.9403	2.20E-16
Program:Fuel	7	3.4592	0.49418	307.606	2.20E-16
Program:Vehicle	14	19.7279	1.40913	877.1332	2.20E-16
Program:Fuel:Vehicle	77	0.8154	0.01059	6.5913	2.20E-16
Residuals	125	0.2008	0.00161		

Table 28 shows the paired differences in mean PM among fuels within program for match blending.

Table 28. Fuel differences within program pairs for match blend data.

Fuel Pairs/Program	diff	lwr	upr	p adj
E94_2:B-E94_2:A	0.2728	0.2347	0.3110	0
E94_2:C-E94_2:B	-0.3323	-0.3716	-0.2930	0
E94_2:D-E94_2:A	0.2164	0.1779	0.2550	0
E94_2:D-E94_2:C	0.2759	0.2362	0.3155	0
E94_2:E-E94_2:B	-0.2578	-0.2956	-0.2199	0
E94_2:E-E94_2:D	-0.2014	-0.2395	-0.1632	0
E94_2:F-E94_2:A	0.1856	0.1467	0.2245	0
E94_2:F-E94_2:C	0.2450	0.2050	0.2850	0
E94_2:F-E94_2:E	0.1705	0.1319	0.2091	0
E94_2:G-E94_2:B	-0.3561	-0.3942	-0.3179	0
E94_2:G-E94_2:D	-0.2997	-0.3382	-0.2611	0
E94_2:G-E94_2:F	-0.2688	-0.3077	-0.2299	0
E94_2:H-E94_2:A	0.1418	0.1029	0.1807	0
E94_2:H-E94_2:C	0.2013	0.1612	0.2413	0
E94_2:H-E94_2:G	0.2250	0.1861	0.2639	0
E94_2:H-E94_2:B	-0.1310	-0.1699	-0.0922	6.33E-15
E94_2:H-E94_2:E	0.1267	0.0881	0.1653	2.20E-14
E94_2:G-E94_2:E	-0.0983	-0.1361	-0.0605	2.75E-13
E94_2:F-E94_2:B	-0.0873	-0.1262	-0.0484	1.13E-10
E94_2:G-E94_2:A	-0.0832	-0.1214	-0.0451	3.79E-10
E94_2:E-E94_2:C	0.0745	0.0356	0.1135	5.42E-08
E94_2:H-E94_2:D	-0.0746	-0.1139	-0.0354	6.52E-08
E94_2:C-E94_2:A	-0.0595	-0.0988	-0.0202	4.85E-05
E94_2:D-E94_2:B	-0.0564	-0.0949	-0.0179	0.000104
E94_2:H-E94_2:F	-0.0438	-0.0834	-0.0042	0.0153
E94_2:F-E94_2:D	-0.0309	-0.0701	0.0084	0.324541
E94_2:G-E94_2:C	-0.0238	-0.0631	0.0155	0.778207
E94_2:E-E94_2:A	0.0151	-0.0228	0.0529	0.993997

2.8 Pooled Over Programs Involving Splash Blending

The linear model is:

$$PM^{0.25} \sim \text{Program} + \text{Fuel within Program} + \text{Vehicle within Program} + (\text{Fuel \& Vehicle}) \text{ within Program}$$

where the data is associated with splash blending. The two programs involved are E-94-3 and E-129. The ANOVA results are shown in Table 29. All results/factors are highly significant. There is a statistically significant difference between the two programs, there are statistically significant differences among fuels within the two programs, statistically significant differences

among vehicles within the two programs, and a statistically significant Fuel x Vehicle interaction.

The paired differences among fuels within programs that involve splash blending are shown in Table 30. The two paired differences colored (G-E10 vs C-E10 and J-E10 vs D-E10) are not significantly different.

Table 29. ANOVA results for pooled over programs for splash bending.

ANOVA	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Program	1	1.0112	1.01119	530.5997	< 2.2e-16
Program:Fuel	4	0.1879	0.04698	24.6503	3.00E-09
Program:Vehicle	6	4.5278	0.75463	395.9773	< 2.2e-16
Program:Fuel:Vehicle	12	0.2243	0.01869	9.8073	1.67E-07
Residuals	31	0.0591	0.00191		

Table 30. Fuel difference within program for splash blend data.

Fuel Pairs/Program	diff	lwr	upr	p adj
E94_3:H-E10-E94_3:C-E10	0.155	0.082	0.228	0.0000012
E94_3:D-E10-E94_3:C-E10	0.147	0.076	0.218	0.0000018
E94_3:H-E10-E94_3:G-E10	0.098	0.024	0.173	0.0029295
E94_3:G-E10-E94_3:D-E10	-0.091	-0.163	-0.018	0.0053613
E129:CRC-E15-E129:CRC-E10	-0.086	-0.156	-0.015	0.0077965
E94_3:G-E10-E94_3:C-E10	0.056	-0.015	0.127	0.2297758
E94_3:H-E10-E94_3:D-E10	0.008	-0.067	0.082	0.9999999

2.9 Pooled over Blends and Programs

The linear model is:

$$PM^{0.25} \sim \text{Program} + \text{Blend within Program} + \text{Fuel within Blend \& Program} + \text{Vehicle withing Blend \& Program} + \text{Fuel \& Vehicle within Blend \& Program}$$

The ANOVA results are shown in Table 31. Here, all three programs are involved; but unlike the analysis presented in Table 25, this analysis partitions out the variability attributable to blending differences. There are statistically significant differences among the three programs, statistically significant differences among fuels within blends and programs, statistically significant differences among vehicles within blends and programs, and a statistically significant fuel x vehicle interaction. These results are consistent with those presented in Table 25. The p-value associated with blends within programs (Table 31) is 0.06537, implying the blending difference are less significant than the other factors.

The paired differences in mean PM fuels within programs and blends are shown in Table 32. The differences for the six pairs colored in green are not significantly different.

Table 31. ANOVA results for pooled over blends and programs model.

ANOVA	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Program	2	2.692	1.34601	807.9351	< 2e-16
Program:Blend	1	0.0057	0.00574	3.444	0.06537
Program:Blend:Fuel	11	3.6471	0.33156	199.0164	< 2e-16
Program:Blend:Vehicle	20	24.2557	1.21278	727.9685	< 2e-16
Program:Blend:Fuel:Vehicle	89	1.0396	0.01168	7.0117	< 2e-16
Residuals	156	0.2599	0.00167		

Table 32. Fuel within blends and programs.

Fuel Pairs/Program & Blend	diff	lwr	upr	p adj
E94_2:Match:B-E94_2:Match:A	0.2728	0.2253	0.3204	0
E94_2:Match:C-E94_2:Match:B	-0.3323	-0.3812	-0.2834	0
E94_2:Match:D-E94_2:Match:A	0.2164	0.1685	0.2644	0
E94_2:Match:D-E94_2:Match:C	0.2759	0.2265	0.3253	0
E94_2:Match:E-E94_2:Match:B	-0.2578	-0.3049	-0.2106	0
E94_2:Match:E-E94_2:Match:C	0.0745	0.0260	0.1231	0
E94_2:Match:E-E94_2:Match:D	-0.2014	-0.2489	-0.1538	0
E94_2:Match:F-E94_2:Match:A	0.1856	0.1371	0.2340	0
E94_2:Match:F-E94_2:Match:B	-0.0873	-0.1357	-0.0388	0
E94_2:Match:F-E94_2:Match:C	0.2450	0.1952	0.2948	0
E94_2:Match:F-E94_2:Match:E	0.1705	0.1224	0.2185	0
E94_2:Match:G-E94_2:Match:A	-0.0832	-0.1308	-0.0357	0
E94_2:Match:G-E94_2:Match:B	-0.3561	-0.4036	-0.3085	0
E94_2:Match:G-E94_2:Match:D	-0.2997	-0.3476	-0.2517	0
E94_2:Match:G-E94_2:Match:E	-0.0983	-0.1454	-0.0512	0
E94_2:Match:G-E94_2:Match:F	-0.2688	-0.3172	-0.2203	0
E94_2:Match:H-E94_2:Match:A	0.1418	0.0934	0.1902	0
E94_2:Match:H-E94_2:Match:B	-0.1310	-0.1795	-0.0826	0
E94_2:Match:H-E94_2:Match:C	0.2013	0.1514	0.2511	0
E94_2:Match:H-E94_2:Match:D	-0.0746	-0.1235	-0.0258	0
E94_2:Match:H-E94_2:Match:E	0.1267	0.0787	0.1748	0
E94_2:Match:H-E94_2:Match:G	0.2250	0.1766	0.2735	0
E94_3:Splash:D-E10-E94_3:Splash:C-E10	0.1470	0.0653	0.2287	0
E94_3:Splash:H-E10-E94_3:Splash:C-E10	0.1546	0.0702	0.2389	0
E94_2:Match:C-E94_2:Match:A	-0.0595	-0.1084	-0.0105	0.001283
E94_2:Match:D-E94_2:Match:B	-0.0564	-0.1044	-0.0084	0.002662
E94_3:Splash:H-E10-E94_3:Splash:G-E10	0.0985	0.0121	0.1849	0.005147
E94_3:Splash:G-E10-E94_3:Splash:D-E10	-0.0909	-0.1747	-0.0070	0.013381
E129:Splash:CRC-E15-E129:Splash:CRC-E10	-0.0857	-0.1675	-0.0040	0.023608
E94_2:Match:H-E94_2:Match:F	-0.0438	-0.0931	0.0056	0.215477
E94_3:Splash:G-E10-E94_3:Splash:C-E10	0.0561	-0.0256	0.1378	0.868218
E94_2:Match:F-E94_2:Match:D	-0.0309	-0.0797	0.0180	0.960518
E94_2:Match:G-E94_2:Match:C	-0.0238	-0.0727	0.0252	0.999935
E94_2:Match:E-E94_2:Match:A	0.0151	-0.0320	0.0622	1
E94_3:Splash:H-E10-E94_3:Splash:D-E10	0.0076	-0.0788	0.0940	1

2.10 Additional Comments

The principal focus of this study is on fuels rather than vehicles, whereas the authors of the E-94-2, E-94-3, and E-129 reports devoted considerable effort to analyzing and explaining vehicle

effects and impacts. A specific task we performed was to see if there was a benefit in pooling the data and/or experimental results from the three studies. We concluded that there was not a benefit.

In consultation with the CRC committee we have assumed that vehicles are fixed and are essentially "blocks" in a randomized block design. As a result of the analyses conducted, we have determined that Vehicle is a statistically significant factor/effect regarding all three studies. Pooling over studies does not change this result. We conclude that the analysis successfully accounts for, and partitions out, the vehicle-to-vehicle variation (as we would hope to be the case in any randomized block experimental design) so we can "see" the truer effect of fuels and identify/detect any statistical differences that exist. Another way to say this is that "blocking has been effective." Unfortunately, we also have a FUEL x VEHICLE interaction, which we would have preferred not to detect. The question of "why" leads us into an exploration of vehicle differences. The previous authors have already looked at vehicle-to-vehicle differences extensively and have not drawn any conclusions other than to say that the PM response differs depending on vehicle. The additional vehicle data we were given does not suggest any obvious reasons. We conclude that (1) there is something mechanically, technically, or instrumentally different about some of the vehicles, (2) something was done differently when testing some of the vehicles or (3) for some reason, the selected vehicles are not appropriate for some of the fuels on which they were tested. The question remains: are there two or three different populations of vehicles?"

In our ANOVA results all the factors are highly statistically significant. When we examine paired differences in mean PM, we find most of them are statistically significant. Those that are not may be different, but it would require additional observations and/or reducing the fuel x vehicle interaction effect to determine this. One way to reduce the fuel x vehicle interaction is to replicate the study, thereby increasing the number of vehicles (experimental units), which may not be practical at this point.

3.0 DHA Analysis

DHA data were provided for each of the combined group of 15 fuels investigated in the E-94-2, E-94-3, and E-192 programs. Other fuels were investigated in the E-129 program that are not included in here. The available data consists of individual values of carbon-group-constituent combinations recorded in terms of Wgt%, volume %, mole %, and area, although values are not available for all such combinations, as described below. Where available, there is a single value for each of Wgt%, volume %, mole %, and area associated with each carbon-group-constituent combination for each fuel. Only a single sample of each fuel was evaluated via DHA. There is no replication.

A separate master DHA file was created containing all the available data for each carbon-group-constituent combination for each fuel. This file consists of a 326 x 63 row-by-column matrix, the 326 rows representing each individual carbon-group-constituent combination and the 63 columns representing the four recorded measurements (Wgt%, volume %, mole %, area) of each

combination for each of the 15 fuels, plus three identifying columns. The 63 columns are the variables of interest. For purposes of the present investigation, and in consultation with the CRC Emissions Committee, the matrix was restricted to values of Wgt% only, thereby reducing the size of the matrix to 326 rows by 18 columns. Appendix D provides a further description.

The master DHA file was constructed by first juxtaposing the columns associated with each fuel in a side-by-side fashion (i.e., horizontal stacking), and then progressively aligning the rows so that all 326 carbon-group-constituent combinations are represented for each fuel. This is significant because the laboratory analysis did not result in the same combinations or the same number of combinations for the individual fuels. The alignment process was necessary to structure the file in such a way that it could be computationally and statistically analyzed (i.e., the same number of rows for each fuel). As a result, the master DHA file contains numerous empty/missing cells representing carbon-group-constituents for which there are no recorded values. This situation is not necessarily bad, because it helps facilitate identification of differences among the fuels. On the other hand, it does present statistical computation challenges when blank cells are encountered.

Table 33 contains a partial listing of the master DHA file by constituent within group within carbon for all 15 fuels. The table lists values of Wgt% only and, to accommodate space restrictions, is limited to the data representing C_9. As already noted, data are absent/missing for some carbon-group-constituent combinations (cells). For purposes of most of the analyses described in this report, no attempt has been made to ascribe or impute specific values (such as zero) to these blank cells.

The DHA results represent a class of data referred to as compositional with regard to carbon number, that is, the values of the various constituents associated with fuel sum to 100% on a Wgt% basis. Similarly, the totals for all the carbon numbers or for all the groups associated with each fuel sum to 100% on a Wgt% basis. Care must be taken when analyzing and interpreting compositional data because the boundedness of the range of values often imposes restrictions on their distribution that cannot be satisfied by the usual distributional assumptions associated with most statistical methods. Despite this concern, issues with compositional data are largely ignored in the present study because they are secondary in importance relative to other considerations (e.g., missing values, absence of replication, etc.)

Table 33. Partial listing of DHA data (Wgt%), by constituent within group within carbon, for all fuels. The table displays data for C_9 only. Note the blank cells.

			FUEL														
Carbon	Group	Constituent	CRC_C	CRC_E10	CRC_E15	C_E10	D_E10	G_E10	H_E10	A	B	C	D	E	F	G	H
C9	Paraffin	n-Nonane	0.908	0.823	0.784	0.631	0.229	0.306	0.29	0.914	0.871	0.688	0.25	0.749	0.505	0.335	0.313
C9	I-Paraffins	2,2,5-Trimethylhexane	1.366	1.233	1.173	0.899	0.959	1.594	1.415	0.364	0.358	0.991	1.058	1.077	0.986	1.758	1.566
C9	I-Paraffins	C9-Isoparaffin-x	0.057	0.051	0.048	0.051	0.035	0.048	0.043	0.036	0.034	0.057	0.039	0.044	0.035	0.053	0.048
C9	I-Paraffins	2,3,5-Trimethylhexane	0.25	0.204	0.194	0.142	0.161	0.232	0.206	0.064	0.062	0.155	0.177	0.156	0.15	0.255	0.227
C9	I-Paraffins	2,4-Dimethylheptane	0.113	0.103	0.098	0.132	0.062	0.072	0.068	0.15	0.137	0.146	0.068	0.117	0.077	0.079	0.075
C9	I-Paraffins	2,2,3-Trimethylhexane		0.011	0.01	0.016	0.013				0.018	0.017	0.013				
C9	I-Paraffins	2,6-Dimethylheptane	0.214	0.182	0.174	0.246	0.062	0.154	0.146	0.29	0.242	0.273	0.068	0.273	0.175	0.168	0.161
C9	I-Paraffins	2,5-Dimethylheptane	0.274	0.247	0.236	0.301	0.165	0.188	0.175	0.328	0.302	0.335	0.183	0.268	0.183	0.206	0.193
C9	I-Paraffins	3,5-Dimethylheptane	0.034	0.031	0.03	0.048	0.008	0.023	0.023	0.055	0.049	0.053	0.008	0.051	0.031	0.026	0.025
C9	I-Paraffins	4-Ethylheptane	0.062	0.056	0.053	0.091	0.037	0.036	0.035	0.108	0.098	0.103	0.041	0.08	0.049	0.04	0.038
C9	I-Paraffins	4-Methyloctane	0.224	0.202	0.193	0.31	0.139	0.118	0.116	0.369	0.337	0.347	0.153	0.261	0.159	0.129	0.126
C9	I-Paraffins	2-Methyloctane	0.277	0.25	0.238	0.376	0.169	0.14	0.137	0.442	0.405	0.417	0.186	0.311	0.191	0.153	0.151
C9	I-Paraffins	Heptane, 3-ethyl-	0.058	0.054	0.051	0.088	0.041	0.033	0.032	0.105	0.098	0.1	0.045	0.073	0.044	0.036	0.034
C9	I-Paraffins	3-Methyloctane	0.424	0.38	0.363	0.586	0.193	0.242	0.237	0.693	0.625	0.647	0.213	0.559	0.344	0.265	0.264
C9	Mono-Aromatics	i-Propylbenzene	0.046	0.042	0.04	0.063	0.092	0.018	0.013	0.091	0.102	0.072	0.1	0.024	0.017	0.02	0.015
C9	Mono-Aromatics	n-Propylbenzene	0.144	0.129	0.123	0.286	0.526	0.409	0.283	0.331	0.626	0.32	0.575	0.469	0.325	0.45	0.311
C9	Mono-Aromatics	1-Methyl-3-ethylbenzene	0.372	0.332	0.317	0.925	1.765	1.669	1.152	0.945	2.106	1.039	1.935	1.82	1.269	1.834	1.261
C9	Mono-Aromatics	1-Methyl-4-ethylbenzene	0.171	0.149	0.142	0.414	0.79	0.766	0.53	0.439	0.971	0.469	0.866	0.855	0.596	0.842	0.58
C9	Mono-Aromatics	1,3,5-Trimethylbenzene	0.229	0.201	0.192	0.497	0.947	1.013	0.702	0.523	1.2	0.568	1.039	1.142	0.801	1.113	0.768
C9	Mono-Aromatics	1-Methyl-2-ethylbenzene	0.129	0.113	0.108	0.322	0.607	0.531	0.367	0.35	0.724	0.362	0.665	0.583	0.407	0.584	0.404
C9	Mono-Aromatics	1,2,4-Trimethylbenzene	0.611	0.541	0.517	1.506	2.943	2.837	1.984	1.534	3.515	1.696	3.227	3.12	2.172	3.118	2.166
C9	Mono-Aromatics	1,2,3-Trimethylbenzene	0.167	0.138	0.132	0.347	0.631	0.424	0.336	0.445	0.758	0.39	0.699	0.474	0.384	0.465	0.37
C9	Naphtheno/Olefino-Benzs	Indan	0.109	0.095	0.09	0.142	0.253	0.165	0.145	0.188	0.315	0.167	0.283	0.206	0.173	0.182	0.159
C9	Mono-Naphthenes	C9 - MonoNaph - 1	0.232	0.209	0.199	0.346	0.011	0.185		0.379	0.333	0.384	0.012	0.403	0.246	0.204	0.2
C9	Mono-Naphthenes	1,1,4-Trimethylcyclohexane	0.035	0.032	0.03	0.052	0.043	0.024	0.024	0.059	0.053	0.058	0.01	0.054	0.033	0.027	0.027
C9	Mono-Naphthenes	1,1,3-Trimethylcyclohexane	0.064	0.058	0.055	0.09	0.014	0.044	0.043	0.104	0.093	0.103	0.016	0.097	0.059	0.049	0.048
C9	Mono-Naphthenes	1c,2t,4t-Trimethylcyclohexane	0.249	0.224	0.214	0.411	0.028	0.225	0.219	0.438	0.381	0.456	0.03	0.487	0.301	0.248	0.243
C9	Mono-Naphthenes	C9 - MonoNaph - 4	0.051	0.047	0.045	0.08	0.013	0.04	0.039	0.092	0.081	0.093	0.015	0.09	0.055	0.043	0.043
C9	Mono-Naphthenes	1c,2t,4c-Trimethylcyclohexane	0.065	0.059	0.056	0.097	0.015	0.049	0.048	0.111	0.099	0.111	0.011	0.117	0.072	0.054	0.052
C9	Mono-Naphthenes	trans-1,3-Diethylcyclopentane	0.229	0.206	0.197	0.208	0.032	0.091	0.09	0.289	0.265	0.232	0.035	0.26	0.163	0.101	0.099
C9	Mono-Naphthenes	1,1-Methylethylcyclohexane	0.145	0.134	0.127	0.097	0.024	0.037	0.036	0.16	0.156	0.111	0.026	0.14	0.091	0.041	0.038
C9	Mono-Naphthenes	1-ethyl-4-t-methylcyclohexane	0.043	0.044	0.042	0.028	0.012	0.008	0.008	0.054	0.05	0.037	0.013	0.036	0.023	0.009	0.009
C9	Mono-Naphthenes	1-Methyl-2-propyl-cyclopentan	0.01	0.009	0.009	0.007		0.003	0.002	0.012	0.01	0.008	0.008	0.006	0.004	0.003	0.003
C9	Mono-Naphthenes	C10-IsoOlefin-4					0.008										
C9	Mono-Naphthenes	1,2,3,5-t-Tetramethylcyclohex	0.106	0.096	0.091	0.049		0.008	0.007	0.109	0.108	0.055		0.088	0.058	0.009	0.009
C9	n-Olefins	C9 - Olefin - 1				0.006	0.007			0.007	0.007	0.007	0.007				
C9	n-Olefins	C9-isoolefin				0.017	0.057	0.112	0.101			0.019	0.069			0.124	0.114
C9	n-Olefins	t-Nonene-3	0.05	0.046	0.044	0.038	0.014	0.015	0.014	0.053	0.049	0.044	0.015	0.042	0.026	0.016	0.016
C9	n-Olefins	trans-4-Nonene				0.009	0.011			0.014	0.014	0.011	0.012				
C9	n-Olefins	c-Nonene-3	0.003	0.003	0.003	0.003	0.005			0.005	0.005	0.004	0.005				
C9	n-Olefins	t-Nonene-2					0.005	0.004	0.004				0.006				
C9	Iso-Olefins	2,3,3-Trimethylhexene-1				0.004	0.008					0.004	0.009				
C9	Iso-Olefins	2,6-Dimethylheptene-1													0.014		
C9	Iso-Olefins	2,3-Dimethyl-3-heptene	0.02	0.018	0.017	0.027	0.008			0.032	0.029		0.008				0.012
C9	Iso-Olefins	2-Methyloctene-1	0.038	0.035	0.033	0.053	0.019	0.025	0.025	0.064	0.058	0.063	0.02	0.056	0.034	0.028	0.027
C9	Iso-Olefins	3-Heptene, 2,6-dimethyl-									0.005	0.005					
C9	Iso-Olefins	2,4-Dimethylheptene-1	0.029	0.027	0.026	0.039	0.02	0.02	0.019	0.045	0.041	0.045	0.021	0.035	0.022	0.022	0.02
C9	Iso-Olefins	2-Methyloctene-2	0.02	0.018	0.018	0.029	0.008	0.013	0.012	0.033	0.029	0.034	0.008	0.029	0.018	0.014	0.013
C9	Iso-Olefins	2,3-Dimethylheptene-2				0.017	0.01		0.004	0.028	0.026	0.007	0.011	0.015	0.009	0.005	0.004
C9	Naphtheno-Olefins	C9 Naph-Olefin -1													0.097		0.086
C9	Naphtheno-Olefins	C9 - NaphOlefin - 2	0.042	0.038	0.037	0.055	0.008	0.025	0.025	0.063	0.056	0.062	0.008	0.059	0.036	0.028	0.028

Tables 34 and Table 35 contain "rolled up" Wgt% values aggregated (summed) over individual constituents within carbons and groups. Table 34 is a partial listing of the data, by group within carbon, for all fuels, and Table 3 is similar partial listing, by carbon within group, for all fuels. The information in the two tables is identical but organized in different ways. Both tables also include associated values of AKI, EtOH, and PMI, as well as the mean and median values of PM, for each respective fuel. The information about AKI, EtOH, and PMI consists of single values associated with the respective fuels, whereas the mean and median PM values are averaged over all tests conducted on all vehicles encompassed by the E-94-2, E-94-3, and E-129 studies. The physical fuel samples on which the DHA evaluations were conducted were different

from the physical fuel samples used for vehicle testing, and due to time lags between the two different data collection protocols, may have shifted in composition.

Table 34. Partial listing of DHA data (Wgt%) by group within carbon for all fuels. Data are summed over all constituents within carbon-group combinations, with summed values only for C_9-C_{12} being displayed. Table rows associated with the same carbon number are color coded to facilitate visual tracking. Values of AKI, EtOH, and PMI associated with each fuel are included, along with mean and median values of PM.

	Median PM	1.75	1.74	1.6	1.77	2.51	5.09	5.17	3.45	7.70	3.10	6.70	4.1	6.7	2.45	6.15
	Mean PM	1.67	1.7	1.3	3.5	6.43	3.84	5.99	4.12	8.59	3.14	7.13	4.23	7.01	3.05	5.92
	AKI	88.2	91.7	92.8	91.5	91.1	96.4	96	87.2	87.1	87.9	88.2	93.6	93.7	93.8	94.1
	EtOH	0	9.97	14.85	9.44	9.71	9.75	9.88	9.55	9.56	0	0	9.56	9.51	0	0
	PMI	1.3	1.16	1.08	1.28	2.45	1.17	2.32	1.42	2.64	1.42	2.65	1.3	2.55	1.27	2.49
Carbon	**Group**	**CRC_C**	**CRC_E10**	**CRC_E15**	**C_E10**	**D_E10**	**G_E10**	**H_E10**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
C9	Paraffin	0.908	0.823	0.784	0.631	0.229	0.306	0.29	0.914	0.871	0.688	0.25	0.749	0.505	0.335	0.313
C9	I-Paraffins	3.353	3.004	2.861	3.286	2.044	2.88	2.633	3.004	2.765	3.641	2.252	3.27	2.424	3.168	2.908
C9	Mono-Aromatics	1.869	1.645	1.571	4.36	8.301	7.667	5.367	4.658	10.002	4.916	9.106	8.487	5.971	8.426	5.875
C9	Iso-Olefins	0.107	0.098	0.094	0.169	0.073	0.058	0.06	0.202	0.188	0.158	0.077	0.135	0.097	0.069	0.076
C9	Naphtheno/Olefino-Benzs	0.109	0.095	0.09	0.142	0.253	0.165	0.145	0.188	0.315	0.167	0.283	0.206	0.173	0.182	0.159
C9	Mono-Naphthenes	1.229	1.118	1.065	1.465	0.2	0.714	0.516	1.807	1.629	1.648	0.176	1.778	1.105	0.788	0.771
C9	n-Olefins	0.053	0.049	0.047	0.073	0.099	0.131	0.119	0.079	0.075	0.085	0.114	0.042	0.036	0.14	0.13
C9	Naphtheno-Olefins	0.042	0.038	0.037	0.055	0.008	0.025	0.025	0.063	0.056	0.062	0.008	0.059	0.133	0.028	0.114
C10	Paraffin	0.169	0.147	0.141	0.171	0.129	0.019	0.032	0.425	0.445	0.201	0.145	0.372	0.256	0.02	0.048
C10	I-Paraffins	1.928	1.681	1.605	1.166	1.076	1.064	0.917	1.463	1.332	1.317	1.173	1.409	1.091	1.163	1.005
C10	Mono-Aromatics	2.042	1.856	1.774	2.323	5.08	2.371	5.114	2.295	5.209	2.466	5.539	2.298	5.603	2.589	5.765
C10	Naphthalenes	0.15	0.133	0.128	0.141	0.389	0.094	0.366	0.157	0.397	0.159	0.425	0.082	0.415	0.097	0.4
C10	Naphtheno/Olefino-Benzs	0.461	0.409	0.391	0.354	1.29	0.424	1.34	0.369	1.242	0.399	1.277	0.478	1.451	0.46	1.464
C10	Mono-Naphthenes	0.073	0.051	0.048	0.046	0.022	0.008	0.006	0.162	0.146	0.07	0.014	0.137	0.092	0.006	0.004
C10	n-Olefins	0.013	0.011	0.011	0.01	0.012	0	0	0.023	0.023	0.012	0.014	0.014	0.009	0	0
C10	Iso-Olefins	0.159	0.126	0.12	0.11	0.025	0.018	0.017	0.246	0.239	0.137	0.049	0.182	0.12	0.02	0.021
C10	Naphtheno-Olefins	0	0	0	0	0.008	0	0	0	0	0	0	0	0	0	0
C11	Paraffin	0.064	0.057	0.054	0.049	0.068	0.033	0.051	0.106	0.089	0.056	0.073	0.063	0.069	0.035	0.053
C11	I-Paraffins	1.133	0.999	0.953	0.85	0.759	0.975	0.891	0.858	0.873	1.019	0.837	1.083	0.912	1.067	0.941
C11	Mono-Aromatics	0.662	0.608	0.58	0.469	1.272	0.573	1.507	0.42	1.431	0.524	1.53	0.556	1.611	0.606	1.627
C11	Naphthalenes	0.179	0.155	0.148	0.19	0.636	0.006	0.623	0.21	0.691	0.214	0.694	0.003	0.667	0.005	0.68
C11	Naphtheno/Olefino-Benzs	0.14	0.114	0.108	0.053	0.174	0.039	0.119	0.098	0.18	0.061	0.192	0.044	0.103	0.036	0.131
C11	Indenes	0.012	0.009	0.009	0.004	0.012	0	0.002	0.01	0.012	0.005	0.013	0	0	0	0.003
C11	n-Olefins	0.052	0.045	0.042	0.04	0.045	0.055	0.05	0.032	0.03	0.048	0.047	0.044	0.041	0.059	0.049
C12	Paraffin	0.018	0.015	0.014	0.009	0.026	0.002	0.004	0.023	0.03	0.01	0.028	0.001	0.003	0.002	0.004
C12	I-Paraffins	0.04	0.056	0.053	0.053	0.089	0.038	0.035	0.071	0.077	0.05	0.098	0.042	0.076	0.037	0.038
C12	Mono-Aromatics	0.35	0.262	0.25	0.158	0.59	0.181	0.512	0.242	0.581	0.177	0.648	0.175	0.547	0.189	0.583
C12	Naphthalenes	0.02	0.016	0.015	0.075	0.271	0.005	0.27	0.057	0.269	0.085	0.264	0	0.29	0.005	0.273
C12	Naphtheno/Olefino-Benzs	0.139	0.11	0.107	0.043	0.203	0.01	0.116	0.111	0.217	0.053	0.217	0.009	0.121	0.008	0.072

Table 35. Partial listing of DHA data (Wgt%), by carbon within group, for all fuels. Data are summed over all constituents within carbon-group combinations, with summed values only for C_9-C_{12} being displayed. Table rows associated with the same group are color coded to facilitate visual tracking. Values of AKI, EtOH, and PMI associated with each fuel are included, along with mean and median values of PM.

	Median PM	1.75	1.74	1.60	1.77	2.51	5.09	5.17	3.45	7.70	3.10	6.70	4.10	6.70	2.45	6.15
	Mean PM	1.67	1.70	1.30	3.50	6.43	3.84	5.99	4.12	8.59	3.14	7.13	4.23	7.01	3.05	5.92
	AKI	88.20	91.70	92.80	91.50	91.10	96.40	96.00	87.20	87.1	87.90	88.20	93.60	93.70	93.80	94.1
	EtOH	0.00	9.97	14.85	9.44	9.71	9.75	9.88	9.55	9.56	0.00	0.00	9.56	9.51	0.00	0
	PMI	1.30	1.16	1.08	1.28	2.45	1.17	2.32	1.42	2.64	1.42	2.65	1.30	2.55	1.27	2.49
Group	**Carbon**	**CRC_C**	**CRC_E10**	**CRC_E15**	**C_E10**	**D_E10**	**G_E10**	**H_E10**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Paraffin	C9	0.908	0.823	0.784	0.631	0.229	0.306	0.29	0.914	0.871	0.688	0.25	0.749	0.505	0.335	0.313
Paraffin	C10	0.169	0.147	0.141	0.171	0.129	0.019	0.032	0.425	0.445	0.201	0.145	0.372	0.256	0.02	0.048
Paraffin	C11	0.064	0.057	0.054	0.049	0.068	0.033	0.051	0.106	0.089	0.056	0.073	0.063	0.069	0.035	0.053
Paraffin	C12	0.018	0.015	0.014	0.009	0.026	0.002	0.004	0.023	0.03	0.01	0.028	0.001	0.003	0.002	0.004
I-Paraffins	C9	3.353	3.004	2.861	3.286	2.044	2.88	2.633	3.004	2.765	3.641	2.252	3.27	2.424	3.168	2.908
I-Paraffins	C10	1.928	1.681	1.605	1.166	1.076	1.064	0.917	1.463	1.332	1.317	1.173	1.409	1.091	1.163	1.005
I-Paraffins	C11	1.133	0.999	0.953	0.85	0.759	0.975	0.891	0.858	0.873	1.019	0.837	1.083	0.912	1.067	0.941
I-Paraffins	C12	0.04	0.056	0.053	0.053	0.089	0.038	0.035	0.071	0.077	0.05	0.098	0.042	0.076	0.037	0.038
Mono-Aromatics	C9	1.869	1.645	1.571	4.36	8.301	7.667	5.367	4.658	10.002	4.916	9.106	8.487	5.971	8.426	5.875
Mono-Aromatics	C10	2.042	1.856	1.774	2.323	5.08	2.371	5.114	2.295	5.209	2.466	5.539	2.298	5.603	2.589	5.765
Mono-Aromatics	C11	0.662	0.608	0.58	0.469	1.272	0.573	1.507	0.42	1.431	0.524	1.53	0.556	1.611	0.606	1.627
Mono-Aromatics	C12	0.35	0.262	0.25	0.158	0.59	0.181	0.512	0.242	0.581	0.177	0.648	0.175	0.547	0.189	0.583
Naphthalenes	C10	0.15	0.133	0.128	0.141	0.389	0.094	0.366	0.157	0.397	0.159	0.425	0.082	0.415	0.097	0.4
Naphthalenes	C11	0.179	0.155	0.148	0.19	0.636	0.006	0.623	0.21	0.691	0.214	0.694	0.003	0.667	0.005	0.68
Naphthalenes	C12	0.02	0.016	0.015	0.075	0.271	0.005	0.27	0.057	0.269	0.085	0.264	0	0.29	0.005	0.273
Naphtheno/Olefino-Benzs	C9	0.109	0.095	0.09	0.142	0.253	0.165	0.145	0.188	0.315	0.167	0.283	0.206	0.173	0.182	0.159
Naphtheno/Olefino-Benzs	C10	0.461	0.409	0.391	0.354	1.29	0.424	1.34	0.369	1.242	0.399	1.277	0.478	1.451	0.46	1.464
Naphtheno/Olefino-Benzs	C11	0.14	0.114	0.108	0.053	0.174	0.039	0.119	0.098	0.18	0.061	0.192	0.044	0.103	0.036	0.131
Naphtheno/Olefino-Benzs	C12	0.139	0.11	0.107	0.043	0.203	0.01	0.116	0.111	0.217	0.053	0.217	0.009	0.121	0.008	0.072
Indenes	C11	0.012	0.009	0.009	0.004	0.012	0	0.002	0.01	0.012	0.005	0.013	0	0	0	0.003
Mono-Naphthenes	C9	1.229	1.118	1.065	1.465	0.2	0.714	0.516	1.807	1.629	1.648	0.176	1.778	1.105	0.788	0.771
Mono-Naphthenes	C10	0.073	0.051	0.048	0.046	0.022	0.008	0.006	0.162	0.146	0.07	0.014	0.137	0.092	0.006	0.004
n-Olefins	C9	0.053	0.049	0.047	0.073	0.099	0.131	0.119	0.079	0.075	0.085	0.114	0.042	0.036	0.14	0.13
n-Olefins	C10	0.013	0.011	0.011	0.01	0.012	0	0	0.023	0.023	0.012	0.014	0.014	0.009	0	0
n-Olefins	C11	0.052	0.045	0.042	0.04	0.045	0.055	0.05	0.032	0.03	0.048	0.047	0.044	0.041	0.059	0.049
Iso-Olefins	C9	0.107	0.098	0.094	0.169	0.073	0.058	0.06	0.202	0.188	0.158	0.077	0.135	0.097	0.069	0.076
Iso-Olefins	C10	0.159	0.126	0.12	0.11	0.025	0.018	0.017	0.246	0.239	0.137	0.049	0.182	0.12	0.02	0.021
Naphtheno-Olefins	C9	0.042	0.038	0.037	0.055	0.008	0.025	0.025	0.063	0.056	0.062	0.008	0.059	0.133	0.028	0.114
Naphtheno-Olefins	C10	0	0	0	0	0.008	0	0	0	0	0	0	0	0	0	0

Table 36 is a summary listing of the total Wgt% values of each carbon (summed over groups and constituents within groups) associated with of the 15 fuels. The table also contains the values of AKI, EtOH, and PMI plus the mean and median values of PM associated with the respective fuels. The fuels (rows in the table) are presented in order of mean PM, from low to high. Table 37 is a corresponding summary listing with the fuels (rows in the table) presented in order of median PM, from low to high. The information presented in Table 36 and Table 37 is identical except for the low-to-high listing of fuels (rows) based on mean or median PM.

Table 36. Summary listing of the total Wgt% values associated with each carbon number for each of the 15 fuels: the respective values of AKI, EtOH, PMI and the mean and median PM listed row-wise in low-to-high order relative to mean PM.

Fuel	Mean Wtd PM	Median Wtd PM	AKI	EtOH	PMI	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	>C15	C10+
CRC-ETOH15	1.3	1.6	92.8	14.85	1.08	15.25	0.042	2.467	8.36	12.15	19.96	27.63	6.588	4.216	1.896	0.44	0.023	0.014	0	0.972	7.561
CRC-FUELC	1.67	1.74	88.2	0	1.3	0	0.051	3.163	10.13	14.38	23.34	32.22	7.671	4.993	2.243	0.566	0.028	0.016	0	1.207	9.053
CRC-ETOH10	1.7	1.73	91.7	9.97	1.16	9.796	0.046	2.822	9.344	13.01	21.08	29.06	6.909	4.418	1.986	0.461	0.024	0.014	0	1.024	7.927
G	3.05	2.45	93.8	0	1.27	0	0	2.009	16.08	6.921	15.25	39.33	13.13	4.355	1.808	0.242	0.015	0.02	0.004	0.845	7.289
C	3.13	3.1	87.9	0	1.42	0	0.028	3.811	7.195	11.44	16.93	40.4	11.36	4.759	1.928	0.374	0.011	0.007	0.001	1.748	8.828
C-E10	3.50	1.76	91.5	9.44	1.28	9.778	0.02	3.364	6.644	10.52	15.36	36.84	10.24	4.321	1.654	0.339	0.01	0.006	0.001	0.91	7.241
G-E10	3.83	5.09	96.4	9.75	1.17	10.14	0	1.676	14.04	6.194	13.83	35.46	11.95	3.997	1.684	0.236	0.014	0.018	0	0.752	6.701
A	4.12	3.45	87.2	9.55	1.42	9.661	0.002	1.529	9.164	14.89	20.08	25.22	11	5.137	1.734	0.504	0.028	0.015	0.003	1.035	8.456
E	4.24	4.1	93.6	9.56	1.3	9.666	0	0.344	13.2	7.132	13.45	33.24	14.73	4.974	1.792	0.226	0.013	0.008	0	1.222	8.235
H	5.91	6.15	94.1	0	2.49	0	0.001	1.949	15.61	6.006	12.67	39.29	10.37	8.707	3.485	0.971	0.017	0.015	0.003	0.908	14.11
H-E10	5.98	5.17	96	9.88	2.32	10.13	0.001	1.625	13.6	5.355	11.56	35.39	9.156	7.788	3.244	0.936	0.016	0.015	0.002	1.182	13.18
D-E10	6.43	2.51	91.1	9.71	2.45	9.838	0.002	2.076	9.525	15.14	12.1	26.97	11.21	8.033	2.968	1.179	0.048	0.014	0.003	0.893	13.14
F	7.01	6.7	93.7	9.51	2.55	9.703	0	0.323	12.35	8.727	14.86	29.09	10.45	9.039	3.405	1.037	0.02	0	0	1.003	14.5
D	7.12	6.7	88.2	0	2.65	0	0	2.507	10.69	16.96	13.44	29.86	12.27	8.634	3.385	1.255	0.047	0.013	0.003	0.948	14.29
B	8.59	7.7	87.1	9.56	2.64	9.61	0	1.209	9.981	16.58	13.02	18.53	15.98	9.036	3.308	1.173	0.035	0.007	0.002	1.528	15.09

* Mean and median PM are averaged over all vehicles and tests within each fuel. In this table zero is used as a placeholder in cells for which there are no recorded values.

Table 37. Summary listing of the total Wgt% values associated with each carbon number for each of the 15 fuels: the respective values of AKI, EtOH, PMI and mean and median PM, listed row-wise in low-to-high order relative to median PM.

Fuel	Mean Wtd PM	Median Wtd PM	AKI	EtOH	PMI	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	>C15	C10+
CRC-ETOH15	1.3	1.6	92.8	14.85	1.08	15.25	0.042	2.467	8.36	12.15	19.96	27.63	6.588	4.216	1.896	0.44	0.023	0.014	0	0.972	7.561
CRC-ETOH10	1.7	1.73	91.7	9.97	1.16	9.796	0.046	2.822	9.344	13.01	21.08	29.06	6.909	4.418	1.986	0.461	0.024	0.014	0	1.024	7.927
CRC-FUELC	1.67	1.74	88.2	0	1.3	0	0.051	3.163	10.13	14.38	23.34	32.22	7.671	4.993	2.243	0.566	0.028	0.016	0	1.207	9.053
C-E10	3.50	1.76	91.5	9.44	1.28	9.778	0.02	3.364	6.644	10.52	15.36	36.84	10.24	4.321	1.654	0.339	0.01	0.006	0.001	0.91	7.241
G	3.05	2.45	93.8	0	1.27	0	0	2.009	16.08	6.921	15.25	39.33	13.13	4.355	1.808	0.242	0.015	0.02	0.004	0.845	7.289
D-E10	6.43	2.51	91.1	9.71	2.45	9.838	0.002	2.076	9.525	15.14	12.1	26.97	11.21	8.033	2.968	1.179	0.048	0.014	0.003	0.893	13.14
C	3.13	3.1	87.9	0	1.42	0	0.028	3.811	7.195	11.44	16.93	40.4	11.36	4.759	1.928	0.374	0.011	0.007	0.001	1.748	8.828
A	4.12	3.45	87.2	9.55	1.42	9.661	0.002	1.529	9.164	14.89	20.08	25.22	11	5.137	1.734	0.504	0.028	0.015	0.003	1.035	8.456
E	4.24	4.1	93.6	9.56	1.3	9.666	0	0.344	13.2	7.132	13.45	33.24	14.73	4.974	1.792	0.226	0.013	0.008	0	1.222	8.235
G-E10	3.83	5.09	96.4	9.75	1.17	10.14	0	1.676	14.04	6.194	13.83	35.46	11.95	3.997	1.684	0.236	0.014	0.018	0	0.752	6.701
H-E10	5.98	5.17	96	9.88	2.32	10.13	0.001	1.625	13.6	5.355	11.56	35.39	9.156	7.788	3.244	0.936	0.016	0.015	0.002	1.182	13.18
H	5.91	6.15	94.1	0	2.49	0	0.001	1.949	15.61	6.006	12.67	39.29	10.37	8.707	3.485	0.971	0.017	0.015	0.003	0.908	14.11
F	7.01	6.7	93.7	9.51	2.55	9.703	0	0.323	12.35	8.727	14.86	29.09	10.45	9.039	3.405	1.037	0.02	0	0	1.003	14.5
D	7.12	6.7	88.2	0	2.65	0	0	2.507	10.69	16.96	13.44	29.86	12.27	8.634	3.385	1.255	0.047	0.013	0.003	0.948	14.29
B	8.59	7.7	87.1	9.56	2.64	9.61	0	1.209	9.981	16.58	13.02	18.53	15.98	9.036	3.308	1.173	0.035	0.007	0.002	1.528	15.09

* Mean and median PM are averaged over all vehicles and tests within each fuel. In this table zero is used as a placeholder in cells for which there are no recorded values.

Similar to Table 36, Table 38 is a summary listing of the total Wgt% values of each group (summed over carbons and constituents within carbons) associated with of the 15 fuels. The table also contains the values of AKI, EtOH, and PMI plus the mean and median values of PM associated with the respective fuels. The fuels (rows in the table) are presented in order of mean PM, from low to high. Table 39 is the corresponding summary listing with the fuels (rows in the table) presented in order of median PM, from low to high. The information presented in Tables 38 and Table 39 is identical except for the low-to-high listing of fuels (rows) based on mean or median PM.

Table 38. Summary listing of the total Wgt% values associated with each group for each of the 15 fuels: the respective values of AKI, EtOH, PMI and mean and median PM listed row-wise in low-to-high order relative to mean PM.

Fuel	Mean Wt PM	Median Wt PM	AKI	EtOH	PMI	Paraffin	I-Paraffins	Mono-Aromatics	Naphthalenes	Naphtheno/Olefino-Benzs	Indenes	Mono-Naphthenes	n-Olefins	Iso-Olefins	Naphtheno-Olefins	Di-Olefins	Oxygenates
CRC-ETOH15	1.3	1.6	92.8	14.85	1.08	6.564	36.747	28.774	0.291	0.696	0.009	4.879	4.328	1.199	0.157	0	15.376
CRC-FUELC	1.67	1.74	88.2	0	1.3	7.89	43.473	33.673	0.349	0.849	0.012	5.582	5.168	1.456	0.181	0	0.157
CRC-ETOH10	1.7	1.73	91.7	9.97	1.16	7.154	39.239	30.238	0.304	0.728	0.009	5.107	4.656	1.439	0.168	0	9.937
G	3.05	2.45	93.8	0	1.27	4.173	53.238	30.826	0.107	0.686	0	4.686	0.206	5.212	0.028	0	0
C	3.13	3.1	87.9	0	1.42	9.104	48.02	28.809	0.458	0.68	0.005	5.844	2.83	2.231	0.273	0	0
C-E10	3.50	1.76	91.5	9.44	1.28	8.19	43.666	25.955	0.406	0.592	0.004	5.629	2.587	2.038	0.245	0	9.778
G-E10	3.83	5.09	96.4	9.75	1.17	3.695	47.526	27.984	0.105	0.638	0	4.205	0.19	4.706	0.049	0	10.141
A	4.12	3.45	87.2	9.55	1.42	9.803	34.675	30.525	0.424	0.766	0.01	8.084	1.927	2.722	0.365	0	9.661
E	4.24	4.1	93.6	9.56	1.3	3.971	39.744	31.777	0.085	0.737	0	6.671	0.173	5.891	0.059	0	9.666
H-E10	5.91	6.15	94.1	0	2.49	3.396	46.983	26.521	1.259	1.72	0.002	3.862	0.174	4.571	0.206	0	10.128
H	5.91	6.15	94.1	0	2.49	3.848	52.83	29.19	1.353	1.826	0.003	4.686	0.181	5.055	0.114	0	0
D-E10	6.43	2.51	91.1	9.71	2.45	8.364	44.247	25.173	1.296	1.92	0.012	3.733	2.445	1.81	0.268	0	9.838
F	7.01	6.7	93.7	9.51	2.55	5.838	38.156	31.976	1.372	1.848	0	4.054	0.104	5.781	0.147	0.008	9.703
D	7.12	6.7	88.2	0	2.65	9.441	49.393	27.795	1.383	1.969	0.013	4.084	2.762	1.931	0.29	0	0
B	8.59	7.7	87.1	9.56	2.64	10.056	34.903	27.953	1.357	1.954	0.012	7.821	1.769	2.641	0.379	0	9.61

* Mean and median PM are averaged over all vehicles and tests within each fuel. In this table zero is used as a placeholder in cells for which there are no recorded values.

Table 39. Summary listing of the total Wgt% values associated with each group for each of the 15 fuels: the respective values of AKI, EtOH, PMI and mean and median PM listed row-wise in low-to-high order relative to median PM.

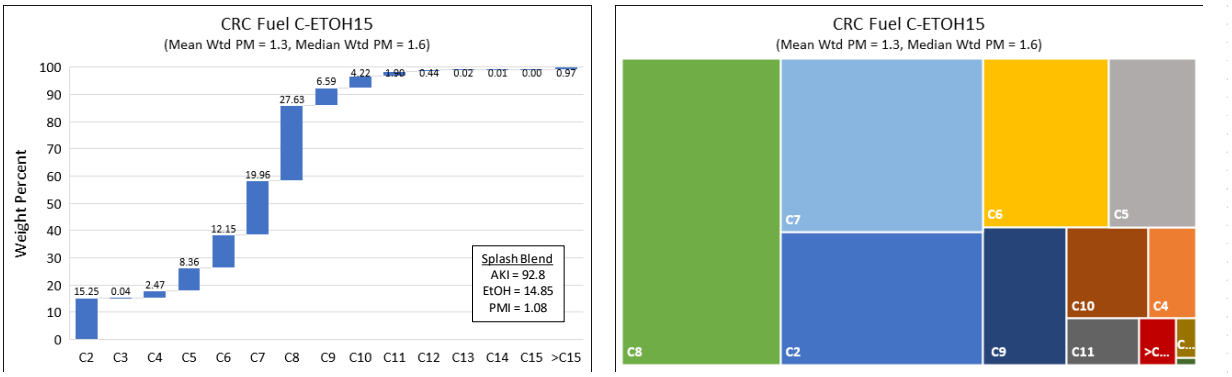
Fuel	Mean Wt PM	Median Wt PM	AKI	EtOH	PMI	Paraffin	I-Paraffins	Mono-Aromatics	Naphthalenes	Naphtheno/Olefino-Benzs	Indenes	Mono-Naphthenes	n-Olefins	Iso-Olefins	Naphtheno-Olefins	Di-Olefins	Oxygenates
CRC-ETOH15	1.3	1.6	92.8	14.85	1.08	6.564	36.747	28.774	0.291	0.696	0.009	4.879	4.328	1.199	0.157	0	15.376
CRC-ETOH10	1.7	1.73	91.7	9.97	1.16	7.154	39.239	30.238	0.304	0.728	0.009	5.107	4.656	1.439	0.168	0	9.937
CRC-FUELC	1.67	1.74	88.2	0	1.3	7.89	43.473	33.673	0.349	0.849	0.012	5.582	5.168	1.456	0.181	0	0.157
C-E10	3.50	1.76	91.5	9.44	1.28	8.19	43.666	25.955	0.406	0.592	0.004	5.629	2.587	2.038	0.245	0	9.778
G	3.05	2.45	93.8	0	1.27	4.173	53.238	30.826	0.107	0.686	0	4.686	0.206	5.212	0.028	0	0
D-E10	6.43	2.51	91.1	9.71	2.45	8.364	44.247	25.173	1.296	1.92	0.012	3.733	2.445	1.81	0.268	0	9.838
C	3.13	3.1	87.9	0	1.42	9.104	48.02	28.809	0.458	0.68	0.005	5.844	2.83	2.231	0.273	0	0
A	4.12	3.45	87.2	9.55	1.42	9.803	34.675	30.525	0.424	0.766	0.01	8.084	1.927	2.722	0.365	0	9.661
E	4.24	4.1	93.6	9.56	1.3	3.971	39.744	31.777	0.085	0.737	0	6.671	0.173	5.891	0.059	0	9.666
G-E10	3.83	5.09	96.4	9.75	1.17	3.695	47.526	27.984	0.105	0.638	0	4.205	0.19	4.706	0.049	0	10.141
H-E10	5.91	6.15	94.1	0	2.49	3.396	46.983	26.521	1.259	1.72	0.002	3.862	0.174	4.571	0.206	0	10.128
H	5.91	6.15	94.1	0	2.49	3.848	52.83	29.19	1.353	1.826	0.003	4.686	0.181	5.055	0.114	0	0
F	7.01	6.7	93.7	9.51	2.55	5.838	38.156	31.976	1.372	1.848	0	4.054	0.104	5.781	0.147	0.008	9.703
D	7.12	6.7	88.2	0	2.65	9.441	49.393	27.795	1.383	1.969	0.013	4.084	2.762	1.931	0.29	0	0
B	8.59	7.7	87.1	9.56	2.64	10.056	34.903	27.953	1.357	1.954	0.012	7.821	1.769	2.641	0.379	0	9.61

* Mean and median PM are averaged over all vehicles and tests within each fuel. In this table zero is used as a placeholder in cells for which there are no recorded values.

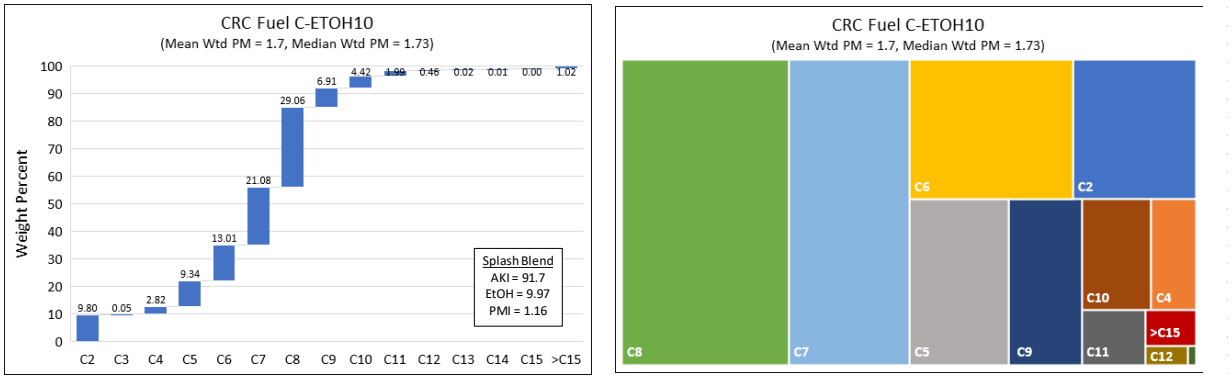
Figure 20 (A-O) presents the compositional makeup (Wgt%) of all 15 fuels on a carbon number basis (C_2-C_{15} and $>C_{15}$) derived from the DHA results (information presented in Table 36 and Table 37). In each case (A-O), the left side of the figure is a waterfall plot and the right side of the figure is a corresponding tree map. The waterfall plots and the tree maps present the same information from different perspectives and include the values of AKI, EtOH, and PMI, plus the mean and median values of PM associated with each respective fuel. The graphs associated with the respective fuels are presented in order of median PM, from low to high; that is, Figure 20 A (top) represents Fuel ETOH15 which has the lower median PM, and Figure 20 O (bottom) represents Fuel B which has the highest median PM.

Figure 20 illustrates that all the fuels except for Fuel B are dominated by C_8 and that the second and third most important carbons in terms of Wgt% vary from one fuel to the next. For example, for the three fuels from the E-129 program, C_7 is always the second most important carbon on a Wgt% basis, whereas this is not necessarily the case for the fuels from the E-94-2 and E-94-3 programs. On the basis of Figure 20 there do not appear to be any other discernable trends in the compositional makeup of the 15 fuels beyond these observations, except to note, as expected, that C_2 is present only when EtOH>0 and C_3, C_4, and C_{11+} are relatively miniscule in all fuels.

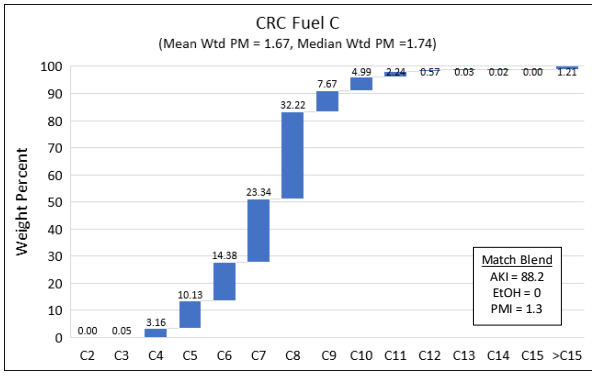
(A)

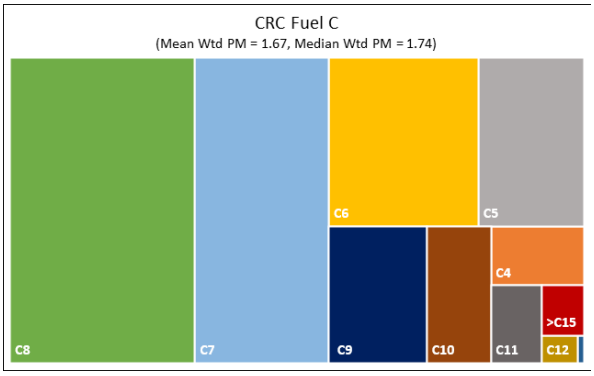


(B)

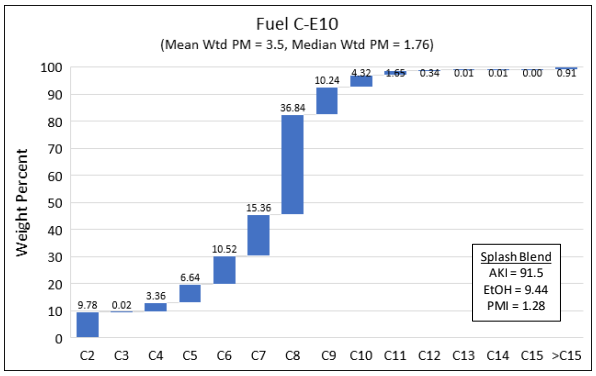


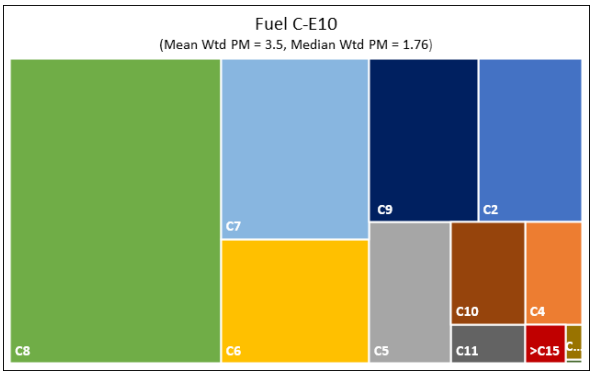
(C)


CRC Fuel C
(Mean Wtd PM = 1.67, Median Wtd PM =1.74)
Weight Percent
0.00 0.05 3.16 10.13 14.38 23.34 32.22 7.67 4.99 2.24 0.57 0.03 0.02 0.00 1.21
C2 C3 C4 C5 C6 C7 C8 C9 C10 C11 C12 C13 C14 C15 >C15
Match Blend
AKI = 88.2
EtOH = 0
PMI = 1.3

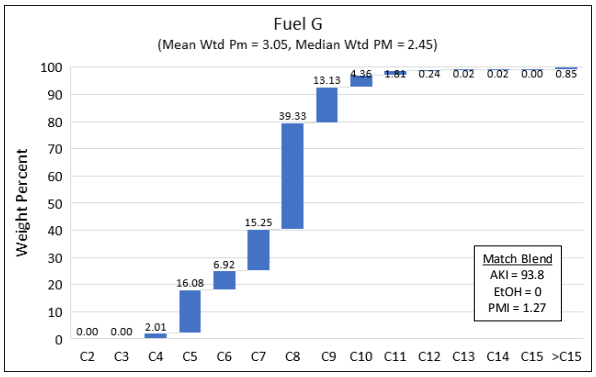

CRC Fuel C
(Mean Wtd PM = 1.67, Median Wtd PM = 1.74)
C8
C7
C6
C5
C9
C10
C11
C4
>C15
C12

(D)


Fuel C-E10
(Mean Wtd PM = 3.5, Median Wtd PM = 1.76)
Weight Percent
9.78 0.02 3.36 6.64 10.52 15.36 36.84 10.24 4.32 1.65 0.34 0.01 0.01 0.00 0.91
C2 C3 C4 C5 C6 C7 C8 C9 C10 C11 C12 C13 C14 C15 >C15
Splash Blend
AKI = 91.5
EtOH = 9.44
PMI = 1.28


Fuel C-E10
(Mean Wtd PM = 3.5, Median Wtd PM = 1.76)
C8
C6
C7
C5
C9
C2
C10
C4
C11
>C15

(E)


Fuel G
(Mean Wtd Pm = 3.05, Median Wtd PM = 2.45)
Weight Percent
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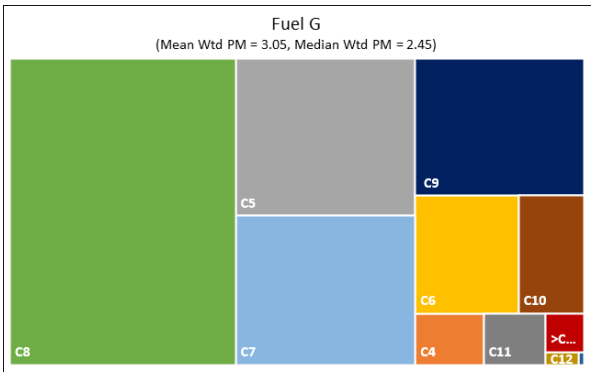
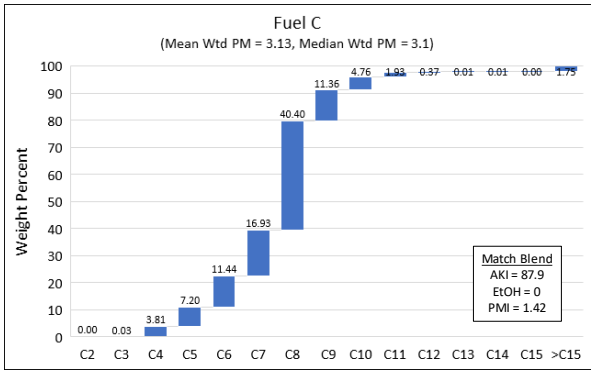
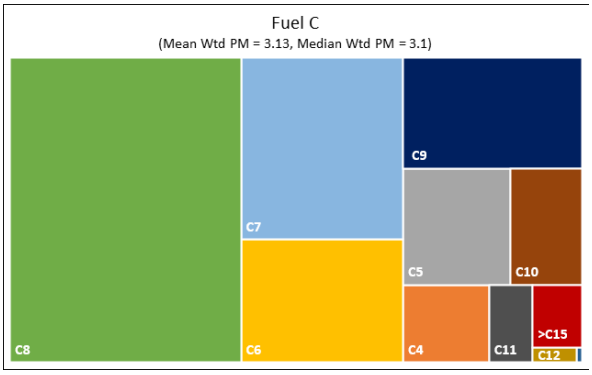
C2 C3 C4 C5 C6 C7 C8 C9 C10 C11 C12 C13 C14 C15 >C15
Match Blend
AKI = 93.8
EtOH = 0
PMI = 1.27

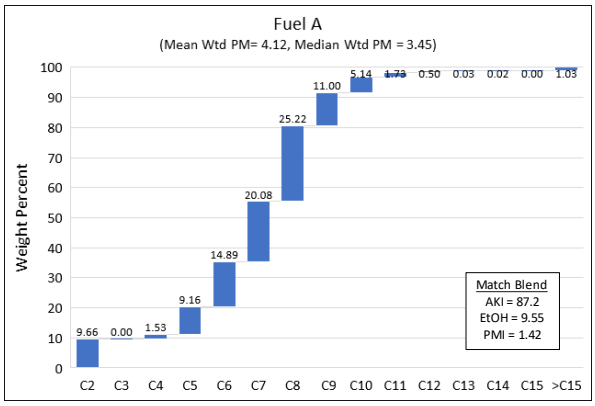

Fuel G
(Mean Wtd PM = 3.05, Median Wtd PM = 2.45)
C8
C7
C5
C9
C6
C10
C4
C11
>C...
C12

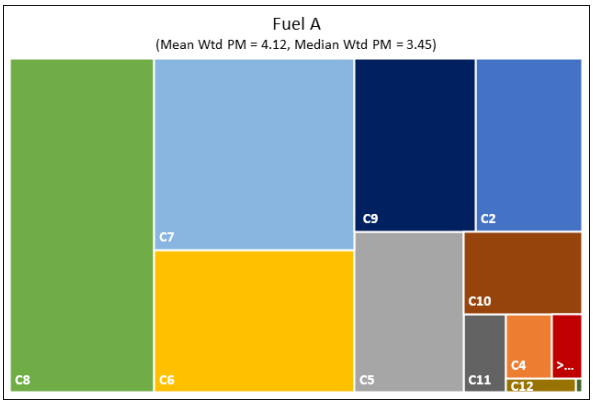
(F)


Fuel C
(Mean Wtd PM = 3.13, Median Wtd PM = 3.1)
Weight Percent
0.00 0.03 3.81 7.20 11.44 16.93 40.40 11.36 4.76 1.93 0.37 0.01 0.01 0.00 1.75
C2 C3 C4 C5 C6 C7 C8 C9 C10 C11 C12 C13 C14 C15 >C15
Match Blend
AKI = 87.9
EtOH = 0
PMI = 1.42

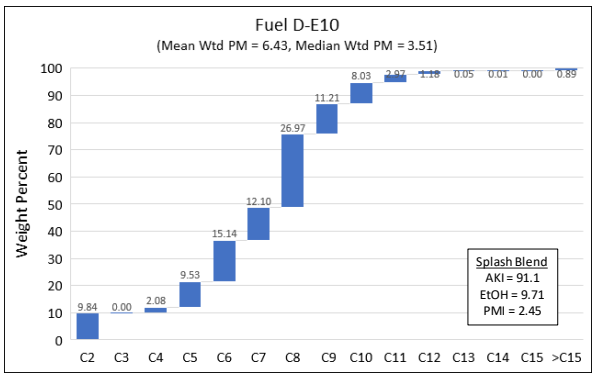

Fuel C
(Mean Wtd PM = 3.13, Median Wtd PM = 3.1)
C8
C6
C7
C9
C5
C10
C4
C11
>C15
C12

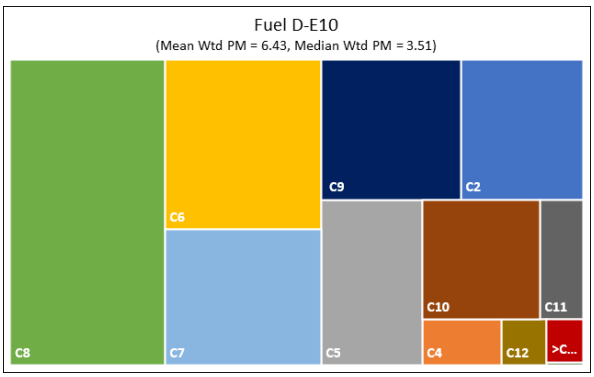
(G)


Fuel A
(Mean Wtd PM= 4.12, Median Wtd PM = 3.45)
Weight Percent
9.66 0.00 1.53 9.16 14.89 20.08 25.22 11.00 5.14 1.73 0.50 0.03 0.02 0.00 1.03
C2 C3 C4 C5 C6 C7 C8 C9 C10 C11 C12 C13 C14 C15 >C15
Match Blend
AKI = 87.2
EtOH = 9.55
PMI = 1.42

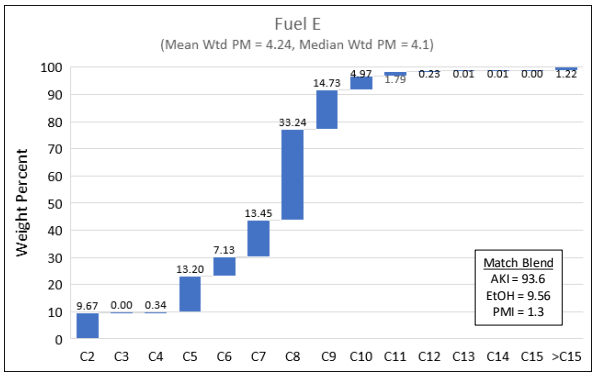

Fuel A
(Mean Wtd PM = 4.12, Median Wtd PM = 3.45)
C8
C6
C7
C9
C2
C5
C10
C11
C4
>...
C12

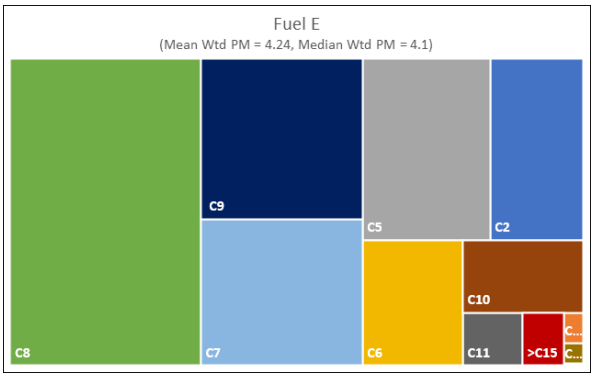
(H)


Fuel D-E10
(Mean Wtd PM = 6.43, Median Wtd PM = 3.51)
Weight Percent
9.84 0.00 2.08 9.53 15.14 12.10 26.97 11.21 8.03 2.97 1.18 0.05 0.01 0.00 0.89
C2 C3 C4 C5 C6 C7 C8 C9 C10 C11 C12 C13 C14 C15 >C15
Splash Blend
AKI = 91.1
EtOH = 9.71
PMI = 2.45

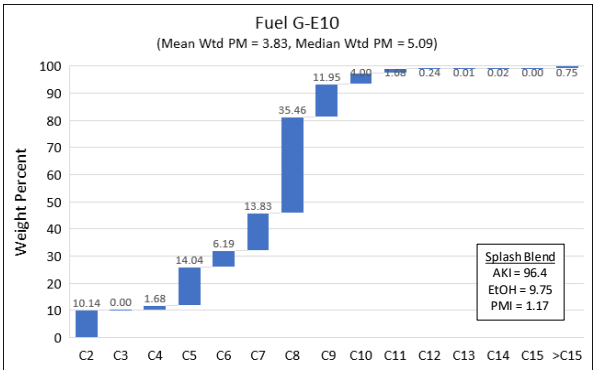

Fuel D-E10
(Mean Wtd PM = 6.43, Median Wtd PM = 3.51)
C8
C6
C7
C9
C2
C5
C10
C11
C4
C12
>C...

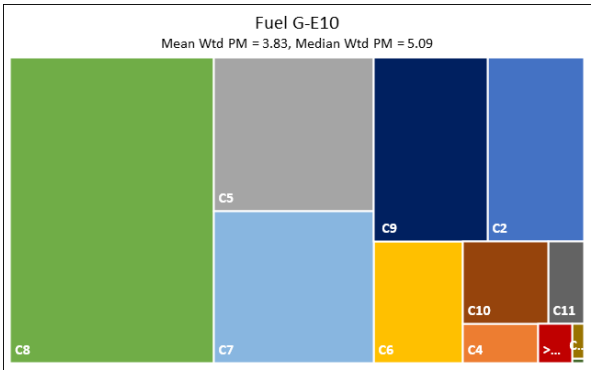
(I)


Fuel E
(Mean Wtd PM = 4.24, Median Wtd PM = 4.1)
Weight Percent
100
90
80
70
60
50
40
30
20
10
0
9.67
0.00
0.34
13.20
7.13
13.45
33.24
14.73
4.97
1.79
0.23
0.01
0.01
0.00
1.22
C2 C3 C4 C5 C6 C7 C8 C9 C10 C11 C12 C13 C14 C15 >C15
Match Blend
AKI = 93.6
EtOH = 9.56
PMI = 1.3

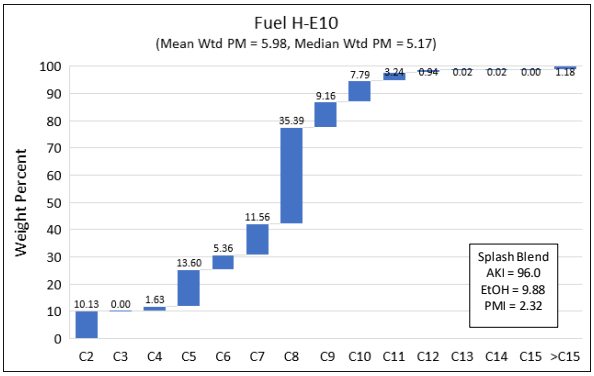

Fuel E
(Mean Wtd PM = 4.24, Median Wtd PM = 4.1)
C8
C9
C7
C5
C6
C2
C10
C11
>C15

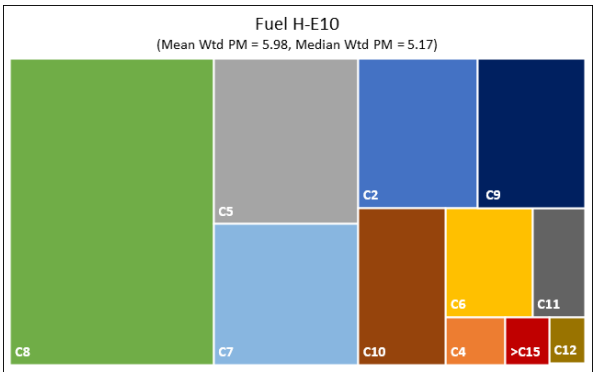
(J)


Fuel G-E10
(Mean Wtd PM = 3.83, Median Wtd PM = 5.09)
Weight Percent
100
90
80
70
60
50
40
30
20
10
0
10.14
0.00
1.68
14.04
6.19
13.83
35.46
11.95
4.00
1.68
0.24
0.01
0.02
0.00
0.75
C2 C3 C4 C5 C6 C7 C8 C9 C10 C11 C12 C13 C14 C15 >C15
Splash Blend
AKI = 96.4
EtOH = 9.75
PMI = 1.17

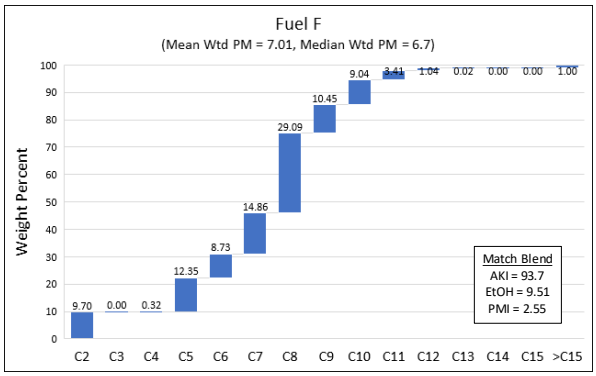

Fuel G-E10
Mean Wtd PM = 3.83, Median Wtd PM = 5.09
C8
C5
C7
C9
C6
C2
C10
C11
C4
>...

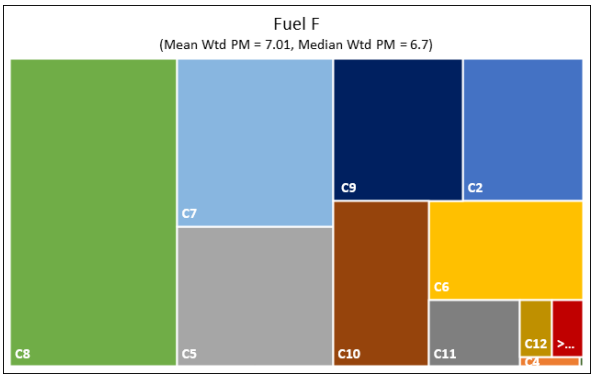
(K)


Fuel H-E10
(Mean Wtd PM = 5.98, Median Wtd PM = 5.17)
Weight Percent
100
90
80
70
60
50
40
30
20
10
0
10.13
0.00
1.63
13.60
5.36
11.56
35.39
9.16
7.79
3.24
0.94
0.02
0.02
0.00
1.18
C2 C3 C4 C5 C6 C7 C8 C9 C10 C11 C12 C13 C14 C15 >C15
Splash Blend
AKI = 96.0
EtOH = 9.88
PMI = 2.32

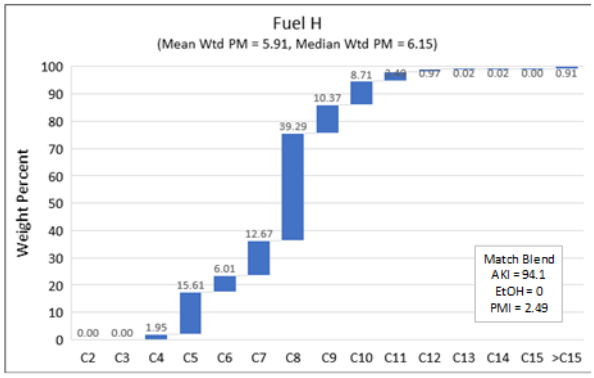

Fuel H-E10
(Mean Wtd PM = 5.98, Median Wtd PM = 5.17)
C8
C5
C2
C9
C7
C10
C6
C11
C4
>C15
C12

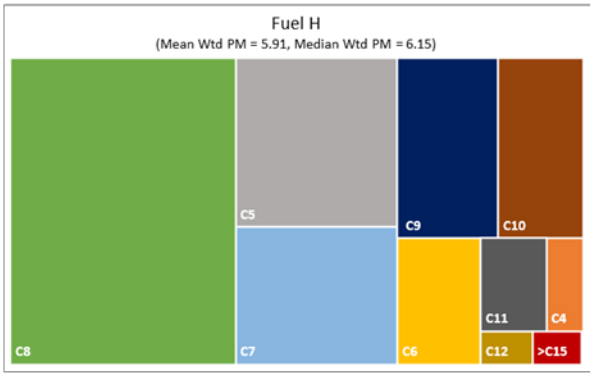
(L)


Fuel F
(Mean Wtd PM = 7.01, Median Wtd PM = 6.7)
Weight Percent
9.70 0.00 0.32 12.35 8.73 14.86 29.09 10.45 9.04 3.41 1.04 0.02 0.00 0.00 1.00
C2 C3 C4 C5 C6 C7 C8 C9 C10 C11 C12 C13 C14 C15 >C15
Match Blend
AKI = 93.7
EtOH = 9.51
PMI = 2.55

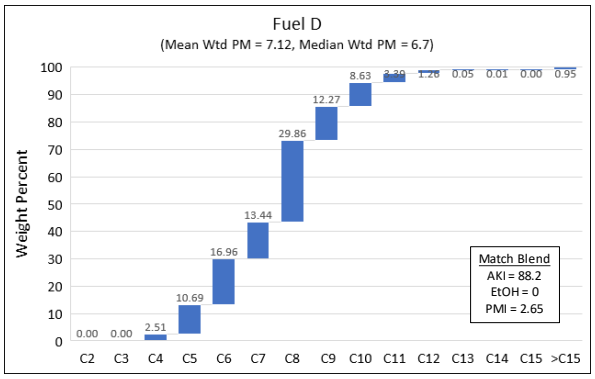

Fuel F
(Mean Wtd PM = 7.01, Median Wtd PM = 6.7)
C8
C7
C5
C9
C2
C10
C6
C11
C12
>...

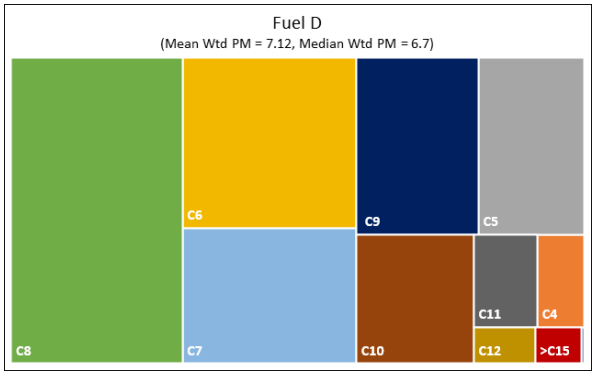
(M)


Fuel H
(Mean Wtd PM = 5.91, Median Wtd PM = 6.15)
Weight Percent
0.00 0.00 1.95 15.61 6.01 12.67 39.29 10.37 8.71 0.97 0.02 0.02 0.00 0.91
C2 C3 C4 C5 C6 C7 C8 C9 C10 C11 C12 C13 C14 C15 >C15
Match Blend
AKI = 94.1
EtOH = 0
PMI = 2.49


Fuel H
(Mean Wtd PM = 5.91, Median Wtd PM = 6.15)
C8
C5
C7
C9
C10
C6
C11
C12
C4
>C15

(N)


Fuel D
(Mean Wtd PM = 7.12, Median Wtd PM = 6.7)
Weight Percent
0.00 0.00 2.51 10.69 16.96 13.44 29.86 12.27 8.63 1.26 0.05 0.01 0.00 0.95
C2 C3 C4 C5 C6 C7 C8 C9 C10 C11 C12 C13 C14 C15 >C15
Match Blend
AKI = 88.2
EtOH = 0
PMI = 2.65


Fuel D
(Mean Wtd PM = 7.12, Median Wtd PM = 6.7)
C8
C6
C7
C9
C5
C10
C11
C12
C4
>C15

(O)

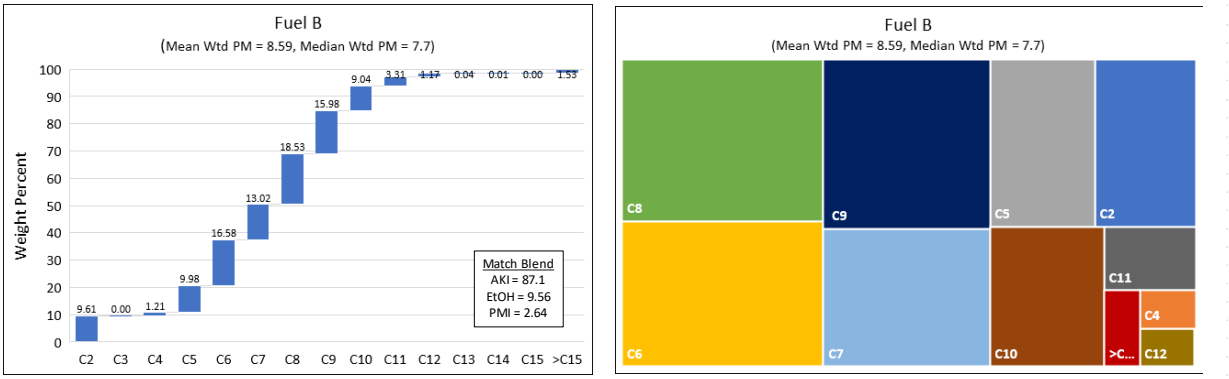


Figure 20. Waterfall graphs (left) and tree maps (right) demonstrating the compositional makeup of each respective fuel on a carbon number basis, presented in order of the median values of PM associated with the respective fuels, from low to high.

In an effort to investigate linkages and relationships among the 15 fuels, Table 40 contains pairwise correlations between their total Wgt% values on a carbon number basis; the respective values of AKI, EtOH, PMI; mean PM and median PM shown in Tables 36 and Table 37. In this perspective there are only 15 observations on which to base the correlations, since Table 34 and Table 37 contain 15 rows (15 fuels).[14] The colored cells identify all pairwise correlations exceeding 0.5 in absolute value, with positive values indicated in red and negative values indicated in blue.

Both mean and median PM are positively correlated with PMI but are uncorrelated with AKI and EtOH. Both are also positively correlated with C_9-C_{12}. As expected, EtOH is perfectly correlated with C_2. PMI is highly positively correlated with C_{10}-C_{12}, and moderately positively correlated with C_{13}. There are strong mutually positive correlations among C_{10}, C_{11}, and C_{12}, suggesting the existence of some interplay or multicollinearity among them. Positive correlations exist among a few other carbon number pairs (e.g., C_{12} vs C_{13}) but they do not appear to have immediate explanatory value. In general, the negative correlations (blue cells) are not as strong as the positive ones (red cells). Most notable is the consistent negative correlations between C_7 and C_9-C_{11}. Finally, mean and median PM are moderately negatively correlated with C_3, C_4, and C_7, and AKI is moderately positively correlated with C_5, but negatively correlated with C_6 and C_{13}. Collectively these observations may be useful in further delineating the relative performance of the fuels with regard to PM.

[14] The number of observations is limited to one per fuel because there is only one detailed hydrocarbon analysis per fuel.

Table 40. Pairwise correlations between total Wgt% values of carbons, AKI, EtOH, PMI, and mean and median PM for the 15 fuels. Colored cells indicate pairwise correlations exceeding 0.5 in absolute value. Positive values are shown in red and negative correlations are shown in blue.

	Mean Wtd PM	Median Wtd PM	AKI	EtOH	PMI	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
Mean Wtd PM	1																		
Median Wtd PM	0.86	1																	
AKI	-0.08	0.04	1																
EtOH	-0.01	-0.10	0.27	1															
PMI	0.92	0.77	-0.10	-0.14	1														
C2	-0.01	-0.10	0.28	1.00	-0.14	1													
C3	-0.77	-0.69	-0.26	0.01	-0.56	0.00	1												
C4	-0.53	-0.58	-0.37	-0.38	-0.36	-0.38	0.67	1											
C5	0.24	0.42	0.65	-0.26	0.21	-0.26	-0.55	-0.56	1										
C6	0.12	-0.07	-0.87	0.00	0.17	-0.01	0.29	0.30	-0.68	1									
C7	-0.76	-0.63	-0.40	-0.01	-0.64	-0.02	0.83	0.45	-0.45	0.36	1								
C8	-0.36	-0.23	0.46	-0.52	-0.30	-0.51	0.02	0.35	0.35	-0.70	-0.13	1							
C9	0.60	0.56	-0.14	-0.15	0.32	-0.15	-0.74	-0.47	0.29	0.00	-0.62	-0.12	1						
C10	0.90	0.78	-0.09	-0.11	0.99	-0.12	-0.53	-0.42	0.23	0.16	-0.58	-0.34	0.29	1					
C11	0.81	0.73	-0.01	-0.17	0.96	-0.17	-0.40	-0.32	0.27	0.11	-0.53	-0.26	0.14	0.97	1				
C12	0.82	0.63	-0.23	-0.07	0.95	-0.08	-0.36	-0.23	0.04	0.39	-0.44	-0.46	0.13	0.95	0.94	1			
C13	0.44	0.19	-0.51	-0.02	0.53	-0.03	-0.09	-0.02	-0.22	0.79	-0.05	-0.68	0.08	0.51	0.48	0.71	1		
C14	-0.37	-0.31	0.20	-0.22	-0.29	-0.22	0.08	0.22	0.39	-0.11	0.17	0.20	-0.22	-0.32	-0.23	-0.22	0.12	1	
C15	0.43	0.21	-0.18	-0.41	0.45	-0.41	-0.56	-0.01	0.28	0.12	-0.40	0.04	0.37	0.38	0.33	0.39	0.37	0.38	1

*Mean and median weighted PM are averaged over vehicles and tests within fuels

Similar to Table 40, Table 41 contains pairwise correlations between the total Wgt% values for the 15 fuels on a group basis; the respective values of AKI, EtOH, PMI; mean PM and median PM shown in Table 38 and Table 39. In this perspective there are only 15 observations on which to base the correlations, since Tables 38 and Table 39 contain 15 rows (15 fuels). The colored cells identify all pairwise correlations exceeding 0.5 in absolute value, with positive values indicated in red and negative values indicated in blue.

There are not as many correlations exceeding 0.5 in absolute value in Table 41 as there are in Table 40. Most notably, mean and median PM are moderately to strongly positively correlated with Naphthalenes and Naphtheno/Olefino-Benzs, as is PMI. Naphthalenes and Naptheno/Olefino-Benzs are themselves highly positively correlated, as anticipated. Paraffin is moderately positively correlated with Indenes, n-Olefins, and Naptheno-Olefins and Indenes themselves are moderately positively correlated with both n-Olefins and Naptheno-Olefins, indicating the likely existence of multicollinearity among these groups. EtOH is positively correlated with Oxygenates as anticipated.

AKI is strongly negatively correlated with Paraffin, and moderately negatively correlated with Indenes, Mono-Naphthenes, n-Olefins, and Naptheno-Olefins. Similarly, EtOH is moderately negatively correlated with I-Paraffins. In addition, I-Paraffins themselves are moderately negatively correlated with Mono-Naphthenes and Oxygenates. Further, Indenes and n-Olefins are strongly correlated with Iso-Olefins.

Table 41. Pairwise correlations between total Wgt% values of DHA groups, AKI, EtOH, PMI, and mean and median PM for the 15 fuels. Colored cells indicate pairwise correlations exceeding 0.5 in absolute value. Positive values are shown in red and negative correlations are shown in blue.

	Mean Wtd PM	Median Wtd PM	AKI	EtOH	PMI	Paraffin	I-Paraffins	Mono-Aromatics	Naphthalenes	Naphtheno/ Olefino-Olefino-Benzs	Indenes	Mono-Naphthenes	n-Olefins	Iso-Olefins	Naphtheno-Olefins	Di-Olefins	Oxygenates
Mean Wtd PM	1																
Median Wtd PM	0.86	1															
AKI	-0.11	0.04	1														
EtOH	-0.10	-0.20	0.13	1													
PMI	0.92	0.78	-0.12	-0.27	1												
Paraffin	0.12	-0.12	-0.92	0.14	0.10	1											
I-Paraffins	0.01	0.06	0.33	-0.76	0.11	-0.42	1										
Mono-Aromatics	-0.36	-0.12	-0.05	-0.12	-0.33	-0.14	-0.19	1									
Naphthalenes	0.86	0.71	-0.16	-0.22	0.98	0.18	0.07	-0.37	1								
Naphtheno/Olefino-Benzs	0.88	0.74	-0.10	-0.21	0.99	0.10	0.08	-0.31	0.97	1							
Indenes	0.07	-0.14	-0.78	0.08	0.18	0.81	-0.34	-0.14	0.26	0.25	1						
Mono-Naphthenes	-0.04	-0.03	-0.59	0.24	-0.25	0.47	-0.58	0.28	-0.27	-0.29	0.25	1					
n-Olefins	-0.53	-0.60	-0.56	0.13	-0.35	0.61	-0.31	0.09	-0.22	-0.28	0.75	0.13	1				
Iso-Olefins	0.32	0.49	0.65	-0.16	0.19	-0.76	0.28	0.26	0.06	0.13	-0.85	-0.14	-0.92	1			
Naphtheno-Olefins	0.39	0.17	-0.84	0.06	0.38	0.87	-0.42	-0.36	0.45	0.34	0.72	0.46	0.36	-0.60	1		
Di-Olefins	0.31	0.34	0.21	0.18	0.33	-0.11	-0.24	0.33	0.34	0.31	-0.33	-0.24	-0.29	0.40	-0.12	1	
Oxygenates	-0.02	-0.08	0.27	0.88	-0.13	-0.05	-0.71	-0.27	-0.09	-0.10	-0.03	0.10	0.00	-0.06	0.07	0.15	1

*Mean and median weighted PM are averaged over vehicles and tests within fuels

Using the correlations presented in Table 40 as initial guidance, an investigation was undertaken to determine whether carbon numbers, in terms of total Wgt%, could be used to predict mean and median PM. A progressive series of multiple regression analyses[15] were conducted to test the efficacy of this idea.

Table 42 (A,B) contains the results of the first model (henceforth referred to as the full carbon model) which uses C_4-C_{13} as predictors of mean and median PM, respectively. Cells colored in blue indicate statistical significance. In the case of Table 42 A, the model using C_4-C_{13} as predictors of mean PM is significant overall, but only C_{12} is a statistically significant predictor, suggesting a more parsimonious model might be constructed. In the case of Table 10B, the model is not significant overall and none of the C_4-C_{13} carbon numbers are statistically significant.

An extensive refinement of the full carbon model represented in Table 42 (A,B) resulted in the most parsimonious model possible (henceforth referred to as the small model), the results of which are shown in Table 43 (A,B). In this case, C_9 and C_{10+} are shown to be statistically significant for predicting both mean and median PM, and the model is highly significant overall. The results shown in Table 43 (A,B) suggest that, despite the larger impact of C_8 in the overall composition of all the fuels (see Figure 1), C_9 and the compositive variable C_{10+} are more predictive of the "average value" of PM.

[15] In this case, the multiple regression approach available in Excel was used. Multiple regression is applied to the data presented in Table 36 and Table 37, hence, there are only 15 observations (rows or fuels).

Table 42. Results of using multiple regression analysis to predict mean PM (A, top) and median PM (B, bottom) with the total Wgt% values of C_4-C_{13} as explanatory variables.

(A) Mean PM

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	1.00							
R Square	0.99							
Adjusted R Square	0.98							
Standard Error	0.35							
Observations	15							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	10	69.02	6.90	57.15	0.0007			
Residual	4	0.48	0.12					
Total	14	69.50						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	3.09	2.09	1.48	0.21	-2.72	8.90	-2.72	8.90
C4	-1.06	0.58	-1.83	0.14	-2.65	0.54	-2.65	0.54
C5	0.21	0.18	1.16	0.31	-0.30	0.72	-0.30	0.72
C6	0.42	0.37	1.15	0.32	-0.60	1.44	-0.60	1.44
C7	-0.19	0.19	-1.03	0.36	-0.71	0.33	-0.71	0.33
C8	0.10	0.08	1.29	0.27	-0.12	0.32	-0.12	0.32
C9	0.19	0.23	0.82	0.46	-0.45	0.82	-0.45	0.82
C10	-0.87	0.90	-0.97	0.39	-3.36	1.63	-3.36	1.63
C11	-2.54	1.28	-1.98	0.12	-6.08	1.01	-6.08	1.01
C12	15.53	5.51	2.82	0.05	0.24	30.82	0.24	30.82
C13	-191.12	76.11	-2.51	0.07	-402.42	20.19	-402.42	20.19

*Median and mean PM are averaged over all vehicles and tests within each fuel.

(B) Median PM

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.94							
R Square	0.87							
Adjusted R Square	0.56							
Standard Error	1.40							
Observations	15							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	10	54.40	5.44	2.79	0.17			
Residual	4	7.81	1.95					
Total	14	62.20						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-1.35	8.42	-0.16	0.88	-24.72	22.01	-24.72	22.01
C4	-2.61	2.31	-1.13	0.32	-9.04	3.81	-9.04	3.81
C5	0.68	0.74	0.92	0.41	-1.37	2.74	-1.37	2.74
C6	1.59	1.47	1.08	0.34	-2.51	5.68	-2.51	5.68
C7	-0.54	0.75	-0.72	0.51	-2.62	1.53	-2.62	1.53
C8	0.24	0.32	0.75	0.49	-0.64	1.11	-0.64	1.11
C9	-0.20	0.92	-0.21	0.84	-2.75	2.36	-2.75	2.36
C10	-2.94	3.61	-0.81	0.46	-12.97	7.10	-12.97	7.10
C11	3.19	5.14	0.62	0.57	-11.07	17.45	-11.07	17.45
C12	13.28	22.14	0.60	0.58	-48.18	74.74	-48.18	74.74
C13	-416.29	305.92	-1.36	0.25	-1265.66	433.08	-1265.66	433.08

*Median and mean PM are averaged over all vehicles and tests within each fuel.

Table 43. Results of using multiple regression analysis to predict mean PM (A, top) and median PM (B, bottom) with the total Wgt% values of C_9 and C_{10+} as explanatory variables.

(A) Mean PM

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.85							
R Square	0.72							
Adjusted R Square	0.67							
Standard Error	1.21							
Observations	15							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	2	44.76	22.38	15.40	0.0005			
Residual	12	17.44	1.45					
Total	14	62.20						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-3.91	1.55	-2.53	0.03	-7.28	-0.54	-7.28	-0.54
C9	0.31	0.13	2.47	0.03	0.04	0.59	0.04	0.59
C10+	0.44	0.10	4.19	0.001	0.21	0.66	0.21	0.66

*Median and mean PM are averaged over all vehicles and tests within each fuel.

(B) Median PM

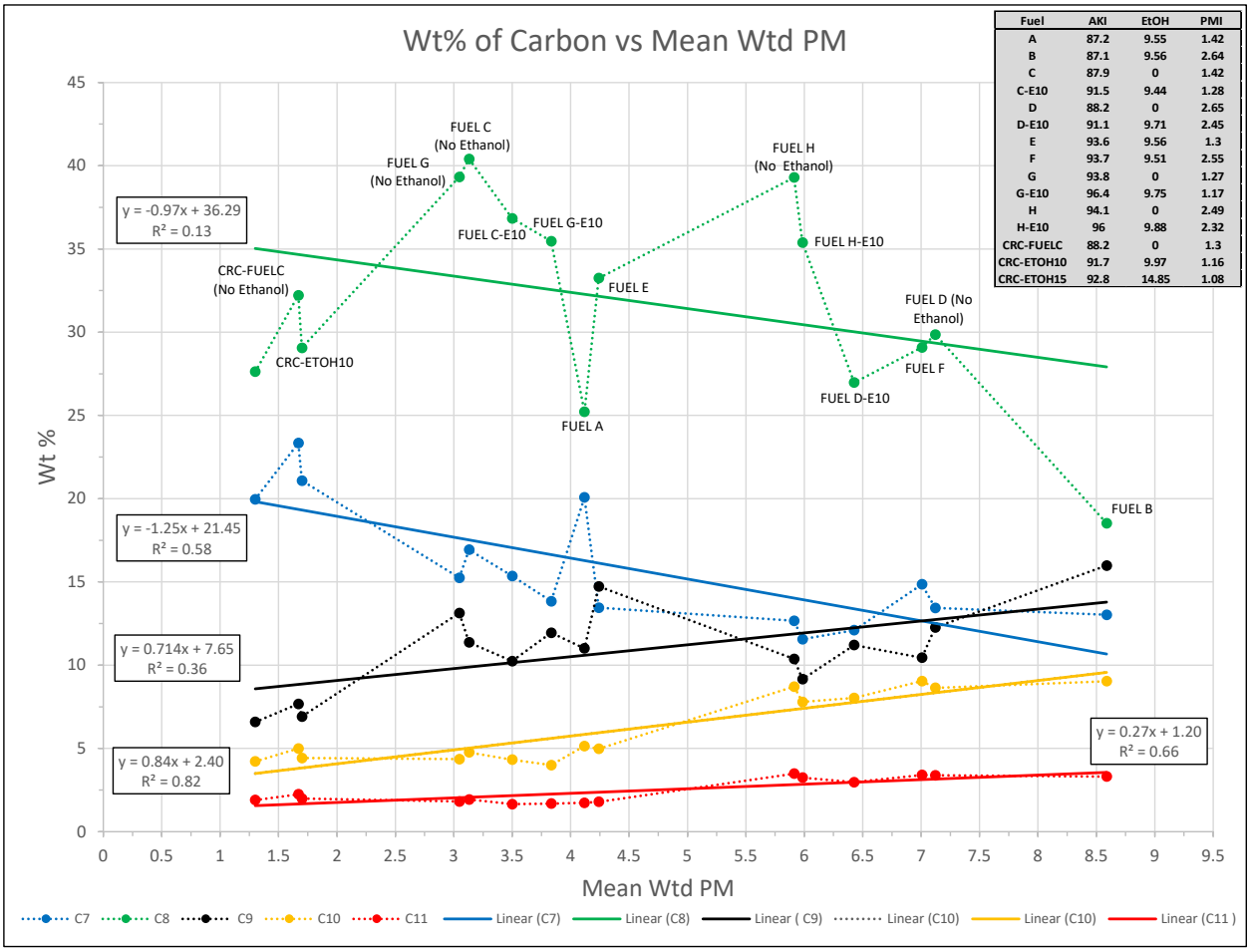
SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.96							
R Square	0.93							
Adjusted R Square	0.92							
Standard Error	0.65							
Observations	15							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	2	64.50	32.25	77.36	0.0000001			
Residual	12	5.00	0.42					
Total	14	69.50						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-4.84	0.83	-5.84	0.0001	-6.65	-3.03	-6.65	-3.03
C9	0.34	0.07	5.08	0.0003	0.20	0.49	0.20	0.49
C10+	0.54	0.06	9.71	0.0000005	0.42	0.66	0.42	0.66

*Median and mean PM are averaged over all vehicles and tests within each fuel.

Following on the results contained in Table 43 (A,B), Figure 21 shows the relationship between total Wgt% associated with each of the C_7-C_{11} versus mean and median PM, along with the respective least-squares regression lines and goodness-of-fit statistics. Figure 3 consists of similar graphs of total carbon number Wgt% versus mean and median PM, but in this case C_{11} is aggregated into a composite C_{10+} variable. Figure 21 and Figure 22 confirm the overall relationship between total Wgt% of individual carbon numbers and mean or median PM is not strong but the relationship is strongest (and positive) for C_{10} and above. It is worth noting, in general, the relationships depicted in Figures 21 and 22 are weaker when predicting median PM than when predicting mean PM, which is attributable to the factors impacting the mean PM values discussed in Section 2 of this report.

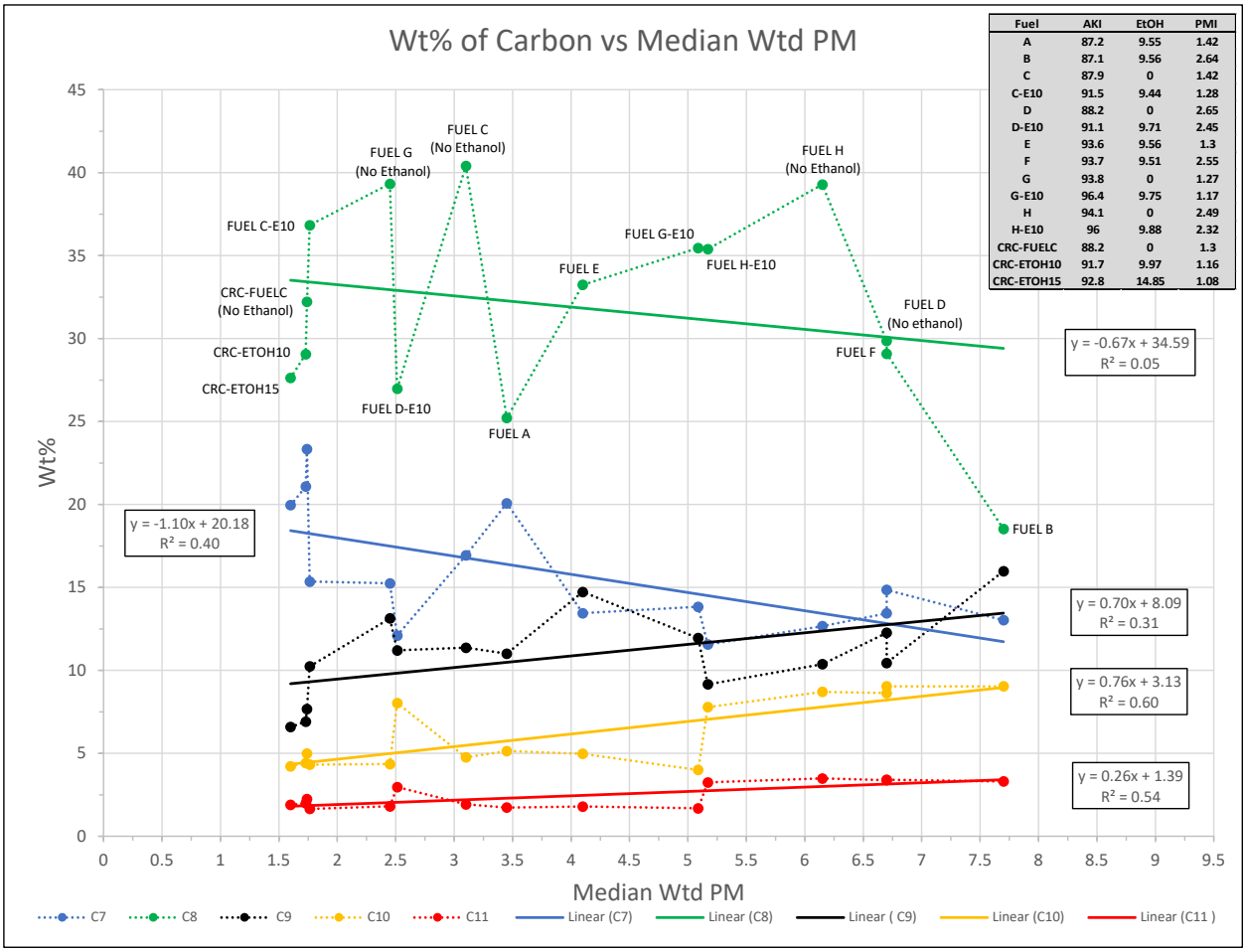
Figure 21 and Figure 22 also illustrate the relationship among the fuels included in the investigation, particularly with regard to those with and without ethanol.

(A) Mean PM



Fuel	AKI	EtOH	PMI
A	87.2	9.55	1.42
B	87.1	9.56	2.64
C	87.9	0	1.42
C-E10	91.5	9.44	1.28
D	88.2	0	2.65
D-E10	91.1	9.71	2.45
E	93.6	9.56	1.3
F	93.7	9.51	2.55
G	93.8	0	1.27
G-E10	96.4	9.75	1.17
H	94.1	0	2.49
H-E10	96	9.88	2.32
CRC-FUELC	88.2	0	1.3
CRC-ETOH10	91.7	9.97	1.16
CRC-ETOH15	92.8	14.85	1.08

(B) Median PM



Fuel	AKI	EtOH	PMI
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B	87.1	9.56	2.64
C	87.9	0	1.42
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D-E10	91.1	9.71	2.45
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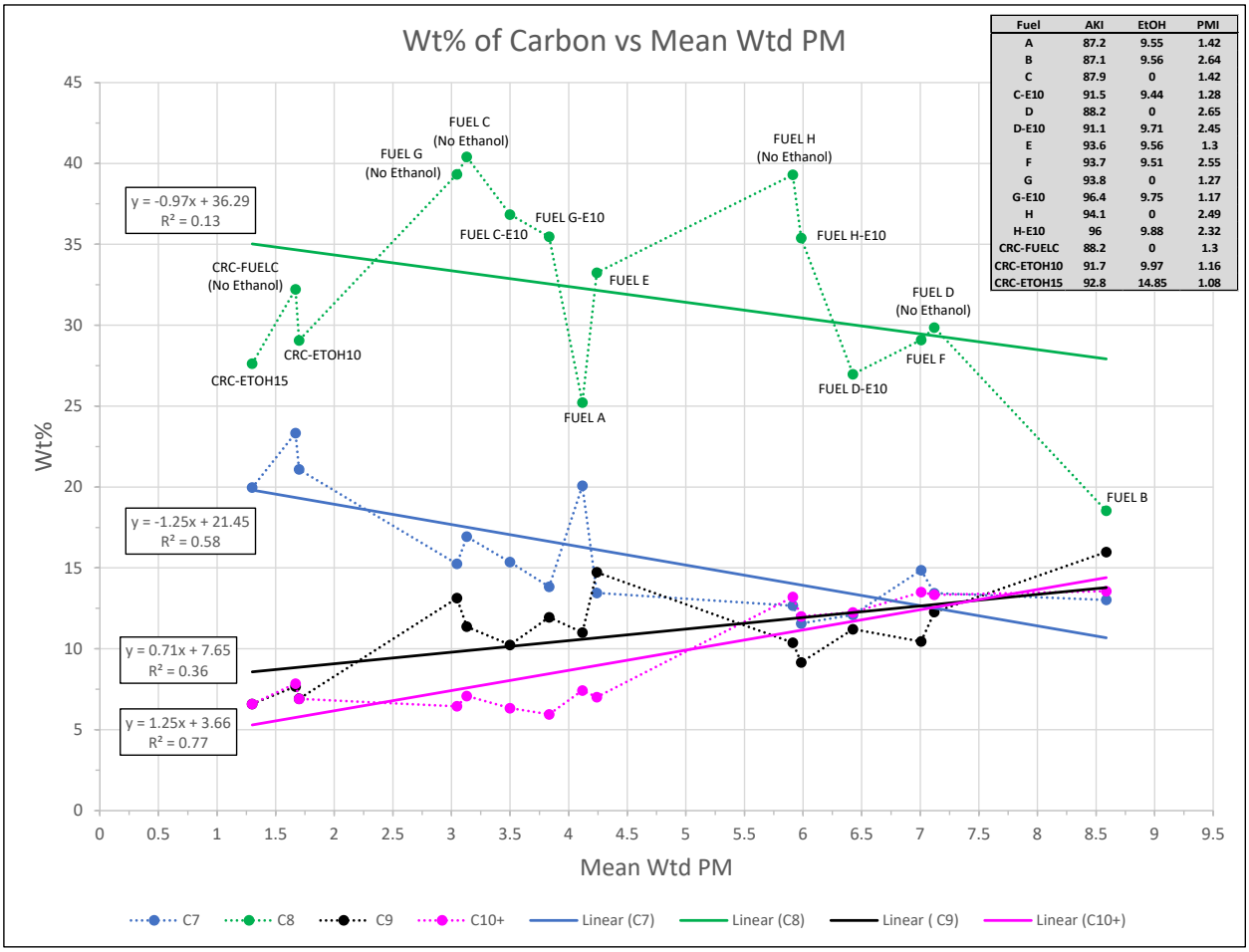
F	93.7	9.51	2.55
G	93.8	0	1.27
G-E10	96.4	9.75	1.17
H	94.1	0	2.49
H-E10	96	9.88	2.32
CRC-FUELC	88.2	0	1.3
CRC-ETOH10	91.7	9.97	1.16
CRC-ETOH15	92.8	14.85	1.08

Figure 21. Total Wgt% of C_7-C_{11} versus mean (A, Top) and median (B, Bottom) PM, with associated regression lines and goodness of fit statistics. Median and mean PM are averaged over all vehicles and tests within each fuel.

(A) Mean PM



Fuel	AKI	EtOH	PMI
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C	87.9	0	1.42
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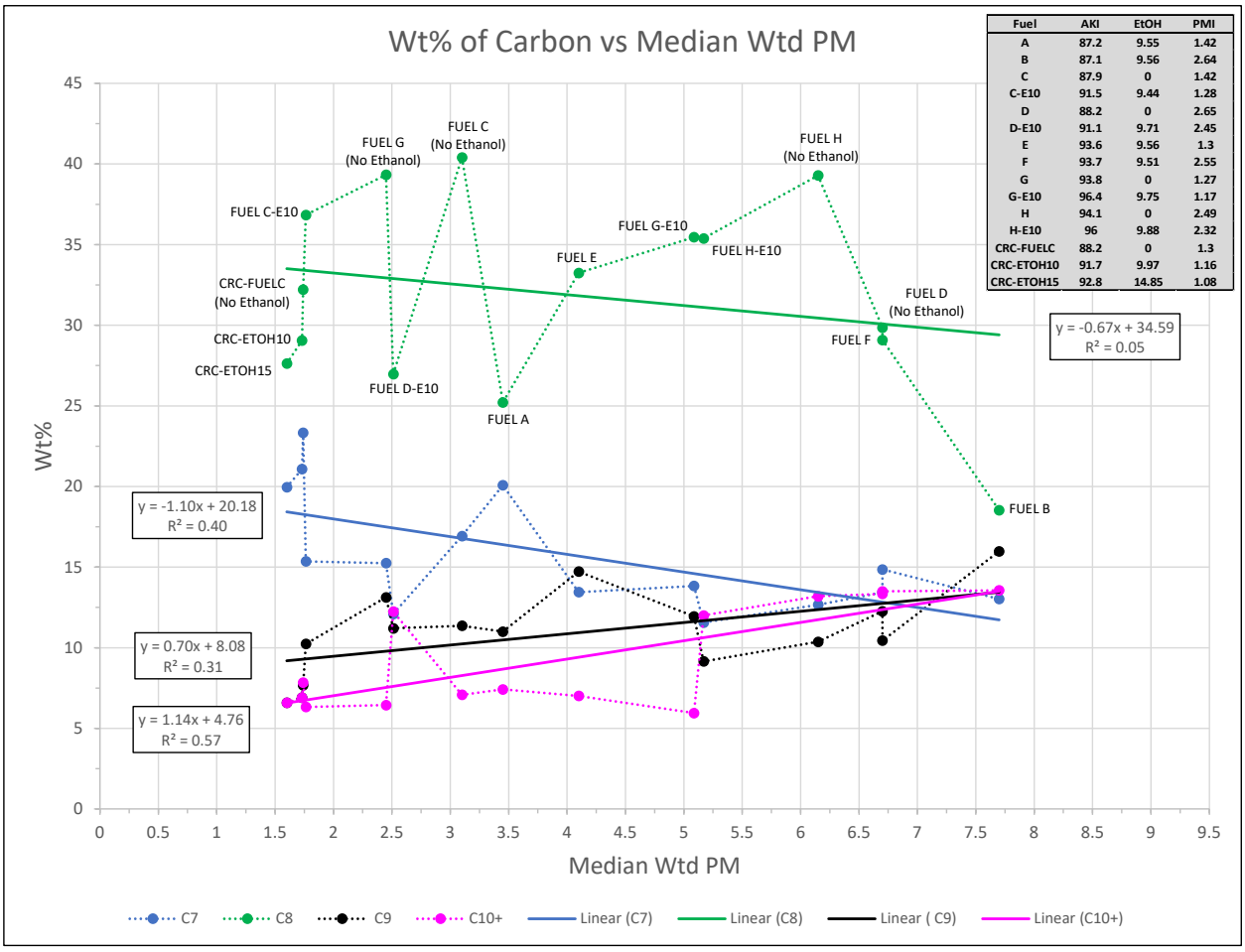
D	88.2	0	2.65
D-E10	91.1	9.71	2.45
E	93.6	9.56	1.3
F	93.7	9.51	2.55
G	93.8	0	1.27
G-E10	96.4	9.75	1.17
H	94.1	0	2.49
H-E10	96	9.88	2.32
CRC-FUELC	88.2	0	1.3
CRC-ETOH10	91.7	9.97	1.16
CRC-ETOH15	92.8	14.85	1.08

(B) Median PM



Fuel	AKI	EtOH	PMI
A	87.2	9.55	1.42
B	87.1	9.56	2.64
C	87.9	0	1.42
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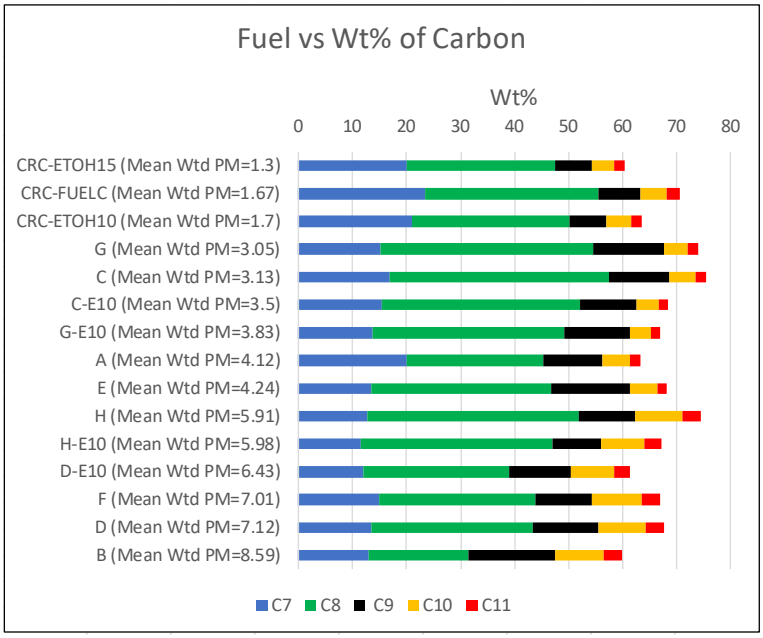
D-E10	91.1	9.71	2.45
E	93.6	9.56	1.3
F	93.7	9.51	2.55
G	93.8	0	1.27
G-E10	96.4	9.75	1.17
H	94.1	0	2.49
H-E10	96	9.88	2.32
CRC-FUELC	88.2	0	1.3
CRC-ETOH10	91.7	9.97	1.16
CRC-ETOH15	92.8	14.85	1.08

Figure 22. Total Wgt% of C_7-C_{10+} versus mean (A, Top) and median (B, Bottom) PM, with associated regression lines and goodness of fit statistics. Median and mean PM are averaged over all vehicles and tests within each fuel.

Figures 21 and 22 suggest that positive, though not strong, relationships exist between total Wgt% of carbons and mean and median PM. In this sense there is some indication that, at least for the higher carbon numbers, as average PM increases, so does total Wgt%. These observations are further underscored in the horizonal stacked bar charts depicted in Figure 23 and Figure 24. Figure 23 illustrates the changing composition of the 15 fuels relative to C_7-C_{11} and Figure 24 illustrates the same effects relative to C_7-C_{10}+. The top panel in each figure presents the fuels listed in order of their mean PM values from low to high and the bottom panel presents the fuels listed in order of the median PM values, from low to high. In these views, the total Wgt% of C_9 and higher tends to increase as "average PM" increases.

(A) Fuels sorted by Mean PM from low to high



Fuel	AKI	EtOH	PMI
A	87.2	9.55	1.42
B	87.1	9.56	2.64
C	87.9	0	1.42
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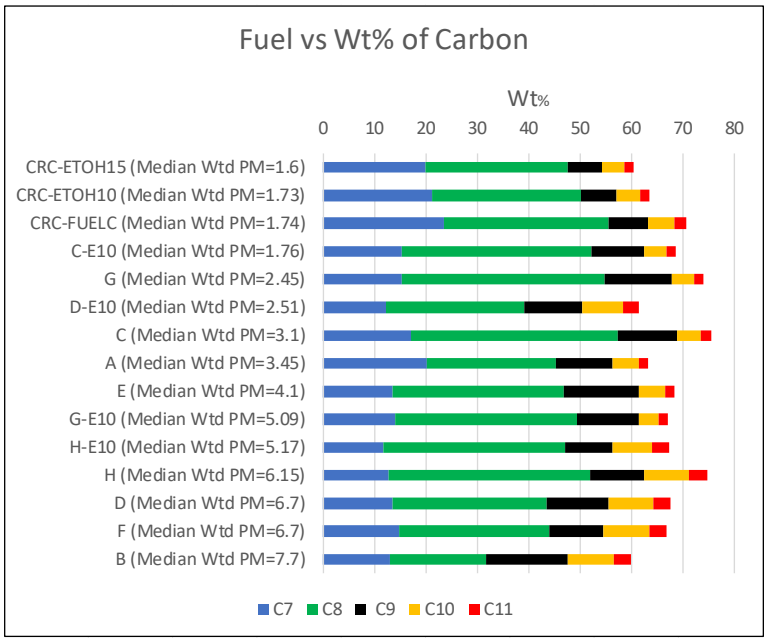
D	88.2	0	2.65
D-E10	91.1	9.71	2.45
E	93.6	9.56	1.3
F	93.7	9.51	2.55
G	93.8	0	1.27
G-E10	96.4	9.75	1.17
H	94.1	0	2.49
H-E10	96	9.88	2.32
CRC-FUELC	88.2	0	1.3
CRC-ETOH10	91.7	9.97	1.16
CRC-ETOH15	92.8	14.85	1.08

(B) Fuels sorted by Median PM from low to high



Fuel	AKI	EtOH	PMI
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C	87.9	0	1.42
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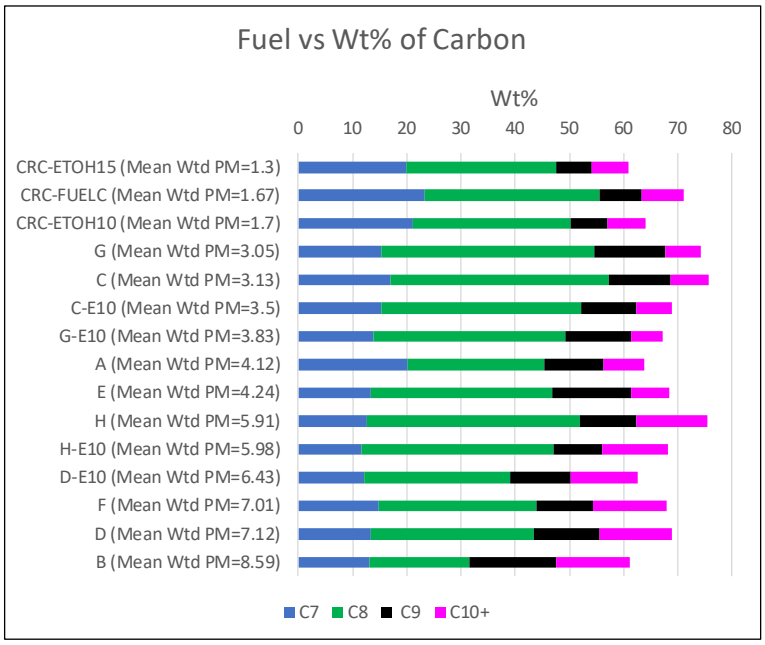
F	93.7	9.51	2.55
G	93.8	0	1.27
G-E10	96.4	9.75	1.17
H	94.1	0	2.49
H-E10	96	9.88	2.32
CRC-FUELC	88.2	0	1.3
CRC-ETOH10	91.7	9.97	1.16
CRC-ETOH15	92.8	14.85	1.08

Figure 23. Horizontal stacked bar charts showing the composition of C_7-C_{11} for each of the 15 fuels, with fuels ordered in terms of mean (A, Top) and median (B, Bottom), from low to high. Median and mean PM are averaged over all vehicles and tests within each fuel.

(A) Fuels sorted by Mean PM from low to high



Fuel	AKI	EtOH	PMI
A	87.2	9.55	1.42
B	87.1	9.56	2.64
C	87.9	0	1.42
C-E10	91.5	9.44	1.28
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D-E10	91.1	9.71	2.45
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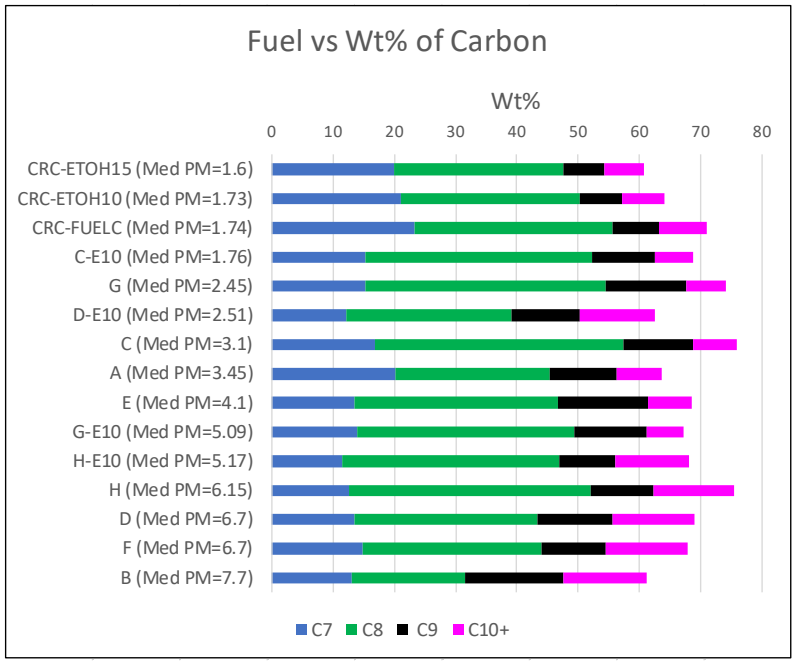
G-E10	96.4	9.75	1.17
H	94.1	0	2.49
H-E10	96	9.88	2.32
CRC-FUELC	88.2	0	1.3
CRC-ETOH10	91.7	9.97	1.16
CRC-ETOH15	92.8	14.85	1.08

(B) Fuels sorted by Median PM from low to high



Fuel	AKI	EtOH	PMI
A	87.2	9.55	1.42
B	87.1	9.56	2.64
C	87.9	0	1.42
C-E10	91.5	9.44	1.28
D	88.2	0	2.65
D-E10	91.1	9.71	2.45
E	93.6	9.56	1.3
F	93.7	9.51	2.55
G	93.8	0	1.27
G-E10	96.4	9.75	1.17
H	94.1	0	2.49
H-E10	96	9.88	2.32
CRC-FUELC	88.2	0	1.3
CRC-ETOH10	91.7	9.97	1.16
CRC-ETOH15	92.8	14.85	1.08

Figure 24. Horizonal stacked bar charts showing the composition of C_7 thru C_{10+} for each of the 15 fuels with fuels ordered in terms of mean (A, Top) and median (B, Bottom) from low to high. Median and mean PM are averaged over all vehicles and tests within each fuel.

Similar to Figure 21 and Figure 22, Figure 25 thru Figure 29 depict the relationships between median PM and the Wgt% within six selected groups: Mono-Aromatics, I-Paraffins, Naphtheno/Olefino-Benzs, Paraffin, Mono-Naphthenes, and Naphthene. However, for these analyses the data is restricted to C_9-C_{12} as a way to further investigate the role of the higher carbons numbers to explain average PM. The data (an aggregate form of the information contained in Table 38 and Table 39 is contained in Table 44.[16] The first four groups (colored rows in Table 44) are present in all four carbon numbers C_9-C_{12}, and the latter two (gray rows in Table 44) were included because of their relatively large Wgt% values when summed across the four carbons.

Table 44. Total Wgt% of C_9 thru C_{12} within groups for each of the 15 fuels.

Median PM	**1.75**	**1.74**	**1.60**	**1.77**	**2.51**	**5.09**	**5.17**	**3.45**	**7.70**	**3.10**	**6.70**	**4.10**	**6.70**	**2.45**	**6.15**
Mean PM	1.67	1.70	1.30	3.50	6.43	3.84	5.99	4.12	8.59	3.14	7.13	4.23	7.01	3.05	5.92
AKI	88.20	91.70	92.80	91.50	91.10	96.40	96.00	87.20	87.1	87.90	88.20	93.60	93.70	93.80	94.1
EtOH	0.00	9.97	14.85	9.44	9.71	9.75	9.88	9.55	9.56	0.00	0.00	9.56	9.51	0.00	0
PMI	1.30	1.16	1.08	1.28	2.45	1.17	2.32	1.42	2.64	1.42	2.65	1.30	2.55	1.27	2.49
Group	**CRC_C**	**CRC_E10**	**CRC_E15**	**C_E10**	**D_E10**	**G_E10**	**H_E10**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Mono-Aromatics	4.923	4.371	4.175	7.31	15.243	10.792	12.5	7.615	17.223	8.083	16.823	11.516	13.732	11.81	13.85
I-Paraffins	6.454	5.74	5.472	5.355	3.968	4.957	4.476	5.396	5.047	6.027	4.36	5.804	4.503	5.435	4.892
Naphtheno/Olefino-Benzs	0.849	0.728	0.696	0.592	1.92	0.638	1.72	0.766	1.954	0.68	1.969	0.737	1.848	0.686	1.826
Paraffin	1.159	1.042	0.993	0.86	0.452	0.36	0.377	1.468	1.435	0.955	0.496	1.185	0.833	0.392	0.418
Mono-Naphthenes	1.302	1.169	1.113	1.511	0.222	0.722	0.522	1.969	1.775	1.718	0.19	1.915	1.197	0.794	0.775
Naphthalenes	0.349	0.304	0.291	0.406	1.296	0.105	1.259	0.424	1.357	0.458	1.383	0.085	1.372	0.107	1.353
Iso-Olefins	0.266	0.224	0.214	0.279	0.098	0.076	0.077	0.448	0.427	0.295	0.126	0.317	0.217	0.089	0.097
n-Olefins	0.118	0.105	0.1	0.123	0.156	0.186	0.169	0.134	0.128	0.145	0.175	0.1	0.086	0.199	0.179
Naphtheno-Olefins	0.042	0.038	0.037	0.055	0.016	0.025	0.025	0.063	0.056	0.062	0.008	0.059	0.133	0.028	0.114
Indenes	0.012	0.009	0.009	0.004	0.012	0	0.002	0.01	0.012	0.005	0.013	0	0	0	0.003

In this case a robust regression procedure (rlm in R), which down-weights the effects of potential outliers, is used to estimate the relationships shown in Figure 25 thru Figure 29. In each figure the blue dots indicate fuels containing ethanol, while the red ones indicate fuels without ethanol.

[16] Note that not all groups are shown in this view.

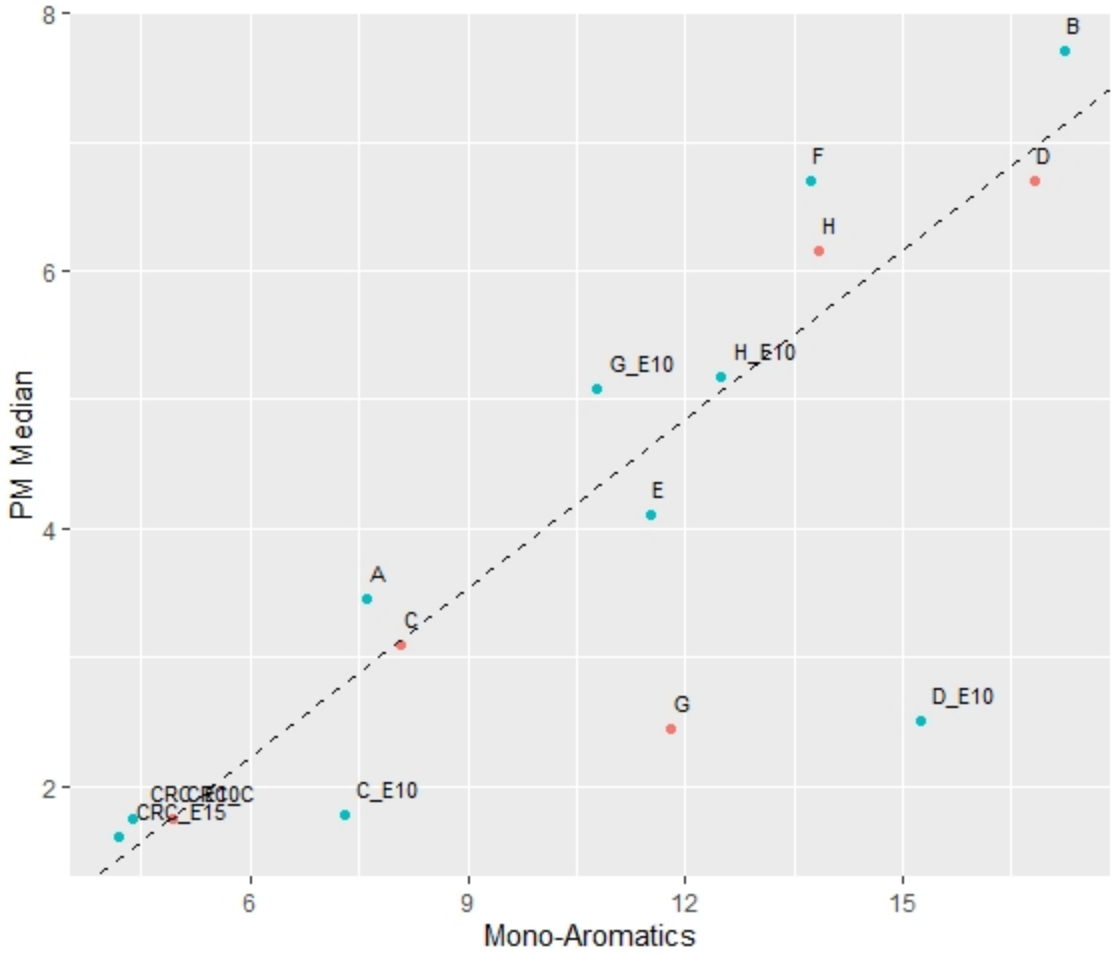


Figure 25. PM median as a function of total Wgt% of C_9 thru C_{12} Mono-Aromatics. Blue dots represent fuels with ethanol; red dots represent fuels without ethanol. Median PM is averaged over all vehicles and tests within each fuel.

Figure 25 shows a strong linear relationship between the total Wgt% of C_9 thru C_{12} Mono-Aromatics and median PM with two likely outliers: Fuel G and Fuel D-E10. The latter contains ethanol and the former does not. Of the four fuels with the highest median PM two contain ethanol and two do not. Of the 10 fuels containing ethanol seven lay above the regression line, which suggests the pattern is not random. It is also worth noting that Fuels G and G-E10 appear to be "misbehaving" relative to the other ethanol/non-ethanol pairs. Given the pattern exhibited by the other fuel pairs, the median PM value for G-E10 would be expected to lay below the regression line and that for G would be expected to lay above the line, but the opposite is true. This same phenomenon can be noted in the subsequent figures described below.

The estimated model coefficients and goodness-of-fit statistics are shown in Table 45. Note the statistical significance of the fitted slope of the regression line.

Table 45. Fitted model parameters and resulting goodness-of-fit statistics for the relationship depicted in Figure 26.

Model Coefficients	Value	Std. Error	t value	p-value
(Intercept)	-0.409	0.627	-0.653	
Slope	0.438	0.055	8.013	0.000002

Figure 26 depicts a negative relationship between the total Wgt% of C_9 thru C_{12} I-Paraffins and median PM. There are two possible outliers: Fuel B, whose median PM value lies above the line, and Fuel D-E10, whose median PM value lies below the line.

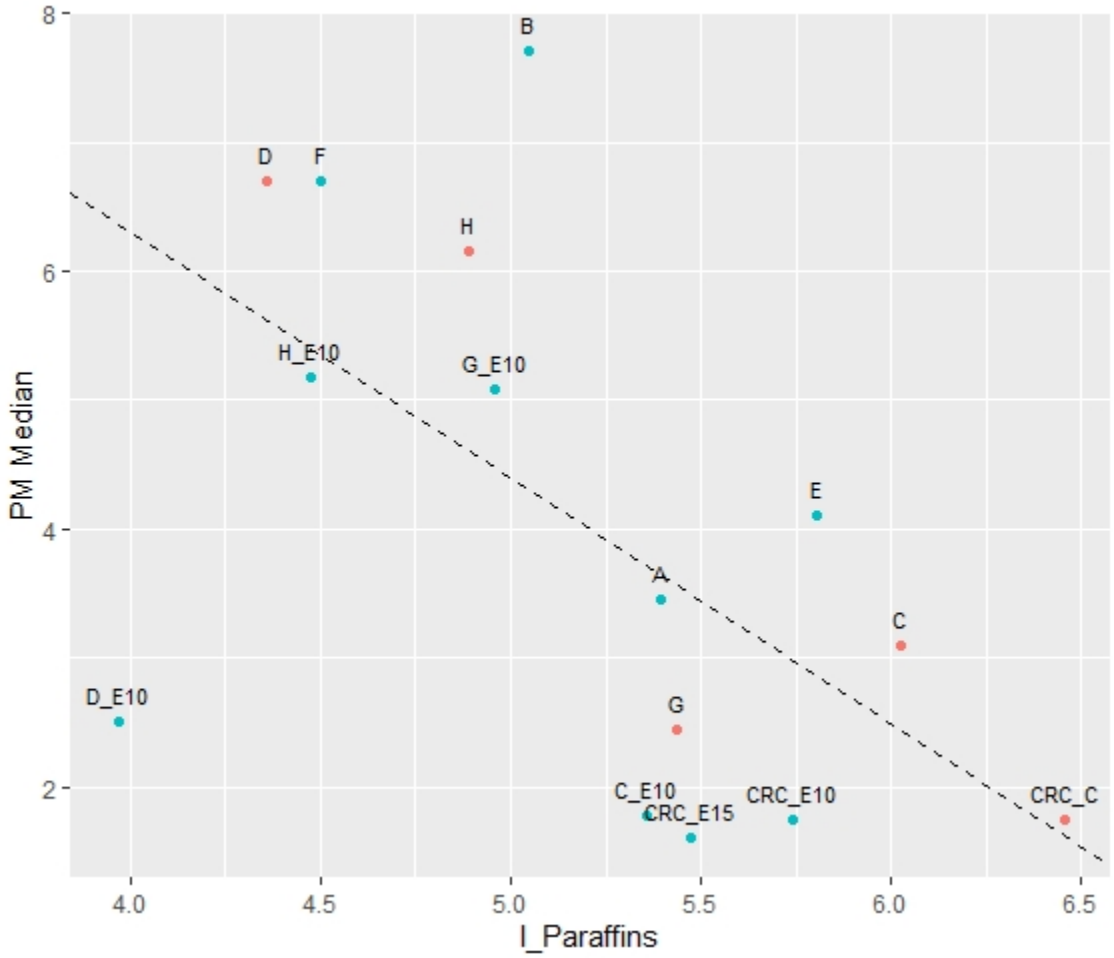


Figure 26. PM median as a function of the total Wgt% of C_9 thru C_{12} I-Paraffins. Blue dots represent fuels with ethanol. Red dots represent fuels without ethanol. Median PM is averaged over all vehicles and tests within each fuel.

The estimated model coefficients and goodness-of-fit statistics are shown in Table 46. Note the statistical significance of the fitted slope of the regression line.

Table 46. Fitted model parameters and resulting goodness-of-fit statistics for the relationship depicted in Figure 26.

Model Coefficients:	Value	Std. Error	t value	p-value
(Intercept)	13.9245	3.6862	3.7775	
Slope	-1.9057	0.7043	-2.7059	0.018

Figure 8 depicts a strong positive relationship between the total Wgt% of C_9-C_{12} Naphtheno/Olefino-Benzs and median PM. Note the appearance of two separate groups of fuels: one that has total Wgt% values of C_9 thru C_{12} Naphtheno/Olefino-Benzs that are low, and a second one that has higher values of the total Wgt% C_9-C_{12} Naphtheno/Olefino-Benzs. There are two potential outliers among the fuels—G-E10 and D-E10—but otherwise there are no obvious patterns with respect to fuels that contain ethanol.

The estimated model coefficients and goodness-of-fit statistics are shown in Table 47. Note the statistical significance of the fitted slope of the regression line.

Table 47. Fitted model parameters and resulting goodness-of-fit statistics for the relationship depicted in Figure 27.

Model Coefficients	Value	Std. Error	t value	p-value
(Intercept)	0.4185	0.7945	0.5268	
Slope	3.1137	0.6076	5.1243	0.0002

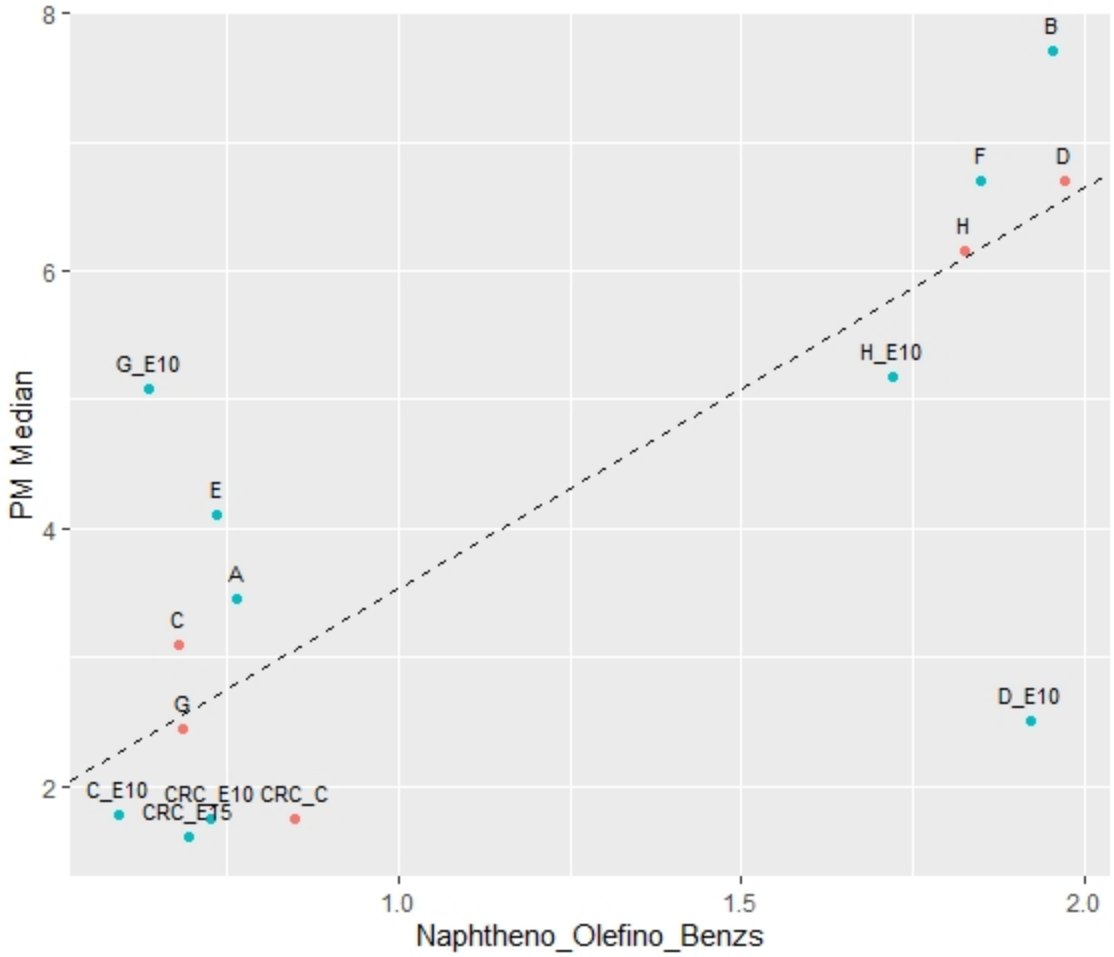


Figure 27. PM median as a function of the total Wgt% of C_9 thru C_{12} Naphtheno/Olefino-Benzs. Blue dots represent fuels with ethanol. Red dots represent fuels without ethanol. Median PM is averaged over all vehicles and tests within each fuel.

Figure 28 shows the relationship between the Wgt% of C_9-C_{12} Paraffin and median PM. The relationship is not statistically significant and there is no noteworthy pattern among fuels related to ethanol.

The estimated model coefficients and goodness-of-fit statistics are shown in Table 48. Note the lack of statistical significance for the fitted slope of the regression line.

Table 48. Fitted model parameters and resulting goodness-of-fit statistics for the relationship depicted in Figure 28.

Model Coefficients	Value	Std. Error	t value	p-value
(Intercept)	4.6429	1.4138	3.2839	
Slope	-0.8178	1.5532	-0.5265	0.607
Residual standard error:		2.776	13	df

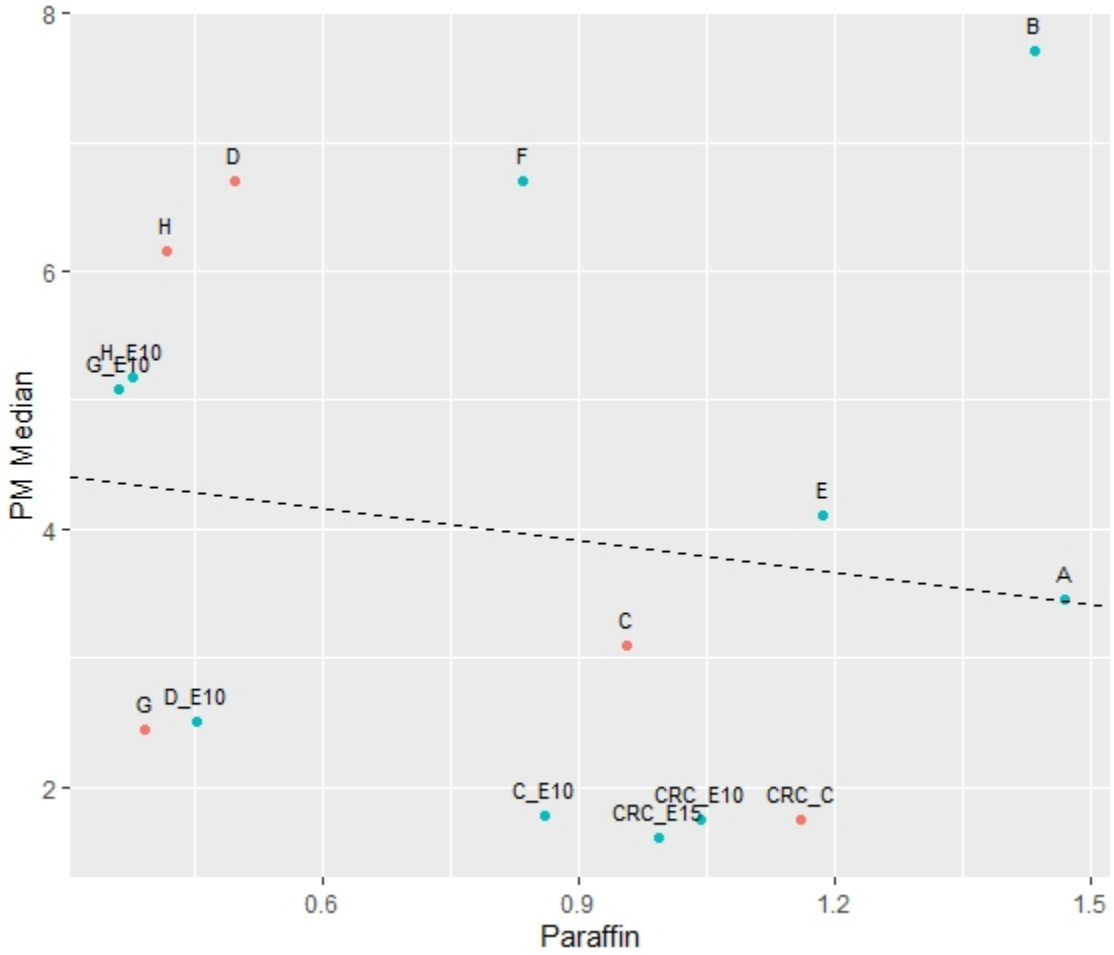


Figure 28. PM median as a function of the total Wgt% of C9 thru C12 Paraffin. Blue dots represent fuels with ethanol. Red dots represent fuels without ethanol. Median PM is averaged over all vehicles and tests within each fuel.

Figure 29 shows the relationship between the Wgt% of C_9 Mono-Naphthenes and median PM. The relationship is not statistically significant and there is no noteworthy pattern among fuels related to ethanol.

The estimated model coefficients and goodness-of-fit statistics are shown in Table 49. Note the lack of statistical significance for the fitted slope of the regression line.

Table 49. Fitted model parameters and resulting goodness-of-fit statistics for the relationship depicted in Figure 29.

Mono-Naphthenes				
Model Coefficients	Value	Std. Error	t value	p-value
(Intercept)	4.5277	1.3516	3.35	
Slope	-0.4724	1.0736	-0.44	0.667

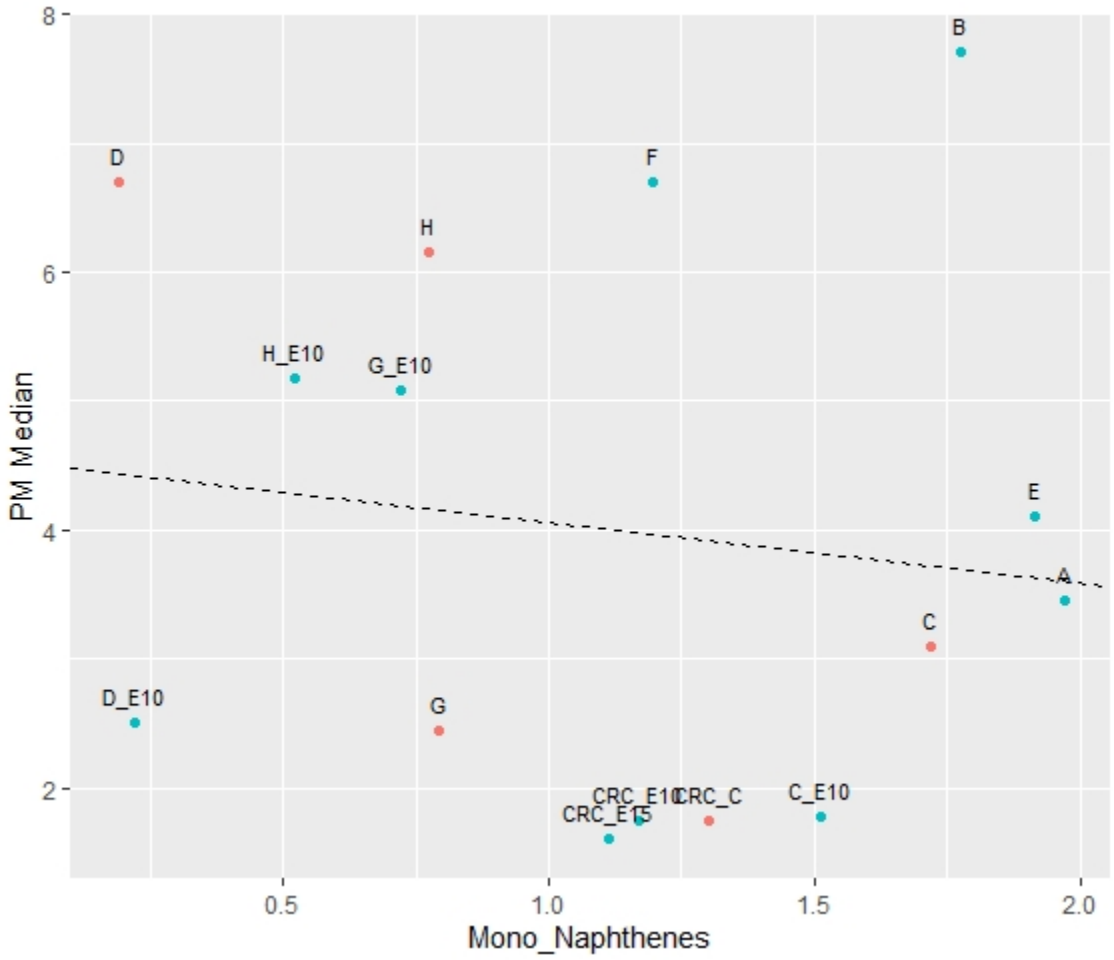


Figure 29. PM median as a function of the total Wgt% of C_9 thru C_{12} Mono-Naphthenes. Blue dots represent fuels with ethanol. Red dots represent fuels without ethanol. Median PM is averaged over all vehicles and tests within each fuel.

Figure 30 shows the relationship between the total Wgt% of C_9 thru C_{12} Naphthalenes and median PM. The relationship is statistically significant.

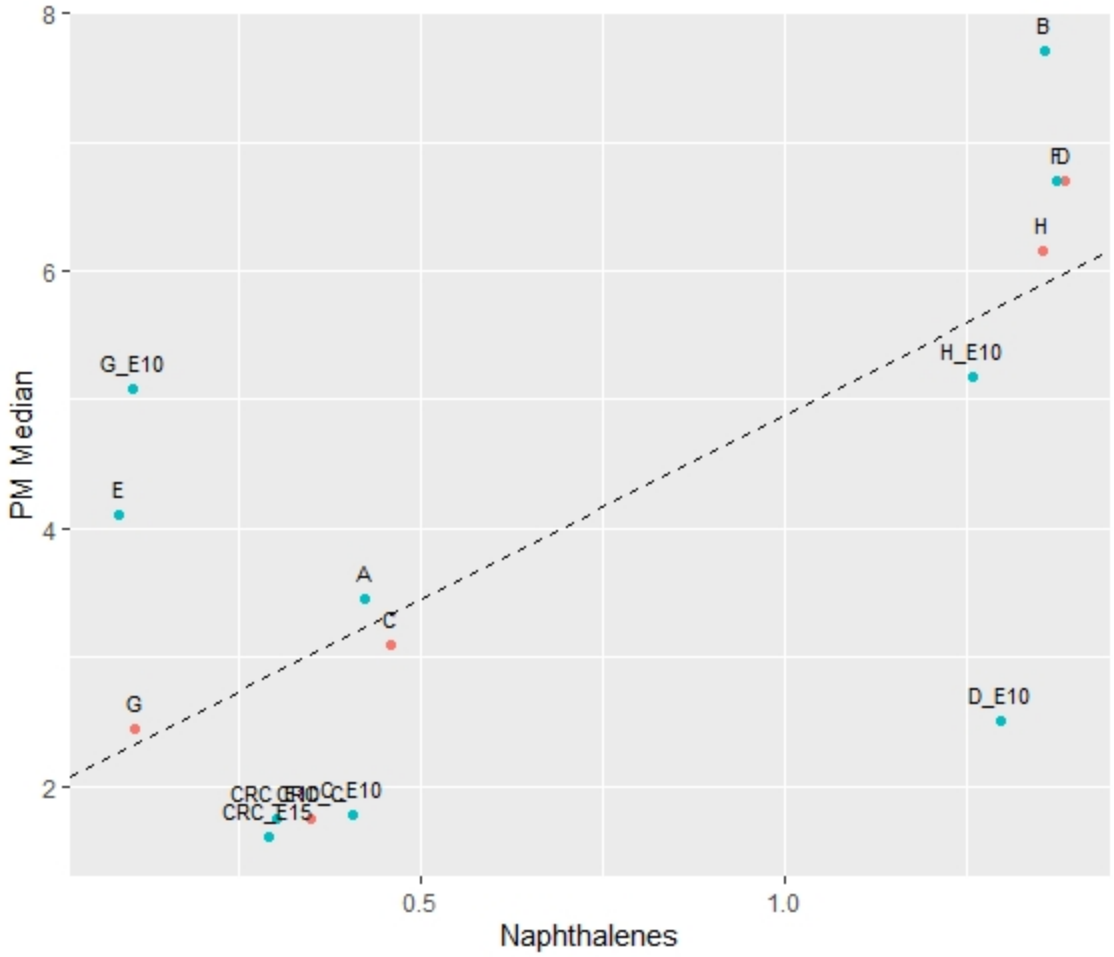


Figure 30. PM median as a function of the total Wgt% of C_9 thru C_{12} Naphthalenes. Blue dots represent fuels with ethanol. Red dots represent fuels without ethanol. Median PM is averaged over all vehicles and tests within each fuel.

The estimated model coefficients and goodness-of-fit statistics are shown in Table 50. Note the lack of statistical significance for the fitted slope of the regression line.

Table 50. Fitted model parameters and resulting goodness-of-fit statistics for the relationship depicted in Figure 30.

Model Coefficients	Value	Std. Error	t value	p-value
(Intercept)	2.0165	0.7029	2.869	
Slope	2.8603	0.7987	3.5809	0.0033

Table 51 summarizes the results regarding statistical significance of the relationship between the total Wgt% values of C_9 thru C_{12} in selected groups and median PM that are depicted in Figure 25 thru Figure 30 and Table 45 thru Table 50.

Table 51. Summary of the results depicted in Figures 6-11 and Table 44 thru Table 49.

Group	Statistically Significant Relationship with Median PM	Slope	p-Value Associated with Fitted Slope	Direction
Mono-Aromatics	Yes	0.438	0.000002	Positive
I-Paraffins	Yes	-1.906	0.018	Negative
Naphtheno/Olefino-Benzs	Yes	3.114	0.0002	Positive
Paraffin	No	-0.818	0.607	-
Mono-Naphthenes	No	-0.472	0.667	-
Naphthalenes	Yes	2.860	0.0033	Positive

Table 52 contains the pairwise correlations between mean and median PM and the total Wgt% values of the six DHA groups (within C_9 thru C_{12} only) represented in Figure 25 thru Figure 30. Colored cells contain correlations that are >0.5 in absolute value. Red cells indicate positive correlations and blue cells indicate negative ones. Table 52 is similar to Table 41 except for the restriction to group values within C_9 thru C_{12}. The correlations contained in Table 52 further confirm the relationships exhibited in Figure 25 thru Figure 30. Note the additional positive correlations between Mono-Aromatics and Naphtheno/Olefinos-Benzs, Mono-Aromatics and Naphthalenes and between Naphtheno/Olefinos-Benzs and Naphthalenes, suggesting the presence of multicollinearity. Also note the positive correlation between Paraffin and Mono-Naphthenes. Finally, I-Paraffins are negatively correlated with Naphtheno/Olefinos-Benzs and Naphthalenes and Mono-Aromatics are negatively correlated with I-Paraffins, again suggesting the possibility of multicollinearity.

Table 52. Pairwise correlations between total Wgt% values of DHA groups within C_9 thru C_{12}, mean PM, and median PM, based on 15 fuels. Colored cells indicate pairwise correlations exceeding 0.5 in absolute value. Positive values are shown in red and negative correlations are shown in blue.

	Median PM	Mean PM	Mono-Aromatics	I-Paraffins	Naphtheno/Olefino-Benzs	Paraffin	Mono-Naphthenes	Naphthalenes
Median PM	1							
Mean PM	0.86	1						
Mono-Aromatics	0.80	0.93	1					
I-Paraffins	-0.54	-0.76	-0.74	1				
Naphtheno/Olefino-Benzs	0.73	0.88	0.82	-0.77	1			
Paraffin	-0.13	-0.17	-0.37	0.57	-0.28	1		
Mono-Naphthenes	-0.13	-0.24	-0.39	0.67	-0.48	0.87	1	
Naphthalenes	0.69	0.86	0.74	-0.75	0.97	-0.25	-0.42	1

Some additional observations are worth noting. Fuel D-E10 appears to be an outlier with regard to Figures 25, 27 and 30, all of which exhibit a strong positive relationship between median PM and the total Wgt% of C_9-C_{12}, for the three respective groups (Mono-Aromatics, Naphtheno/Olefino-Benzs and Naphthalenes). In all three cases, median PM lays relatively far

below the regression line. However, since D-E10 contains ethanol, one would expect it to exhibit a low median PM value. Whether D-E10 is an outlier may be a moot point.

On the other hand, as previously mentioned, Fuel G-E10 exhibits behavior that is not within expectations. Since Fuel G-E10 is a splash blended fuel, one possible explanation is that splash blending may not have produced the desired results.

The findings of the foregoing analyses notwithstanding, a question remains as to whether differences in DHA results can help explain the differences in mean and median PM among the 15 fuels. To investigate this question more thoroughly, we conducted a number of analyses based on the comparative rank ordering of the Wgt% the various constituents within fuels.

Similar to Table 33, Table 53 contains a partial listing of the Wgt% of various constituents within groups for C_9 for selected fuels. The three groups displayed are color-coded to improve the visual aesthetics. The color coding and selection of fuels is for illustration purposes only. For each of the fuels, the table also includes the rank ordering, from high to low, of each constituent's Wgt% on a group-by-group basis. For example, the Wgt% values of the thirteen I-Paraffin constituents for Fuel CRC-C are ranked from 13 (highest) to 1 (lowest), as are the Wgt% values for the other four fuels. Note that zero values are assigned as placeholders for missing/empty cells (i.e., cases for which no constituent value is recorded or reported). This same process is repeated for the eight Mono-Aromatics constituents, and then again for the 10 Mono-Naphthenes constituents. In this way it is possible to observe the commonality of relative importance of constituents among the various fuels. For example, for all five fuels, 2,2,5-Trimethylhexane has the largest Wgt%, and presumably is the most important, among the 13 C_9 I-Paraffin constituents.

Table 53. Partial listing of Wgt% of constituents within groups (C_9 only) for selected fuels, plus the rank order, from high to low, of each constituent within each fuel on a per-group basis.

Carbon	Group	Constituent	CRC_C	CRC_E10	CRC_E15	D_E10	G_E10	RankCRC_C	RankCRC_E10	RankCRC_E15	Rank_D_E10	Rank_G_E10
C9	I-Paraffins	2,2,5-Trimethylhexane	1.366	1.233	1.173	0.959	1.594	13	13	13	13	13
C9	I-Paraffins	C9-Isoparaffin-x	0.057	0.051	0.048	0.035	0.048	3	3	3	3	5
C9	I-Paraffins	2,3,5-Trimethylhexane	0.25	0.204	0.194	0.161	0.232	9	9	9	9	11
C9	I-Paraffins	2,4-Dimethylheptane	0.113	0.103	0.098	0.062	0.072	6	6	6	6	6
C9	I-Paraffins	2,2,3-Trimethylhexane	0	0.011	0.01	0.013	0	1	1	1	2	1
C9	I-Paraffins	2,6-Dimethylheptane	0.214	0.182	0.174	0.062	0.154	7	7	7	7	9
C9	I-Paraffins	2,5-Dimethylheptane	0.274	0.247	0.236	0.165	0.188	10	10	10	10	10
C9	I-Paraffins	3,5-Dimethylheptane	0.034	0.031	0.03	0.008	0.023	2	2	2	1	2
C9	I-Paraffins	4-Ethylheptane	0.062	0.056	0.053	0.037	0.036	5	5	5	4	4
C9	I-Paraffins	4-Methyloctane	0.224	0.202	0.193	0.139	0.118	8	8	8	8	7
C9	I-Paraffins	2-Methyloctane	0.277	0.25	0.238	0.169	0.14	11	11	11	11	8
C9	I-Paraffins	Heptane, 3-ethyl-	0.058	0.054	0.051	0.041	0.033	4	4	4	5	3
C9	I-Paraffins	3-Methyloctane	0.424	0.38	0.363	0.193	0.242	12	12	12	12	12
C9	Mono-Aromatics	i-Propylbenzene	0.046	0.042	0.04	0.092	0.018	1	1	1	1	1
C9	Mono-Aromatics	n-Propylbenzene	0.144	0.129	0.123	0.526	0.409	3	3	3	2	2
C9	Mono-Aromatics	1-Methyl-3-ethylbenzene	0.372	0.332	0.317	1.765	1.669	7	7	7	7	7
C9	Mono-Aromatics	1-Methyl-4-ethylbenzene	0.171	0.149	0.142	0.79	0.766	5	5	5	5	5
C9	Mono-Aromatics	1,3,5-Trimethylbenzene	0.229	0.201	0.192	0.947	1.013	6	6	6	6	6
C9	Mono-Aromatics	1-Methyl-2-ethylbenzene	0.129	0.113	0.108	0.607	0.531	2	2	2	3	4
C9	Mono-Aromatics	1,2,4-Trimethylbenzene	0.611	0.541	0.517	2.943	2.837	8	8	8	8	8
C9	Mono-Aromatics	1,2,3-Trimethylbenzene	0.167	0.138	0.132	0.631	0.424	4	4	4	4	3
C9	Mono-Naphthenes	C9 - MonoNaph - 1	0.232	0.209	0.199	0.011	0.185	9	9	9	2	9
C9	Mono-Naphthenes	1,1,4-Trimethylcyclohexane	0.035	0.032	0.03	0.043	0.024	2	2	2	10	3
C9	Mono-Naphthenes	1,1,3-Trimethylcyclohexane	0.064	0.058	0.055	0.014	0.044	5	5	5	5	6
C9	Mono-Naphthenes	1c,2t,4t-Trimethylcyclohexane	0.249	0.224	0.214	0.028	0.225	10	10	10	8	10
C9	Mono-Naphthenes	C9 - MonoNaph - 4	0.051	0.047	0.045	0.013	0.04	4	4	4	4	5
C9	Mono-Naphthenes	1c,2t,4c-Trimethylcyclohexane	0.065	0.059	0.056	0.015	0.049	6	6	6	6	7
C9	Mono-Naphthenes	trans-1,3-Diethylcyclopentane	0.229	0.206	0.197	0.032	0.091	8	8	8	9	8
C9	Mono-Naphthenes	1,1-Methylethylcyclohexane	0.145	0.134	0.127	0.024	0.037	7	7	7	7	4
C9	Mono-Naphthenes	1-ethyl-4-t-methylcyclohexane	0.043	0.044	0.042	0.012	0.008	3	3	3	3	2
C9	Mono-Naphthenes	1-Methyl-2-propyl-cyclopentan	0.01	0.009	0.009	0	0.003	1	1	1	1	1

While this approach might produce some interesting insights, it is descriptive, rather than inferential, and there are too many cells to produce results that are immediately informative. All combined (with all 15 fuels), there are 326 rows, of which 185 are associated with C_9-C_{12}. Hence, looking only at C_9 thru C_{12}, there are 185 rows times 15 fuels yielding 2,775 cells. However, among the 2,775 there are 476 missing/empty cells, which in a table similar to Table 53 would be replaced by zeroes.

An alternative approach based on the rank ordering of Wgt% is to essentially stack the values for all 15 fuels (irrespective of carbon, group, or constituent) in a single column listing, ignoring the empty cells, and then rank (sort) all the values from high to low. Hence, using the counts from above, there are 2,775 - 476 = 2,299 Wgt% values to stack in a single column and sort from high to low. Eliminating the empty cells means the number of observations (rows) per fuel will differ.

This is the process on which the Kruskal-Wallis test is based. The Kruskal-Wallis test is a nonparametric version of the well-known one-way analysis of variance procedure, and it provides an alternative way to evaluate differences among the fuel down to the level of individual constituents. The idea is to perform the stacking and ranking, separate out all the ranks associated with each fuel, compute and evaluate the Kruskal-Wallis test statistic, and compare results the results for pairs of fuels.

Table 54 shows the 15 fuels listed in order of the mean of their assigned ranks (Left) and a separate listing of the 15 fuels listed in order of their mean PM values (Right). Table 55 shows the fuels listed in order of the median of their assigned ranks (Left) and a separate listing of them in order of their median PM values (Right). Table 56 presents the fuels listed in order of the mean of their assigned ranks (Left), as in Table 54, compared to an ordering of the fuels on the basis of PMI (Right). Similarly, Table 57 depicts the fuels listed in order of the median of their assigned ranks (Left), as in Table 55, compared to ordering them on the basis of PMI (Right).

None of the foregoing comparisons demonstrates a close correspondence between the fuels on the basis of the various rankings, suggesting that the relative compositional importance of constituents within fuels is not necessarily tied to "average PM" or PMI, at least within the C_9-C_{12} carbon numbers

As noted above, the Kruskal-Wallis test is a rank-sum equivalent to one-way analysis of variance and can be used to see if there are differences among fuels. The null hypothesis is that there are no differences among them. The results of the test are shown in Table 58. Clearly there are differences among the fuels when considering the constituents associated with C_9-C_{12} and the null hypothesis is rejected.

Table 54. Ranking of fuels on the basis of the mean of ranks assigned to their individual constituents (C_9 thru C_{12}), compared the ranking of fuels on the basis of mean PM.

Fuel	Number of Observations	Mean of Ranks	Median of Ranks
B	169	1376	1437
F	158	1289	1318
E	146	1248	1342
CRC-C	153	1247	1296
H	152	1215	1239
A	167	1214	1245
D	167	1206	1155
D-E10	165	1177	1139
H-E10	151	1169	1124
C	166	1156	1147
CRC-ETOH10	163	1124	1155
CRC-ETOH15	163	1100	1124
C-E10	167	1087	1028
G	139	1085	1028
G-E10	141	1040	988

Fuel	Mean PM	Median PM	AKI	EtOH	PMI
B	8.59	7.70	87.1	9.56	2.64
D	7.13	6.70	88.2	0	2.65
F	7.01	6.70	93.7	9.51	2.55
D-E10	6.43	2.51	91.1	9.71	2.45
H-E10	5.99	5.17	96.0	9.88	2.32
H	5.92	6.15	94.1	0	2.49
E	4.23	4.10	93.6	9.56	1.30
A	4.12	3.45	87.2	9.55	1.42
G-E10	3.84	5.09	96.4	9.75	1.17
C-E10	3.50	1.77	91.5	9.44	1.28
C	3.14	3.10	87.9	0	1.42
G	3.05	2.45	93.8	0	1.27
CRC-ETOH10	1.70	1.74	91.7	9.97	1.16
CRC-C	1.67	1.75	88.2	0	1.30
CRC-ETOH15	1.30	1.60	92.8	14.85	1.08

*Median and mean PM are "averaged over" all vehicles and tests within each fuel.

Table 55. Ranking of fuels on the basis of the median of ranks assigned to their individual constituents (C_9 thru C_{12}), compared the ranking of fuels on the basis of median PM.

Fuel	Number of Observations	Median of Ranks	Mean of Ranks
B	169	1437	1376
E	146	1342	1248
F	158	1318	1289
CRC-C	153	1296	1247
A	167	1245	1214
H	152	1239	1215
D	167	1155	1206
CRC-ETOH10	163	1155	1124
C	166	1147	1156
D-E10	165	1139	1177
H-E10	151	1124	1169
CRC-ETOH15	163	1124	1100
C-E10	167	1028	1087
G	139	1028	1085
G-E10	141	988	1040

Fuel	Median PM	Mean PM	AKI	EtOH	PMI
B	7.70	8.59	87.1	9.56	2.64
D	6.70	7.13	88.2	0	2.65
F	6.70	7.01	93.7	9.51	2.55
D-E10	6.15	5.92	94.1	0	2.49
H-E10	5.17	5.99	96.0	9.88	2.32
H	5.09	3.84	96.4	9.75	1.17
E	4.10	4.23	93.6	9.56	1.30
A	3.45	4.12	87.2	9.55	1.42
G-E10	3.10	3.14	87.9	0	1.42
C-E10	2.51	6.43	91.1	9.71	2.45
C	2.45	3.05	93.8	0	1.27
G	1.77	3.50	91.5	9.44	1.28
CRC-ETOH10	1.75	1.67	88.2	0	1.30
CRC-C	1.74	1.70	91.7	9.97	1.16
CRC-ETOH15	1.60	1.30	92.8	14.85	1.08

*Median and mean PM are "averaged over" all vehicles and tests within each fuel.

Table 56. Ranking of fuels on the basis of the mean of ranks assigned to their individual constituents (C_9 thru C_{12}), compared the ranking of fuels on the basis of PMI.

Fuel	Number of Observations	Mean of Ranks	Median of Ranks
B	169	1376	1437
F	158	1289	1318
E	146	1248	1342
CRC-C	153	1247	1296
H	152	1215	1239
A	167	1214	1245
D	167	1206	1155
D-E10	165	1177	1139
H-E10	151	1169	1124
C	166	1156	1147
CRC-ETOH10	163	1124	1155
CRC-ETOH15	163	1100	1124
C-E10	167	1087	1028
G	139	1085	1028
G-E10	141	1040	988

Fuel	PMI	AKI	EtOH	Mean PM	Median PM
D	2.65	88.2	0	7.13	6.70
B	2.64	87.1	9.56	8.59	7.70
F	2.55	93.7	9.51	7.01	6.70
H	2.49	94.1	0	5.92	6.15
D-E10	2.45	91.1	9.71	6.43	2.51
H-E10	2.32	96.0	9.88	5.99	5.17
A	1.42	87.2	9.55	4.12	3.45
C	1.42	87.9	0	3.14	3.10
E	1.30	93.6	9.56	4.23	4.10
CRC-C	1.30	88.2	0	1.67	1.75
C-E10	1.28	91.5	9.44	3.50	1.77
G	1.27	93.8	0	3.05	2.45
G-E10	1.17	96.4	9.75	3.84	5.09
CRC-ETOH10	1.16	91.7	9.97	1.70	1.74
CRC-ETOH15	1.08	92.8	14.85	1.30	1.60

*Median and mean PM are "averaged over" all vehicles and tests within each fuel.

Table 57. Ranking of fuels on the basis of the median of ranks assigned to their individual constituents (C_9 thru C_{12}), compared the ranking of fuels on the basis of PMI.

Fuel	Number of Observations	Median of Ranks	Mean of Ranks
B	169	1437	1376
E	146	1342	1248
F	158	1318	1289
CRC-C	153	1296	1247
A	167	1245	1214
H	152	1239	1215
D	167	1155	1206
CRC-ETOH10	163	1155	1124
C	166	1147	1156
D-E10	165	1139	1177
H-E10	151	1124	1169
CRC-ETOH15	163	1124	1100
C-E10	167	1028	1087
G	139	1028	1085
G-E10	141	988	1040

Fuel	PMI	AKI	EtOH	Median PM	Mean PM
D	2.65	88.2	0	6.70	7.13
B	2.64	87.1	9.56	7.70	8.59
F	2.55	93.7	9.51	6.70	7.01
H	2.49	94.1	0	6.15	5.92
D-E10	2.45	91.1	9.71	2.51	6.43
H-E10	2.32	96.0	9.88	5.17	5.99
A	1.42	87.2	9.55	3.45	4.12
C	1.42	87.9	0	3.10	3.14
E	1.30	93.6	9.56	4.10	4.23
CRC-C	1.30	88.2	0	1.75	1.67
C-E10	1.28	91.5	9.44	1.77	3.50
G	1.27	93.8	0	2.45	3.05
G-E10	1.17	96.4	9.75	5.09	3.84
CRC-ETOH10	1.16	91.7	9.97	1.74	1.70
CRC-ETOH15	1.08	92.8	14.85	1.60	1.30

*Median and mean PM are "averaged over" all vehicles and tests within each fuel.

Table 58. Results of the Kruskal-Wallis test (C_9-C_{12} only)

Test Statistic H = 6955
df = 14
Chi-sq = 23.7, 14 df, alpha = 0.05
Prob(H > 23.7) = 0.0000

The Mann-Whitney (Wilcoxon) U-Test, a nonparametric version of the ordinary two-sample t-test, is an extension of the Kruskal-Wallis test that permits a comparison of the rank-sums associated with pairs of fuels. Since there are 15 fuels, there are 105 paired comparisons to consider.[17] The results of the test are shown in Table 59. Pairs of fuels for which the difference in rank sums is statistically significant at the .10 level are indicated in yellow.

[17] While an adjustment could be made using the Bonferroni method to accommodate consideration of multiple comparisons, no such procedure is applied here.

Table 59. Results of the Mann-Whitney (Wilcoxon) U-test showing the significance of differences in rank sums for all pairs of fuels, listed in p-value order.

Fuel 1	Fuel 2	p-Value
G_E10	B	3.40E-05
C_E10	B	9.22E-05
CRC_E15	B	0.000129
B	G	0.000336
CRC_E10	B	0.000457
G_E10	F	0.00249
B	C	0.00283
D_E10	B	0.006923
C_E10	F	0.007191
CRC_C	G_E10	0.007734
CRC_E15	F	0.011042
H_E10	B	0.012523
F	G	0.01286
G_E10	E	0.014625
B	D	0.021512
A	B	0.024379
CRC_E10	F	0.025721
G_E10	A	0.026201
CRC_C	C_E10	0.02808
G_E10	D	0.033534
CRC_C	CRC_E15	0.035771
CRC_C	G	0.037429
C_E10	E	0.039255
G_E10	H	0.041707
CRC_E15	E	0.045852
E	G	0.052396

Fuel 1	Fuel 2	p-Value
CRC_C	B	0.056342
B	H	0.05765
C_E10	A	0.072962
CRC_C	CRC_E10	0.075209
D_E10	G_E10	0.075409
C	F	0.078461
CRC_E10	E	0.081006
A	G	0.101336
B	E	0.106242
C_E10	D	0.108879
CRC_E15	A	0.121416
G_E10	C	0.12169
D	G	0.122974
C_E10	H	0.137912
G	H	0.141343
D_E10	F	0.144381
H_E10	F	0.145914
CRC_E15	H	0.152703
G_E10	H_E10	0.153689
CRC_E15	D	0.178938
C_E10	D_E10	0.214205
CRC_C	C	0.21471
CRC_E10	A	0.218143
CRC_E10	G_E10	0.218448
D_E10	G	0.222394
C	E	0.228204

Fuel 1	Fuel 2	p-Value
CRC_E10	H	0.245485
D	F	0.269658
B	F	0.278643
A	F	0.290706
CRC_E10	D	0.303239
CRC_C	D_E10	0.315024
C_E10	C	0.327231
CRC_E15	G_E10	0.337159
C	G	0.343538
H_E10	G	0.348701
CRC_E15	D_E10	0.349655
C_E10	H_E10	0.356729
D_E10	E	0.36124
F	H	0.38522
H_E10	E	0.401654
CRC_C	H_E10	0.405046
CRC_E15	H_E10	0.409778
A	C	0.426797
C	H	0.464507
CRC_E15	C	0.466912
C	D	0.471095
C_E10	G_E10	0.472777
CRC_C	F	0.49059
CRC_E10	D_E10	0.530163
CRC_E10	G	0.53953
H_E10	H	0.544555

Fuel 1	Fuel 2	p-Value
CRC_E10	C_E10	0.550313
G_E10	G	0.565281
CRC_C	D	0.571718
CRC_E10	H_E10	0.575555
D_E10	A	0.6032
D	E	0.606838
H_E10	A	0.609223
H_E10	D	0.610926
E	F	0.637295
CRC_C	A	0.657079
CRC_E10	CRC_E15	0.664496
A	E	0.670331
D_E10	H	0.672575
D_E10	D	0.681767
CRC_E10	C	0.684475
CRC_E15	G	0.729521
D_E10	C	0.755094
CRC_E15	C_E10	0.768077
E	H	0.790018
CRC_C	H	0.799081
CRC_C	E	0.831497
D_E10	H_E10	0.861521
C_E10	G	0.874708
H_E10	C	0.889235
A	D	0.919651
D	H	0.942343
A	H	0.942828

Table 60 compares the results shown in Table 59 above with those obtained from an analysis of the combined PM data from the E-94-2, E-94-3, and E-129 programs, ignoring program and vehicle differences (Table A2 in the Appendix, Column F). While Table 60 is not strictly an "apples to apples" comparison (because one procedure is parametric and the other is non-parametric, and the two types of data are different), it does provide an approximate picture of how differences among the fuels are assessed based on mean PM and how they are assessed based on the sum of ranks assigned to DHA constituents.

Table 60. Comparison of the results of evaluating differences among fuels based on two different statistical approaches: (1) differences in mean PM and (2) differences in sum of ranks assigned to constituents within C_9 thru C_{12}.

Fuel 1	Fuel 2	Significant Difference Mean PM	Significant Difference Sum of Ranks
A	B	Yes	Yes
A	C	No	No
A	D	No	No
A	E	No	No
A	F	No	No
A	G	No	No
A	H	No	No
A	C_E10	No	Yes
A	D_E10	No	No
A	G_E10	No	Yes
A	H_E10	No	No
A	CRC_C	No	No
A	CRC_E10	No	No
A	CRC_E15	No	No
B	C	Yes	Yes
B	D	No	Yes
B	E	No	No
B	F	No	No
B	G	Yes	Yes
B	H	No	Yes
B	C_E10	Yes	Yes
B	D_E10	No	Yes
B	G_E10	No	Yes
B	H_E10	No	Yes
B	CRC_C	Yes	Yes
B	CRC_E10	Yes	Yes
B	CRC_E15	Yes	Yes
C	D	Yes	No
C	E	No	No
C	F	Yes	Yes
C	G	No	No
C	H	No	No
C	C_E10	No	No
C	D_E10	No	No
C	G_E10	No	No
C	H_E10	No	No
C	CRC_C	No	No
C	CRC_E10	No	No
C	CRC_E15	No	No
D	E	No	No
D	F	Yes	No
D	G	No	No
D	H	No	No
D	C_E10	No	No
D	D_E10	No	No
D	G_E10	No	Yes
D	H_E10	No	No
D	CRC_C	Yes	No
D	CRC_E10	Yes	No
D	CRC_E15	Yes	No
E	F	No	No
E	G	No	Yes
E	H	No	No
E	C_E10	No	Yes
E	D_E10	No	No
E	G_E10	No	Yes
E	H_E10	No	No
E	CRC_C	No	No
E	CRC_E10	No	Yes
E	CRC_E15	No	Yes
F	G	Yes	Yes
F	H	No	No
F	C_E10	No	Yes
F	D_E10	No	No
F	G_E10	No	Yes
F	H_E10	No	No
F	CRC_C	Yes	No
F	CRC_E10	Yes	Yes
F	CRC_E15	Yes	Yes
G	H	No	No
G	C_E10	No	No
G	D_E10	No	No
G	G_E10	No	No
G	H_E10	No	No
G	CRC_C	No	Yes
G	CRC_E10	No	No
G	CRC_E15	No	No
H	C_E10	No	No
H	D_E10	No	No
H	G_E10	No	Yes
H	H_E10	No	No
H	CRC_C	No	No
H	CRC_E10	No	No
H	CRC_E15	No	No
C_E10	D_E10	No	No
C_E10	G_E10	No	No
C_E10	H_E10	No	No
C_E10	CRC_C	No	Yes
C_E10	CRC_E10	No	No
C_E10	CRC_E15	No	No
D_E10	G_E10	No	Yes
D_E10	H_E10	No	No
D_E10	CRC_C	No	No
D_E10	CRC_E10	No	No
D_E10	CRC_E15	No	No
G_E10	H_E10	No	No
G_E10	CRC_C	No	Yes
G_E10	CRC_E10	No	No
G_E10	CRC_E15	No	No
H_E10	CRC_C	No	No
H_E10	CRC_E10	No	No
H_E10	CRC_E15	No	No
CRC_C	CRC_E10	No	Yes
CRC_C	CRC_E15	No	Yes
CRC_E10	CRC_E15	No	No

Table 61 summarizes the comparative results shown in Table 60. The results of the two methods match with respect to 73.4% of the pairs.

Table 61. Summary of the results of comparing pairs of fuels on the basis of two different approaches: (1) difference in mean PM and (2) difference in sum of ranks assigned to DHA constituents within C_9-C_{12}.

		Based on Differences in Sums of Ranks Assigned to DHA Constituents: Yes	Based on Differences in Sums of Ranks Assigned to DHA Constituents: No	
Based on Differences in Mean PM	Yes	11 10.5%	6 5.7%	17 16.2%
	No	22 21.0%	66 62.9%	88 83.8%
		33 31.4%	72 68.6%	105

Yes=Statistically significant difference

Whereas the Kruskal-Wallis test is a non-parametric equivalent to one-way analysis of variance, it is also possible to investigate the ranks assigned to constituents organized as a two-analysis of variance. In this case, the Friedman rank sum test is the non-parametric equivalent. The

difference here is that the constituents within fuels must be exactly the same (i.e., the data arrangement must be completely balanced). Consequently, in order to conduct the Friedman test, it is necessary to omit all rows from the equivalent of Table 53 for which the constituent is missing in any fuel. This results in reducing the number of possible constituents (rows) from 185 to 112, thereby giving up information on some of the fuels. However, in most cases, the omitted values are associated with small ranks (i.e., small constituent Wgt% values) and the overall effect is generally minimal. The results of the Friedman test, which are shown for completeness only, are reported in Table 62. The results again suggest that there is, indeed, a difference among the fuels on the basis of their constituent makeup relative to C_9-C_{12}, but because of the data reduction issue, no further assessment of differences in fuel pairs was performed.

Table 62. Results of the Friedman rank sum test

Friedman Chi-squared (X^2) = 196.47, df = 14, p-value < 2.2e-16

In lieu of conducting a formal test of differences in pairs of fuels based on the Friedman rank sum test, a purely descriptive, quasi-two-way examination can be made by constructing a balanced file organized so that all possible constituents are represented in every fuel. To achieve the required two-way balance, values of zero are assigned to missing/empty cells, and the zeroes are included in any ordering process. The file is limited to the 185 rows associated with C_9-C_{12}.

A partial listing of this file is shown in Table 63, with constituent Wgt% values sorted (high to low) on the basis of Fuel B. The cells that are color coded within each fuel represent the top 25% constituents in terms of Wgt%. Note that they are not rank order for any fuel except for Fuel B. The top panel shows the first 37 rows (first 20%) and the bottom panel shows the second 37 rows (second 20%).

In this view it is apparent that constituents within C_9 and C_{10} dominate the top quartile for every fuel. Observe the relative absence of constituents associated with C_{11} and C_{12}. Further observe the predominance of Mono-Aromatics in the top panel, and the appearance of more I-Paraffins in the bottom panel. These observations lend credence to the regression results contained in Table 42 and Figures 25 and 26 concerning the importance of C_9, C_{10}, Mono-Aromatics, and I-Paraffins for predicting mean and median PM. The presence of a few Naphtheno/Olefino-Benzs constituents in the top panel and only one in the bottom panel, lends credence to the regression results shown in Figure 27 concerning the dual grouping of fuels, since most of the Naphtheno/Olefino-Benzs constituents have Wgt% values that are small and found in the lower quartiles for each fuel (not shown here).

Table 63 (A,B). Partial listing of Wgt% of constituents within groups and carbons, with values ordered from high to low within each fuel: (A) first 37 rows, or first 20% and (B) second 37 rows, or second 20%. Cells associated with the top quartile of constituents in terms of Wgt% within each fuel are color coded. Zeroes are assigned to empty cells as placeholders.

(A)

			Median PM	1.75	1.74	1.60	1.77	2.51	5.09	5.17	3.45	7.70	3.10	6.70	4.10	6.70	2.45	6.15
			Mean PM	1.67	1.70	1.30	3.50	6.43	3.84	5.99	4.12	8.59	3.14	7.13	4.23	7.01	3.05	5.92
			AKI	88.20	91.70	92.80	91.50	91.10	96.40	96.00	87.20	87.1	87.90	88.20	93.60	93.70	93.80	94.1
			EtOH	0.00	9.97	14.85	9.44	9.71	9.75	9.88	9.55	9.56	0.00	0.00	9.56	9.51	0.00	0
			PMI	1.30	1.16	1.08	1.28	2.45	1.17	2.32	1.42	2.64	1.42	2.65	1.30	2.55	1.27	2.49
Carbon	**Group**	**Constituent**		**CRC_C**	**CRC_E10**	**CRC_E15**	**C_E10**	**D_E10**	**G_E10**	**H_E10**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
C9	Mono-Aromatics	1,2,4-Trimethylbenzene		0.611	0.541	0.517	1.506	2.943	2.837	1.984	1.534	3.515	1.696	3.227	3.120	2.172	3.118	2.166
C9	Mono-Aromatics	1-Methyl-3-ethylbenzene		0.372	0.332	0.317	0.925	1.765	1.669	1.152	0.945	2.106	1.039	1.935	1.820	1.269	1.834	1.261
C9	Mono-Aromatics	1,3,5-Trimethylbenzene		0.229	0.201	0.192	0.497	0.947	1.013	0.702	0.523	1.200	0.568	1.039	1.142	0.801	1.113	0.768
C9	Mono-Aromatics	1-Methyl-4-ethylbenzene		0.171	0.149	0.142	0.414	0.790	0.766	0.530	0.439	0.971	0.469	0.866	0.855	0.596	0.842	0.580
C10	Mono-Aromatics	1,2,3,5-Tetramethylbenzene		0.281	0.252	0.241	0.252	0.843	0.300	1.022	0.186	0.894	0.284	0.918	0.334	1.102	0.328	1.115
C9	Paraffin	n-Nonane		0.908	0.823	0.784	0.631	0.229	0.306	0.290	0.914	0.871	0.688	0.250	0.749	0.505	0.335	0.313
C10	Mono-Aromatics	1,2-Dimethyl-4-ethylbenzene		0.285	0.253	0.241	0.288	0.748	0.257	0.788	0.295	0.783	0.313	0.814	0.294	0.858	0.281	0.869
C9	Mono-Aromatics	1,2,3-Trimethylbenzene		0.167	0.138	0.132	0.347	0.631	0.424	0.336	0.445	0.758	0.390	0.699	0.474	0.384	0.465	0.370
C9	Mono-Aromatics	1-Methyl-2-ethylbenzene		0.129	0.113	0.108	0.322	0.607	0.531	0.367	0.350	0.724	0.362	0.665	0.583	0.407	0.584	0.404
C10	Mono-Aromatics	1,2,4,5-Tetramethylbenzene		0.202	0.181	0.173	0.193	0.593	0.219	0.725	0.132	0.627	0.219	0.646	0.249	0.796	0.239	0.789
C9	Mono-Aromatics	n-Propylbenzene		0.144	0.129	0.123	0.286	0.526	0.409	0.283	0.331	0.626	0.320	0.575	0.469	0.325	0.450	0.311
C9	I-Paraffins	3-Methyloctane		0.424	0.380	0.363	0.586	0.193	0.242	0.237	0.693	0.625	0.647	0.213	0.559	0.344	0.265	0.264
C10	Mono-Aromatics	1-Methyl-3-n-propylbenzene		0.373	0.333	0.318	0.335	0.535	0.381	0.463	0.362	0.504	0.379	0.587	0.345	0.439	0.416	0.508
C10	Naphtheno/Olefino-Benzs	4-Methylindan		0.167	0.149	0.142	0.120	0.453	0.159	0.545	0.100	0.483	0.135	0.496	0.177	0.588	0.172	0.594
C11	Naphthalenes	2-MethylNaphthalene		0.129	0.107	0.102	0.129	0.430	0.005	0.429	0.139	0.465	0.146	0.473	0.003	0.46	0.005	0.469
C10	Paraffin	n-Decane		0.169	0.147	0.141	0.171	0.129	0.019	0.032	0.425	0.445	0.201	0.145	0.372	0.256	0.020	0.048
C9	I-Paraffins	2-Methyloctane		0.277	0.250	0.238	0.376	0.169	0.140	0.137	0.442	0.405	0.417	0.186	0.311	0.191	0.153	0.151
C10	Naphthalenes	Naphthalene		0.150	0.133	0.128	0.141	0.389	0.094	0.366	0.157	0.397	0.159	0.425	0.082	0.415	0.097	0.400
C10	Mono-Aromatics	1,3-Dimethyl-4-ethylbenzene		0.000	0.000	0.000	0.268	0.447	0.000	0.353	0.177	0.386	0.126	0.486	0.106	0.409	0.000	0.583
C10	Mono-Aromatics	1,3-Dimethyl-5-ethylbenzene		0.121	0.107	0.103	0.149	0.351	0.100	0.297	0.199	0.386	0.170	0.385	0.121	0.33	0.110	0.324
C9	Mono-Naphthenes	1c,2t,4t-Trimethylcyclohexane		0.249	0.224	0.214	0.411	0.028	0.225	0.219	0.438	0.381	0.456	0.030	0.487	0.301	0.248	0.243
C10	Naphtheno/Olefino-Benzs	5-Methylindan		0.142	0.126	0.121	0.095	0.349	0.124	0.410	0.093	0.367	0.106	0.382	0.135	0.441	0.135	0.448
C9	I-Paraffins	2,2,5-Trimethylhexane		1.366	1.233	1.173	0.899	0.959	1.594	1.415	0.364	0.358	0.991	1.058	1.077	0.986	1.758	1.566
C10	Mono-Aromatics	1,4,Dimethyl-2-ethylbenzene		0.000	0.085	0.081	0.118	0.328	0.409	0.311	0.165	0.358	0.134	0.357	0.094	0.431	0.446	0.325
C9	I-Paraffins	4-Methyloctane		0.224	0.202	0.193	0.310	0.139	0.118	0.116	0.369	0.337	0.347	0.153	0.261	0.159	0.129	0.126
C9	Mono-Naphthenes	C9 - MonoNaph - 1		0.232	0.209	0.199	0.346	0.011	0.185	0.000	0.379	0.333	0.384	0.012	0.403	0.246	0.204	0.200
C9	Naphtheno/Olefino-Benzs	Indan		0.109	0.095	0.090	0.142	0.253	0.165	0.145	0.188	0.315	0.167	0.283	0.206	0.173	0.182	0.159
C10	Naphtheno/Olefino-Benzs	2-Methylindan(1)		0.091	0.080	0.077	0.088	0.411	0.096	0.329	0.105	0.306	0.098	0.316	0.107	0.357	0.104	0.361
C9	I-Paraffins	2,5-Dimethylheptane		0.274	0.247	0.236	0.301	0.165	0.188	0.175	0.328	0.302	0.335	0.183	0.268	0.183	0.206	0.193
C9	Mono-Naphthenes	trans-1,3-Diethylcyclopentane		0.229	0.206	0.197	0.208	0.032	0.091	0.090	0.289	0.265	0.232	0.035	0.260	0.163	0.101	0.099
C10	Mono-Aromatics	1,4-Diethylbenzene		0.168	0.116	0.111	0.150	0.261	0.124	0.228	0.152	0.262	0.174	0.286	0.134	0.305	0.135	0.250
C10	Mono-Aromatics	1,2-Dimethyl-3-ethylbenzene		0.126	0.073	0.070	0.076	0.258	0.070	0.292	0.098	0.244	0.083	0.280	0.084	0.3	0.076	0.315
C9	I-Paraffins	2,6-Dimethylheptane		0.214	0.182	0.174	0.246	0.062	0.154	0.146	0.290	0.242	0.273	0.068	0.273	0.175	0.168	0.161
C11	Naphthalenes	1-MethylNaphthalene		0.050	0.044	0.042	0.061	0.206	0.001	0.194	0.065	0.220	0.068	0.221	0.000	0.207	0.000	0.211
C11	Mono-Aromatics	tert-Pentylbenzene		0.078	0.065	0.066	0.050	0.192	0.067	0.217	0.051	0.205	0.062	0.211	0.071	0.235	0.070	0.233
C11	Mono-Aromatics	1-methyl-4-(1-methylpropyl)be		0.076	0.067	0.064	0.050	0.183	0.066	0.217	0.046	0.193	0.056	0.200	0.072	0.234	0.071	0.241

(B)

			Median PM	1.75	1.74	1.60	1.77	2.51	5.09	5.17	3.45	7.70	3.10	6.70	4.10	6.70	2.45	6.15
			Mean PM	1.67	1.70	1.30	3.50	6.43	3.84	5.99	4.12	8.59	3.14	7.13	4.23	7.01	3.05	5.92
			AKI	88.20	91.70	92.80	91.50	91.10	96.40	96.00	87.20	87.1	87.90	88.20	93.60	93.70	93.80	94.1
			EtOH	0.00	9.97	14.85	9.44	9.71	9.75	9.88	9.55	9.56	0.00	0.00	9.56	9.51	0.00	0
			PMI	1.30	1.16	1.08	1.28	2.45	1.17	2.32	1.42	2.64	1.42	2.65	1.30	2.55	1.27	2.49
Carbon	**Group**	**Constituent**		**CRC_C**	**CRC_E10**	**CRC_E15**	**C_E10**	**D_E10**	**G_E10**	**H_E10**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
C10	I-Paraffins	2,2,4-trimethylheptane		0.309	0.279	0.266	0.185	0.117	0.195	0.177	0.191	0.180	0.207	0.128	0.235	0.177	0.214	0.195
C10	Mono-Aromatics	1-Methyl-2-n-propylbenzene		0.056	0.049	0.047	0.067	0.141	0.034	0.110	0.105	0.177	0.078	0.153	0.062	0.178	0.037	0.119
C12	Mono-Aromatics	1,4-Di-i-propylbenzene		0.055	0.048	0.046	0.044	0.161	0.057	0.187	0.039	0.170	0.049	0.176	0.064	0.209	0.058	0.204
C9	Mono-Naphthenes	1,1-Methylethylcyclohexane		0.145	0.134	0.127	0.097	0.024	0.037	0.036	0.160	0.156	0.111	0.026	0.140	0.091	0.041	0.038
C10	I-Paraffins	4-Methylnonane		0.067	0.058	0.056	0.068	0.062	0.016	0.011	0.146	0.153	0.079	0.068	0.097	0.065	0.017	0.012
C10	I-Paraffins	3-Methylnonane		0.060	0.050	0.047	0.070	0.078	0.022	0.014	0.137	0.150	0.081	0.089	0.079	0.053	0.023	0.015
C10	Mono-Aromatics	1,3-Diethylbenzene		0.045	0.039	0.037	0.058	0.118	0.044	0.068	0.094	0.145	0.071	0.130	0.063	0.085	0.048	0.075
C12	Mono-Aromatics	1,3-Di-n-propylbenzene		0.078	0.050	0.047	0.038	0.131	0.035	0.118	0.059	0.138	0.042	0.144	0.037	0.128	0.036	0.129
C9	I-Paraffins	2,4-Dimethylheptane		0.113	0.103	0.098	0.132	0.062	0.072	0.068	0.150	0.137	0.146	0.068	0.117	0.077	0.079	0.075
C11	Mono-Aromatics	Benzene, 1-methyl-4-(2-methylp		0.064	0.058	0.055	0.033	0.000	0.043	0.143	0.000	0.129	0.039	0.134	0.046	0.151	0.046	0.154
C11	I-Paraffins	C11-Isoparaffin-5		0.051	0.043	0.041	0.037	0.014	0.003	0.000	0.135	0.128	0.048	0.016	0.088	0.075	0.004	0.000
C10	I-Paraffins	2,6-Dimethyloctane		0.098	0.088	0.084	0.062	0.044	0.012	0.010	0.127	0.125	0.069	0.048	0.090	0.062	0.013	0.013
C11	Mono-Aromatics	C11 - Aromatic - 3		0.073	0.066	0.063	0.043	0.127	0.070	0.162	0.029	0.124	0.050	0.139	0.063	0.166	0.075	0.174
C12	Mono-Aromatics	1,2-Di-i-propylbenzene		0.049	0.043	0.041	0.032	0.117	0.047	0.149	0.024	0.123	0.036	0.128	0.050	0.159	0.051	0.163
C11	I-Paraffins	C11- Isoparaffin-11		0.232	0.207	0.198	0.149	0.171	0.203	0.031	0.119	0.122	0.169	0.186	0.167	0.147	0.221	0.197
C11	Mono-Aromatics	C11 - Aromatic - 7		0.055	0.049	0.046	0.033	0.118	0.044	0.126	0.037	0.121	0.037	0.128	0.044	0.136	0.045	0.137
C10	Mono-Aromatics	1,3-Dimethyl-2-ethylbenzene		0.189	0.167	0.159	0.180	0.191	0.249	0.248	0.092	0.114	0.205	0.204	0.188	0.202	0.271	0.266
C9	Mono-Naphthenes	1,2,3,5-t-Tetramethylcyclohex		0.106	0.096	0.091	0.049	0.000	0.008	0.007	0.109	0.108	0.055	0.000	0.088	0.058	0.009	0.009
C9	Mono-Aromatics	i-Propylbenzene		0.046	0.042	0.040	0.063	0.092	0.018	0.013	0.091	0.102	0.072	0.100	0.024	0.017	0.020	0.015
C11	I-Paraffins	C11-Isoparaffin-7		0.111	0.097	0.092	0.095	0.085	0.106	0.093	0.099	0.101	0.114	0.094	0.128	0.104	0.116	0.104
C11	Mono-Aromatics	C11 - Aromatic - 4		0.050	0.043	0.041	0.031	0.099	0.046	0.123	0.027	0.101	0.036	0.108	0.044	0.129	0.049	0.129
C9	Mono-Naphthenes	1c,2t,4c-Trimethylcyclohexane		0.065	0.059	0.056	0.097	0.015	0.049	0.048	0.111	0.099	0.111	0.011	0.117	0.072	0.054	0.052
C10	Mono-Aromatics	n-Butylbenzene		0.000	0.033	0.032	0.040	0.088	0.018	0.057	0.064	0.099	0.047	0.097	0.024	0	0.020	0.061
C9	I-Paraffins	4-Ethylheptane		0.062	0.056	0.053	0.091	0.037	0.036	0.035	0.108	0.098	0.103	0.041	0.080	0.049	0.040	0.038
C9	I-Paraffins	Heptane, 3-ethyl-		0.058	0.054	0.051	0.088	0.041	0.033	0.032	0.105	0.098	0.100	0.045	0.073	0.044	0.036	0.034
C10	I-Paraffins	2,2,6-Trimethyloctane		0.572	0.513	0.490	0.302	0.310	0.377	0.329	0.217	0.096	0.341	0.340	0.302	0.264	0.412	0.361
C11	Mono-Aromatics	1-Methyl-2-n-butylbenzene		0.037	0.026	0.025	0.022	0.091	0.029	0.097	0.018	0.096	0.024	0.099	0.032	0.108	0.030	0.106
C10	I-Paraffins	2,5-Dimethyloctane		0.077	0.070	0.066	0.057	0.067	0.017	0.000	0.096	0.095	0.055	0.071	0.059	0.041	0.018	0.017
C10	Mono-Aromatics	i-Butylbenzene		0.087	0.076	0.073	0.061	0.076	0.082	0.068	0.067	0.093	0.070	0.085	0.087	0.067	0.090	0.075
C9	Mono-Naphthenes	1,1,3-Trimethylcyclohexane		0.064	0.058	0.055	0.090	0.014	0.044	0.043	0.104	0.093	0.103	0.016	0.097	0.059	0.049	0.048
C12	Naphthalenes	DimethylNaphthalene-5		0.006	0.006	0.005	0.025	0.092	0.000	0.091	0.018	0.092	0.028	0.089	0.000	0.102	0.000	0.102
C11	I-Paraffins	2,5,6-Trimethyloctane		0.224	0.198	0.189	0.249	0.216	0.306	0.272	0.083	0.090	0.295	0.237	0.240	0.216	0.335	0.299
C11	Paraffin	n-Undecane		0.064	0.057	0.054	0.049	0.068	0.033	0.051	0.106	0.089	0.056	0.073	0.063	0.069	0.035	0.053
C10	Naphtheno/Olefino-Benzs	2-Methylindan		0.061	0.054	0.051	0.051	0.077	0.045	0.056	0.071	0.086	0.060	0.083	0.059	0.065	0.049	0.061
C9	Mono-Naphthenes	C9 - MonoNaph - 4		0.051	0.047	0.045	0.080	0.013	0.040	0.039	0.092	0.081	0.093	0.015	0.090	0.055	0.043	0.043
C11	Mono-Aromatics	1-Methyl-4-t-butylbenzene		0.033	0.029	0.028	0.032	0.068	0.020	0.081	0.025	0.078	0.020	0.074	0.036	0.085	0.022	0.086
C11	Mono-Aromatics	Pentamethylbenzene		0.018	0.015	0.014	0.021	0.071	0.000	0.065	0.027	0.078	0.026	0.079	0.000	0.069	0.000	0.071

*Median and mean PM are "averaged over" all vehicles and tests within each fuel.

To underscore the observations from Table 63, Tables 64 and 65 (a revision of Table 44) contain the total Wgt% for C_9-C_{12} summed over all groups and constituents in groups, and the total Wgt% for groups summed over all carbons and constituents in carbons, respectively. The top panel of Table 64 indicates the highest (red) and lowest (blue) totals among all 15 fuels for each of the carbons (row-wise perspective), while the bottom panel indicates the highest (red) and lowest (blue) totals among C_9 thru C_{12} for each individual fuel (column-wise perspective). Note that Fuel B has the highest total with respect to C_9 and the highest mean and median PM. In addition, Fuels F, H, and D has the highest totals with respect to C_{10}, C_{11}, and C_{12}, and are associated with some of the highest mean and median PM values. The bottom panel of Table 64 shows that C_9 has the highest total within each fuel and C_{12} has the lowest (also apparent in Figure 20).

The top panel in Table 65 indicates the highest (red) and lowest (blue) totals among all 15 fuels for each of the groups (row-wise perspective), while the bottom panel indicates the highest (red) and lowest (blue) totals among the groups for each individual fuel (column-wise perspective).

Within the Mono-Aromatics, the largest total is associated with Fuel B, which, again, has the highest mean and median PM values. Within the I-Paraffins, Fuel CRC-C has the largest total. Note that the largest totals within Paraffins, Mono-Naphthenes, and Iso-Olefins are all associated with Fuel A, which has moderately low mean and median PM values, and that the largest totals within Naphtheno/Olefino-Benzs, Naphthalenes, and Indenes are all associated with Fuel D, which has among the highest mean and median PM values. The bottom panel of Table 65 indicates that the largest group total is associated with Mono-Aromatics within all fuels except the three E-129 fuels. For those three fuels, the largest group total is associated with I-Paraffins, suggesting there is something different about these three fuels which are based on the original Fuel C in the E-94-2 program.

Table 64. Total Wgt% for C_9 thru C_{12}, summed over groups and constituents within groups, with (A) highest and lowest values among all 15 fuels within each carbon indicated in red and blue, respectively, and (B) highest and lowest values among all C_9 thru C_{12} within each fuel indicated in red and blue, respectively.

(A)

Median PM	1.75	1.74	1.6	1.77	2.51	5.09	5.17	3.45	7.70	3.10	6.70	4.1	6.7	2.45	6.15
Mean PM	1.67	1.7	1.3	3.5	6.43	3.84	5.99	4.12	8.59	3.14	7.13	4.23	7.01	3.05	5.92
AKI	88.2	91.7	92.8	91.5	91.1	96.4	96	87.2	87.1	87.9	88.2	93.6	93.7	93.8	94.1
EtOH	0	9.97	14.85	9.44	9.71	9.75	9.88	9.55	9.56	0	0	9.56	9.51	0	0
PMI	1.3	1.16	1.08	1.28	2.45	1.17	2.32	1.42	2.64	1.42	2.65	1.3	2.55	1.27	2.49
Carbon	**CRC_C**	**CRC_E10**	**CRC_E15**	**C_E10**	**D_E10**	**G_E10**	**H_E10**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
C9	7.67	6.87	6.549	10.181	11.207	11.946	9.155	10.915	15.901	11.365	12.266	14.726	10.444	13.136	10.346
C10	4.995	4.414	4.218	4.321	8.031	3.998	7.792	5.14	9.033	4.761	8.636	4.972	9.037	4.355	8.707
C11	2.242	1.987	1.894	1.655	2.966	1.681	3.243	1.734	3.306	1.927	3.386	1.793	3.403	1.808	3.484
C12	0.567	0.459	0.439	0.338	1.179	0.236	0.937	0.504	1.174	0.375	1.255	0.227	1.037	0.241	0.97

(B)

Median PM	1.75	1.74	1.6	1.77	2.51	5.09	5.17	3.45	7.70	3.10	6.70	4.1	6.7	2.45	6.15
Mean PM	1.67	1.7	1.3	3.5	6.43	3.84	5.99	4.12	8.59	3.14	7.13	4.23	7.01	3.05	5.92
AKI	88.2	91.7	92.8	91.5	91.1	96.4	96	87.2	87.1	87.9	88.2	93.6	93.7	93.8	94.1
EtOH	0	9.97	14.85	9.44	9.71	9.75	9.88	9.55	9.56	0	0	9.56	9.51	0	0
PMI	1.3	1.16	1.08	1.28	2.45	1.17	2.32	1.42	2.64	1.42	2.65	1.3	2.55	1.27	2.49
Carbon	**CRC_C**	**CRC_E10**	**CRC_E15**	**C_E10**	**D_E10**	**G_E10**	**H_E10**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
C9	7.67	6.87	6.549	10.181	11.207	11.946	9.155	10.915	15.901	11.365	12.266	14.726	10.444	13.136	10.346
C10	4.995	4.414	4.218	4.321	8.031	3.998	7.792	5.14	9.033	4.761	8.636	4.972	9.037	4.355	8.707
C11	2.242	1.987	1.894	1.655	2.966	1.681	3.243	1.734	3.306	1.927	3.386	1.793	3.403	1.808	3.484
C12	0.567	0.459	0.439	0.338	1.179	0.236	0.937	0.504	1.174	0.375	1.255	0.227	1.037	0.241	0.97

*Median and mean PM are “averaged over” all vehicles and tests within each fuel.

Table 65. Total Wgt% for all groups, summed over carbons and constituents within carbons, with (A) highest and lowest values among all 15 fuels within each group indicated in red and blue, respectively, and (B) highest and lowest values among all groups within each fuel indicated in red and blue, respectively.

(A)

Median PM	1.75	1.74	1.60	1.77	2.51	5.09	5.17	3.45	7.70	3.10	6.70	4.10	6.70	2.45	6.15
Mean PM	1.67	1.70	1.30	3.50	6.43	3.84	5.99	4.12	8.59	3.14	7.13	4.23	7.01	3.05	5.92
AKI	88.20	91.70	92.80	91.50	91.10	96.40	96.00	87.20	87.1	87.90	88.20	93.60	93.70	93.80	94.1
EtOH	0.00	9.97	14.85	9.44	9.71	9.75	9.88	9.55	9.56	0.00	0.00	9.56	9.51	0.00	0
PMI	1.30	1.16	1.08	1.28	2.45	1.17	2.32	1.42	2.64	1.42	2.65	1.30	2.55	1.27	2.49
Group	**CRC_C**	**CRC_E10**	**CRC_E15**	**C_E10**	**D_E10**	**G_E10**	**H_E10**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Mono-Aromatics	4.923	4.371	4.175	7.31	15.243	10.792	12.5	7.615	17.223	8.083	16.823	11.516	13.732	11.81	13.85
I-Paraffins	6.454	5.74	5.472	5.355	3.968	4.957	4.476	5.396	5.047	6.027	4.36	5.804	4.503	5.435	4.892
Naphtheno/Olefino-Benzs	0.849	0.728	0.696	0.592	1.92	0.638	1.72	0.766	1.954	0.68	1.969	0.737	1.848	0.686	1.826
Paraffin	1.159	1.042	0.993	0.86	0.452	0.36	0.377	1.468	1.435	0.955	0.496	1.185	0.833	0.392	0.418
Mono-Naphthenes	1.302	1.169	1.113	1.511	0.222	0.722	0.522	1.969	1.775	1.718	0.19	1.915	1.197	0.794	0.775
Naphthalenes	0.349	0.304	0.291	0.406	1.296	0.105	1.259	0.424	1.357	0.458	1.383	0.085	1.372	0.107	1.353
Iso-Olefins	0.266	0.224	0.214	0.279	0.098	0.076	0.077	0.448	0.427	0.295	0.126	0.317	0.217	0.089	0.097
n-Olefins	0.118	0.105	0.1	0.123	0.156	0.186	0.169	0.134	0.128	0.145	0.175	0.1	0.086	0.199	0.179
Naphtheno-Olefins	0.042	0.038	0.037	0.055	0.016	0.025	0.025	0.063	0.056	0.062	0.008	0.059	0.133	0.028	0.114
Indenes	0.012	0.009	0.009	0.004	0.012	0	0.002	0.01	0.012	0.005	0.013	0	0	0	0.003

(B)

Median PM	**1.75**	**1.74**	**1.60**	**1.77**	**2.51**	**5.09**	**5.17**	**3.45**	**7.70**	**3.10**	**6.70**	**4.10**	**6.70**	**2.45**	**6.15**
Mean PM	1.67	1.70	1.30	3.50	6.43	3.84	5.99	4.12	8.59	3.14	7.13	4.23	7.01	3.05	5.92
AKI	88.20	91.70	92.80	91.50	91.10	96.40	96.00	87.20	87.1	87.90	88.20	93.60	93.70	93.80	94.1
EtOH	0.00	9.97	14.85	9.44	9.71	9.75	9.88	9.55	9.56	0.00	0.00	9.56	9.51	0.00	0
PMI	1.30	1.16	1.08	1.28	2.45	1.17	2.32	1.42	2.64	1.42	2.65	1.30	2.55	1.27	2.49
Group	**CRC_C**	**CRC_E10**	**CRC_E15**	**C_E10**	**D_E10**	**G_E10**	**H_E10**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Mono-Aromatics	4.923	4.371	4.175	7.31	15.243	10.792	12.5	7.615	17.223	8.083	16.823	11.516	13.732	11.81	13.85
I-Paraffins	6.454	5.74	5.472	5.355	3.968	4.957	4.476	5.396	5.047	6.027	4.36	5.804	4.503	5.435	4.892
Naphtheno/Olefino-Benzs	0.849	0.728	0.696	0.592	1.92	0.638	1.72	0.766	1.954	0.68	1.969	0.737	1.848	0.686	1.826
Paraffin	1.159	1.042	0.993	0.86	0.452	0.36	0.377	1.468	1.435	0.955	0.496	1.185	0.833	0.392	0.418
Mono-Naphthenes	1.302	1.169	1.113	1.511	0.222	0.722	0.522	1.969	1.775	1.718	0.19	1.915	1.197	0.794	0.775
Naphthalenes	0.349	0.304	0.291	0.406	1.296	0.105	1.259	0.424	1.357	0.458	1.383	0.085	1.372	0.107	1.353
Iso-Olefins	0.266	0.224	0.214	0.279	0.098	0.076	0.077	0.448	0.427	0.295	0.126	0.317	0.217	0.089	0.097
n-Olefins	0.118	0.105	0.1	0.123	0.156	0.186	0.169	0.134	0.128	0.145	0.175	0.1	0.086	0.199	0.179
Naphtheno-Olefins	0.042	0.038	0.037	0.055	0.016	0.025	0.025	0.063	0.056	0.062	0.008	0.059	0.133	0.028	0.114
Indenes	0.012	0.009	0.009	0.004	0.012	0	0.002	0.01	0.012	0.005	0.013	0	0	0	0.003

*Median and mean PM are "averaged over" all vehicles and tests within each fuel.

Summary Comments about the Analysis of DHA Data

The analyses and results of the DHA data presented herein collectively suggest there is relatively strong evidence that the mean and median PM values of the 15 fuels from the E-94-2, E-94-3, and E-129 programs are related to C_9 and C_{10}, most likely in some combination with Mono-Aromatics and I-Paraffins. The evidence suggests that C_9 and C_{10+} can be used to predict mean and median PM, and that median PM is strongly positively related to Mono-Aromatics, Naphtheno/Olefino-Benzs, and Naphthalenes, and strongly negatively related to I-Paraffins. It is possible to tie the mean and median PM values of some of the fuels to high and low total Wgt%

values of some carbons and groups, but there is no overall consistent pattern. Further, a more granular look at individual constituents within carbons and groups does not yield much additional useful information, partly because of the granularity itself (too much detail to easily or readily detect patterns), and partly because of the compositional nature of the data and the lack of consistency of constituents among fuels. Finally, it is possible to detect some statistically significant differences between pairs of fuels using the DHA results, but the results are not totally consistent with those based on analysis of the PM data themselves. An overriding concern is that there is only one set of DHA results per fuel; and without replication it is essentially impossible to draw more definitive conclusions. Additional information on DHA analyses is given in Appendix C.

4.0. A Review of and Comment on Existing Relevant Work

The following bibliography followed by comments on statistical methodology from the three prior reports is provided in response to Tasks 1, 2 and 3 of the CRC Project E-127-1 Statement of Work. The bibliography is comprised of two parts: (1) a body of work that is relevant to the statistical analysis of automotive emissions and (2) selected references that are relevant to the interpretation of the effects on emissions of adding ethanol to gasoline. Because of the nature of the topic, there is some overlap between the two parts.

4.1 Work on the statistical analysis of automotive emissions

Part 1 (see Bibliography, Part 1), which is more extensive but not exhaustive, is a compilation of journal articles, technical reports, presentations, and other materials that are wholly, or partly, devoted to statistical analysis of emissions data. These materials date back to the 1990s when statistical methods began to be more regularly embedded into emissions investigations, partly in response to, and parallel with, research into the human health impacts of emissions. Much of this work found encouragement through the Committee on Statistics and Statistical Software of the Transportation Research Board (TRB) of the National Research Council, but the Society of Automotive Engineers, Coordinating Research Council, American Statistical Association, Bureau of Transportation Statistics, Environmental Protection Agency, and other organizations actively supported such efforts.

While Part 1 primarily contains materials that focus on tailpipe emissions of light-duty vehicle emissions, there are some items that are specifically related to heavy-duty vehicles because of the robustness of the methodologies employed. Part 1 also contains several items that pertain to vehicle emissions, in general, rather than in-lab controlled studies (e.g., on-road investigations or emissions/air pollution detected through indirect means). Further, more of the items pertain to CO, CO_2, NO_x, etc. rather than specifically to particulate matter.

In more recent years, the use of statistical methods has become more ingrained in emissions studies and there have been fewer publications that are particularly focused on the nuances of the quantitative methodologies. In a sense, the techniques have become more well-known and their

application has become somewhat ubiquitous. Nevertheless, with the advent of the age of Big Data, there has been a renewed emphasis on analytics across the emissions landscape, including an expansion into machine learning, artificial intelligence, and various renditions of Monte Carlo simulation.

4.2 Work on recent research on emissions

Part 2 (see Bibliography, Part 2) of the bibliography contains a number of more recent research papers that address the sometimes-conflicting impacts on emissions, including particulate matter, of adding ethanol to gasoline through various blending protocols. These papers are included to provide additional background on, and perhaps some explanations for, the diversity of results observed in the E-94-2, E-94-3, E-129 studies, and confirmed in the present report for the E-127-1 study.

4.3 An evaluation of the statistical methodology used in the three programs

This report is a qualitative evaluation of the statistical methodology used in the E-94-2, E-94-3 and E-129 programs. Specifically, we comment upon appropriateness, validity and comparability.

Overall, the approaches used are reasonable. All the studies were hampered by a lack of observations in relation to the number of variables used. We believe that there is an unusually heavy emphasis on vehicles at the expense of fuels.

In the discussion of the statistical methodology below, references to figures and tables are those associated with the report referenced.

Program E-94-2

The statistical analysis in E-94-2 is the most comprehensive of the three programs. The initial part of the report is about detecting outliers. Given that PM data and other variables are right skewed, the detection and removal of outliers is difficult, especially when sample sizes are small. Leaving or removing an outlier can change the significance of an inference. Our recommendation would be to leave all points in unless there was strong evidence that a point in question was incorrect. Rather, it is often better to make a transformation to achieve a degree of symmetry where that would be needed for a given hypothesis. Much of the analysis (see Table 43) in the E-94-2 report concentrates on the analysis of individual vehicles, where degrees of freedom are only 4. Figure 27 shows differences in mean PM level grouped by vehicles.

In the analysis for vehicle groups (Section 5.2.5.1) a full rank model (Eq. 1) is used and then simplified. There are questionable assumptions about normality of errors. The authors state that "Vehicles, each with their own average emission level $\mu+v_k$, are considered as being drawn at random from the overall SIDI population." This is a strong assumption since elsewhere in this report it is stated that this is a convenience sample. The results of the tests have little power

because of few degrees of freedom. In addition, their measure of goodness of fit R^2 can vary significantly with changes in a few variables.

There is clearly a change in emissions as a function of PMI but considerable variability as a function of EtOH and AKI.

Program E-94-3

In this program four E-10 splash blended fuels were added to the eight match blended fuels from E-94-2. A major model (Eq. 1) on page 28 was used to express emissions as an additive function of vehicles and fuel. A second model compares only differences between splash and matched blends for E10 fuels. Figures (for example Figure 21 on page 36) show AKI, EtOH and PMI comparisons similar to those in the Program E-94-2 report.

Comparisons were made between E0 and E10-S fuels averaged over all vehicles and by AKI and PMI categories. Some differences were found. Many of the comparisons are between three- and four-vehicle groups.

The authors correctly acknowledge in footnote 10 (page 55) the multiple comparison problem that can lead to false positives, that is incorrectly concluding that a null hypothesis is to be rejected.

Program E-129

The discussion in this report focuses on Fuel C, four vehicles, and oxygenation. There is a regression equation (8-2 on page 49) to estimate the coefficients of the four test vehicles for each of the seven experimental fuels. It includes a vehicle random error additive term and a fuel times vehicle random error term, also additive. There is emphasis on differences in vehicles.

Concluding comment

The models used in the three reports are reasonable. The authors point out that their results are tentative due to the small sample sizes, lack of replications, and significant variability. The state correctly that there is a multiple comparison problem and that another sample of the same size could lead to different conclusions.

5.0 General Summary and Recommendations

General summary

Using a meta-analytic approach, the objective of this study was to investigate the relationship between the 15 fuels and other variables in an attempt to explain and/or resolve the conflicting PM results arising from ethanol enhanced fuels in the three prior studies. Fuels, vehicles, the three programs and two types of blending were major factors used to determine the usefulness

and benefit of combining the data for this purpose. Unlike the three previous studies that primarily focused on PM differences attributable to individual vehicles, the major focus of this study was on the fuels themselves.

Two types of data were used. The first type consisted of tailpipe emissions and associated factors, such as the identification of individual fuels, vehicles, and tests, that were also used in the E-94-2, E-94-3, and E-129 studies. PM was expressed in terms mg/mi, weighted over all three test phases. The major auxiliary variables were AKI, EtOH, and PMI.

The second type consisted of DHA results presented in terms of total Wgt% of various carbons, groups, carbon x group combinations, and individual constituent values. Although data were also available in terms volume %, mole %, and area, we restricted our analyses to Wgt% in part because these variables are almost always highly correlated. Note that there are no replications in this data set. Also note that the physical fuel samples used in vehicle testing and in DHA analysis were different, and that there was a time lag between testing in the three programs and the DHA analysis. We did not have any information with which to investigate potential shifts in fuel composition due to the time lag.

The first part of the study addressed the objective of pooling the data from all three previous studies and its potential impact on explaining the conflicting PM results associated with ethanol enhanced fuels observed in those studies. The focus of the second part was to determine if DHA results could be used to further explain the PM behavior of the various fuels.

The major tools used in this study were regression, analysis of variance, rank sum tests, graphical presentation, correlation analysis and tabular presentations, all approaches which are commonly used to statistically analyze automotive emissions. Other statistical methods were explored, but they did not yield additional useful information beyond what is presented in this report.

Our analyses were hampered by two major limiting factors: (1) insufficient, or absence of, replication and (2) too few observations (trials) relative to the hundreds of variables contained in the data sets.

In our study both fuels and vehicles are considered to be fixed effects. In the three previous studies, vehicles were considered to be random effects. However, the authors of those reports stated that the chosen vehicles were a convenience sample rather than a random sample.

The major findings and results of the study are summarized below:

- Initial exploration of the PM data indicates they are not normally distributed, nor or they lognormally distributed. We determined a more optimum transformation of the data that can be used to “normalize” them so that they are more amenable to commonly employed statistical approaches (i.e., the assumptions of normality are satisfied), and we used this transformation throughout most of our analyses.
- We avoided omitting individual observations perceived to be outliers, as was done in the prior studies. Alternatively, we chose to use the median as the preferred measure of centrality, but throughout our report we present results for both metrics for comparison

purposes. On multiple occasions we demonstrate how and why the median is a better characterization of the data.

- Ultimately, we used 10 different renditions (models) of analysis of variance to investigate differences in mean PM among the 15 fuels. Collectively, these analyses encompassed a variety of experimental design factors having the potential to explain the differences in mean PM. We consistently found Fuels, Vehicles, and the Fuel x Vehicle interaction to be statistically significant.
- We approached a number of our analyses from a meta-analytical perspective that involved the combination of data from all three prior studies. This involved the idea of "pooling over" programs and blending protocols. The four primary statistical models of interest involved the following combinations of factors:
  - program, fuel and vehicle
  - program, fuel and vehicle (match blended fuels only)
  - program, fuel and vehicle (splash blended fuels only)
  - blend, program, fuel and vehicle

  We found all factors involved in each of these analyses to be statistically significant.
- In all analyses involving combinations of fuels and vehicles, we found a persistent Fuel x Vehicle interaction that was statistically significant. This result is underscored in a variety of tables and graphs that clearly illustrate the differences that exist. Although we acknowledge the apparent existence of vehicle-to-vehicle differences, we have no physical way to explain such differences or to resolve the observed statistical interaction.
- Contrary to our original hypothesis, our analyses indicate that there was no real benefit to pooling data from the three original studies. Fuels that were determined to have statistically significant differences in mean PM in the three original studies are still determined to have statistically significant differences in all the meta-analytical analyses we conducted. In this case, pooling, which is usually undertaken to increase the total number of observations in an analysis, did not produce the desired effects, primarily to due to incompatibility of the structural experimental design of the original studies. Specifically, pooling did not resolve the conflicting PM results associated with ethanol enhanced fuels observed in the previous studies. We believe this is largely attributable to the persistence of the statistically significant Fuel x Vehicle interaction.
- The impact of vehicles is readily apparent when comparing results obtained from analyses that do and do not include Vehicle as design/model factor. When the vehicle effect is accounted for, over 90 percent of the differences in mean PM between fuels are determined to be statistically significant, whereas when the vehicle effect is not included, relatively few such differences are determined to be statistically significant.
- PMI is an important auxiliary variable when considering differences among fuels with regard to mean and median PM. The correlation between PMI and mean and median PM is positive and strong, but there is essentially no correlation between the other two auxiliary variables, AKI and EtOH, and mean and median PM.
- Analysis of the DHA data suggests that C_9 and C_{10+} (or C_{10}, C_{11}, C_{12} individually), conjunction with Mono-Aromatics, I-Paraffins, Naphtheno/Olefin-Benzs, and

Naphthalenes, all stated in Wgt%, are moderately to strongly correlated with PM (either positively or negatively). PMI is also moderately to strongly correlated with C_{10}, C_{11}, and C_{12}, and with Naphthalenes and Naphtheno/Olefino-Benzs. Limitations of the data set prevent tying these effects directly to differences in mean PM for specific fuel pairs (e.g., ethanol enhanced fuels and their non-ethanol enhanced counterparts); i.e., causality cannot be directly established.

- Further analysis of the DHA data at the level of individual constituents within carbon and group combinations indicates that statistically significant differences can be detected among pairs of fuels that are similar, but not identical, to those observed when analyzing PM, again suggesting the existence of a link between DHA data and PM production. Because there is considerable inconsistency among the individual DHA constituents associated with the various fuels, we believe the data is too granular at this level to be predictive.

Recommendations

We submit the following recommendations for future work:

1. A major factor effecting the results of this study is the fuel x vehicle interaction. It may be that, for reasons presently unknown, one or more of the vehicles is an outlier in the sense that it is from a different population. A way to examine this possibility is to selectively remove one or more vehicles at a time, repeat a subset of the analyses, and assess the impact. Hence, apart from acquiring more compelling physical evidence for eliminating selected vehicles, we recommend mounting a limited sensitivity study of this nature to test the impacts of doing so computationally and statistically. It must be noted, however, that any reduction in the number of vehicles will substantially impact the extensibility of the present results and those in the original three studies.
2. Alternatively, an outright increase in the number of vehicles also has the potential to dampen the fuel x vehicle interaction. The obvious way to do this is to replicate all three prior studies at least once. For various reasons, this would likely be financially and pragmatically impossible to do. An alternative approach is to use simulation to create additional (synthetic) vehicles that have similar properties to those represented in the data set. This provides the potential to increase the number of vehicles at limited cost in an attempt to dampen the fuel x vehicle interaction. We recommend mounting such a study, perhaps in combination with our first recommendation, as the most feasible way to address the issue of the fuel x vehicle interaction. Such a study could produce as many synthetic vehicles as desired. If physical replication were to occur, we recommend doubling of the total number of vehicles encompassed by the three prior studies, at a minimum, with all vehicles being tested on all fuels.
3. Because there is no replication of the DHA results, it is not possible to definitively determine whether or various DHA carbons, groups, or individual constituents play a role in the conflicting PM results of ethanol enhanced fuels. Despite the limitations and difficulties in doing so, we recommend repeating the DHA program at least once to

provide some estimate of statistical variability among the results. Obviously, more repetitions would be better.

4. We do not recommend using simulation to create synthetic DHA results because the multivariate and compositional nature of the system would be more complex and time-consuming to model.
5. Given our current knowledge and understanding of the DHA data, it seems unlikely that additional analyses will produce substantially different results. Nonetheless, apart from acquiring additional DHA data, it may be possible to successfully employ some advanced data analytics algorithms (e.g., neural networks) to further explore the relationships of DHA constituents with PM. We recommend that a limited exploratory study of this nature be undertaken.

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Part 2: Items Related to the Impacts on Emissions of Adding Ethanol to Gasoline

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Appendix A: Extended Comparison of Fuels

While analyzing all the available PM and DHA data, various analyses of variance were conducted to assess the statistical significance of fuels, vehicles, and other factors as explanatory variables for observed differences in mean PM. A noted previously, PM values are expressed in Wgt%, weighted across all three phases; and DHA values are expressed as Wgt% for each individual constituent.

Each of the analyses involved a differently structured the statistical model, but otherwise the process ensued in a consistent fashion. The output of each analysis included an assessment of the statistical significance of paired differences in mean PM (or, in the case of DHA data, sums of ranks) between the 15 fuels originally investigated in the E-94-2, E-94-3, and E-129 programs. Explanations of the processes used and the output obtained are provided elsewhere in the report, and the results are repeated in this appendix. For purposes of completeness and comparison, some additional analyses of variance were conducted, the results from which are reported here as well, but not in the main body of the report.

Table A1 lists all the analyses (models) that were conducted, with references, where appropriate, to previous tables in the report. Table A1 also references various columns in Table A2 which follows. In total, 10 different analyses (models) were conducted.

Table A1. Listing of analyses of variance of PM data under various model specifications, with references to prior report appearances (if applicable) and links to Table A2.

Analysis or Model	Prior Reference or Listing	Link to Table A2
E-94-2 Data Only: Fuel and Vehicle Effects	N/A	Column C
E-94-3 Data Only: Fuel and Vehicle Effects	N/A	Column D
E-129 Data Only: Fuel and Vehicle Effects	N/A	Column E
All Data: Fuel Effects Only (Ignoring Program or Vehicle Effects)	N/A	Column F
All Data: Fuel and Vehicle Effects (Ignoring Program Effects)	N/A	Column G
Pooled Model 1--All Data: Program, Fuel, and Vehicle Effects	Table 26	Column H
Pooled Model 2—Match Blended Data Only: Program, Fuel, and Vehicle Effects	Table 28	Column I

Pooled Model 3--Splash Blended Data Only: Program, Fuel, and Vehicle Effects	Table 30	Column J
Pooled Model 4—All Data: Blending, Program, Fuel, and Vehicle Effects	Table 32	Column K
DHA Data: Sums of Ranks Assigned to Wgt% of Individual Constituents	Table 59	Column L

Table A2 lists the 105 possible fuel pairs and, for each pair, indicates whether the difference in mean PM (or in the case of the DHA data, the difference in sum of ranks) is statistically significant. “Yes” (yellow cells) indicates the difference is statistically significant whereas “no” (blue cells) indicates the difference is not statistically significant. In all cases the significance level is judged to be $p<0.10$. Different results would be indicated if the significance level is set at $p<0.05$. Note that only a “yes” or “no” response is indicated, while the actual significance levels associated with each fuel pair difference changes from one analysis to the next. The uncolored cells in Table A2 containing a dash entry indicate that the respective fuel pair is not included in analysis represented by the column in which it appears. This occurs when the data are restricted to a specific category (e.g., only match-blended fuels).

A following observations can be made about the results presented in Table A2.

- The overall effect of vehicle differences is readily apparent by comparing Columns F and G. The analysis represented by Column F compares fuels irrespective of the program in which they were originally investigated and ignores differences among vehicles. As a result, relatively few fuel pairs exhibit differences in mean PM that are judged to be statistically significant. By comparison, Column G also compares fuels irrespective of programs, but does account for differences among vehicles. In this case, there is a stark difference in the results overall in that very few fuel pairs have differences in mean PM that are not statistically significant. Almost all of them are statistically significant.
- The analyses represented in Columns G, H, and K produced results that are quite similar overall. In fact, for 99 (94.3%) of the 105 fuel pairs, the three analyses lead to identical conclusions about the statistical significance of the respective differences in mean PM. Because the analysis represented by Column G does not incorporate program-to-program differences, whereas the analyses represented by Columns H and K do, the high degree of agreement between the results based on the three different approaches suggests that the meta-analytical objective of “pooling over programs” yielded no new information regarding the observed differences in mean PM for pairs of fuels. Stated another way, the individual analyses represented by Columns H and K indicate there is a statistically significant “program effect” (Tables 25 and 31, respectively), but the pairs of fuels for which the difference in mean PM is statistically significant is unchanged whether that effect is accounted for or not.

- Inspection of the results reported in Columns C, D, and E with those reported in Columns H and L also confirms that meta-analytical pooling of data across programs did not yield much new information at the macro level. In the case of Column C, which represents analysis of the E-94-2 data only, results for 27 (96.4%) of the 28 possible fuel pairs are identical to those reported in Columns H and K. In the case of Column D, which represents analysis of the E-94-3 data only, results for 5 (83.3%) of the six possible fuel pairs are identical to those reported in Columns H and K. Finally, in the case of Column E, which represents analysis of the E-129 data only, results for two (66.7%) of the three possible fuel pairs are identical to those reported in Columns H and K. The combined degree of correspondence on this basis is 91.9% (34 out of 37). Consequently, explicitly accounting for program-to-program differences (along with blend-to-blend differences in the case of Column K) in a meta-analytical way does not materially change what was already known about the differences in mean PM among the fuels determined through individual analyses of the E-94-2, E-94-3, and E-129 data sets.
- Comparison of results associated with the analyses represented by Columns F and L is discussed in the main report (see Tables 60 and 61).
- Further inspection of Table A2 indicates that there are several fuel pairs for which the difference in mean PM is not statistically significant irrespective of the analysis conducted. This group includes: A/E, A/G-E10, C/G, C/C-E10, C/G-E10. D/F, E/G-10, G/C-E10, H/D-E10, H/H-E10, C-E10/G-E10, D-E10/H-E10, CRC-C/CRC-E10. Among this group, for which the differences in mean PM are small, the differences in PMI are all also small, as shown in Table A3. However, the opposite is not necessarily true. There are fuel pairs for which the difference in PMI is small but the difference in their mean PM values is higher and statistically significant (Table A4).
- The previous observation notwithstanding, there is evidence that, for the fuel pairs whose difference in mean PM is statistically significant across multiple analyses (Table A4), the difference in mean PM tends to increase as the difference in PMI increases, as demonstrated in Table A5. This observation does not directly explain why fuels yield different values of PM on average, nor does it in any way explicitly imply causality, it does tend to underscore prior observations of the linkage between PM and PMI (e.g., Figures 4, 8, and 13).

Table A2. Comparison of the statistical significance of paired differences in mean PM between the fuels using 10 different analytical approaches.

(A) Fuel 1	(B) Fuel 2	(C) E-94-2 Only	(D) E-94-3 Only	(E) E-129 Only	(F) All Fuels (No Program or Vehicle Effects)	(G) All Fuels (Vehicles w/i Fuels but No Program Effects)	(H) Pooled Model 1: Programs (Fuels within Programs)	(I) Pooled Model 2: Match Blends (Match Blended Fuels within Programs)	(J) Pooled Model 3: Splash Blends (Splash Blended Fuels within Programs)	(K) Pooled Model 4: Blends & Programs (Fuels within Blends & Programs)	(L) Sum of Ranks
A	B	Yes	-	-	Yes	Yes	Yes	Yes	-	Yes	Yes
A	C	Yes	-	-	No	Yes	Yes	Yes	-	Yes	No
A	D	Yes	-	-	No	Yes	Yes	Yes	-	Yes	No
A	E	No	-	-	No	No	No	No	-	No	No
A	F	Yes	-	-	No	Yes	Yes	Yes	-	Yes	No
A	G	Yes	-	-	No	Yes	Yes	Yes	-	Yes	No
A	H	Yes	-	-	No	Yes	Yes	Yes	-	Yes	No
A	C-E10	-	-	-	No	No	Yes	-	-	No	Yes
A	D-E10	-	-	-	No	Yes	Yes	-	-	Yes	No
A	G-E10	-	-	-	No	No	No	-	-	No	Yes
A	H-E10	-	-	-	No	Yes	Yes	-	-	Yes	No
A	CRC-C	-	-	-	No	Yes	Yes	-	-	Yes	No
A	CRC-E10	-	-	-	No	Yes	Yes	-	-	Yes	No
A	CRC-E15	-	-	-	No	Yes	Yes	-	-	Yes	No
B	C	Yes	-	-	Yes	Yes	Yes	Yes	-	Yes	Yes
B	D	Yes	-	-	No	Yes	Yes	Yes	-	Yes	Yes
B	E	Yes	-	-	No	Yes	Yes	Yes	-	Yes	No
B	F	Yes	-	-	No	Yes	Yes	Yes	-	Yes	No
B	G	Yes	-	-	Yes	Yes	Yes	Yes	-	Yes	Yes
B	H	Yes	-	-	No	Yes	Yes	Yes	-	Yes	Yes
B	C-E10	-	-	-	Yes	Yes	Yes	-	-	Yes	Yes
B	D-E10	-	-	-	No	Yes	Yes	-	-	Yes	Yes
B	G-E10	-	-	-	No	Yes	Yes	-	-	Yes	Yes
B	H-E10	-	-	-	No	Yes	Yes	-	-	Yes	Yes
B	CRC-C	-	-	-	Yes	Yes	Yes	-	-	Yes	Yes
B	CRC-E10	-	-	-	Yes	Yes	Yes	-	-	Yes	Yes
B	CRC-E15	-	-	-	Yes	Yes	Yes	-	-	Yes	Yes
C	D	Yes	-	-	Yes	Yes	Yes	Yes	-	Yes	No
C	E	Yes	-	-	No	Yes	Yes	Yes	-	Yes	No
C	F	Yes	-	-	Yes	Yes	Yes	Yes	-	Yes	Yes
C	G	No	-	-	No	No	No	No	-	No	No
C	H	Yes	-	-	No	Yes	Yes	Yes	-	Yes	No
C	C-E10	-	-	-	No	No	No	-	-	No	No
C	D-E10	-	-	-	No	Yes	Yes	-	-	Yes	No
C	G-E10	-	-	-	No	No	No	-	-	No	No
C	H-E10	-	-	-	No	Yes	Yes	-	-	Yes	No
C	CRC-C	-	-	-	No	Yes	Yes	-	-	Yes	No
C	CRC-E10	-	-	-	No	Yes	Yes	-	-	Yes	No
C	CRC-E15	-	-	-	No	Yes	Yes	-	-	Yes	No
D	E	Yes	-	-	No	Yes	Yes	Yes	-	Yes	No
D	F	No	-	-	Yes	No	No	No	-	No	No
D	G	Yes	-	-	No	Yes	Yes	Yes	-	Yes	No
D	H	Yes	-	-	No	Yes	Yes	Yes	-	Yes	No
D	C-E10	-	-	-	No	Yes	Yes	-	-	Yes	No
D	D-E10	-	-	-	No	No	Yes	-	-	Yes	No
D	G-E10	-	-	-	No	Yes	Yes	-	-	Yes	Yes
D	H-E10	-	-	-	No	Yes	Yes	-	-	Yes	No
D	CRC-C	-	-	-	Yes	Yes	Yes	-	-	Yes	No
D	CRC-E10	-	-	-	Yes	Yes	Yes	-	-	Yes	No
D	CRC-E15	-	-	-	Yes	Yes	Yes	-	-	Yes	No
E	F	Yes	-	-	No	Yes	Yes	Yes	-	Yes	No
E	G	Yes	-	-	No	Yes	Yes	Yes	-	Yes	Yes
E	H	Yes	-	-	No	Yes	Yes	Yes	-	Yes	No
E	C-E10	-	-	-	No	Yes	Yes	-	-	Yes	Yes
E	D-E10	-	-	-	No	Yes	Yes	-	-	Yes	No
E	G-E10	-	-	-	No	No	No	-	-	No	Yes
E	H-E10	-	-	-	No	Yes	Yes	-	-	Yes	No
E	CRC-C	-	-	-	No	Yes	Yes	-	-	Yes	No
E	CRC-E10	-	-	-	No	Yes	Yes	-	-	Yes	Yes
E	CRC-E15	-	-	-	No	Yes	Yes	-	-	Yes	Yes
F	G	Yes	-	-	Yes	Yes	Yes	Yes	-	Yes	Yes
F	H	Yes	-	-	No	Yes	Yes	Yes	-	No	No
F	C-E10	-	-	-	No	Yes	Yes	-	-	Yes	Yes
F	D-E10	-	-	-	No	No	Yes	-	-	Yes	No
F	G-E10	-	-	-	No	Yes	Yes	-	-	Yes	Yes
F	H-E10	-	-	-	No	Yes	Yes	-	-	Yes	No
F	CRC-C	-	-	-	Yes	Yes	Yes	-	-	Yes	No
F	CRC-E10	-	-	-	Yes	Yes	Yes	-	-	Yes	Yes
F	CRC-E15	-	-	-	Yes	Yes	Yes	-	-	Yes	Yes
G	H	Yes	-	-	No	Yes	Yes	Yes	-	Yes	No
G	C-E10	-	-	-	No	No	No	-	-	No	No
G	D-E10	-	-	-	No	Yes	Yes	-	-	Yes	No
G	G-E10	-	-	-	No	Yes	Yes	-	-	Yes	No
G	H-E10	-	-	-	No	Yes	Yes	-	-	Yes	No
G	CRC-C	-	-	-	No	Yes	Yes	-	-	Yes	Yes
G	CRC-E10	-	-	-	No	Yes	Yes	-	-	Yes	No
G	CRC-E15	-	-	-	No	Yes	Yes	-	-	Yes	No
H	C-E10	-	-	-	No	Yes	Yes	-	-	Yes	No
H	D-E10	-	-	-	No	No	No	-	-	No	No
H	G-E10	-	-	-	No	Yes	Yes	-	-	Yes	Yes
H	H-E10	-	-	-	No	No	No	-	-	No	No
H	CRC-C	-	-	-	No	Yes	Yes	-	-	Yes	No
H	CRC-E10	-	-	-	No	Yes	Yes	-	-	Yes	No
H	CRC-E15	-	-	-	No	Yes	Yes	-	-	Yes	No
C-E10	D-E10	-	Yes	-	No	Yes	Yes	-	Yes	Yes	No
C-E10	G-E10	-	Yes	-	No	No	No	-	No	No	No
C-E10	H-E10	-	Yes	-	No	Yes	Yes	-	Yes	Yes	No
C-E10	CRC-C	-	-	-	No	Yes	Yes	-	-	Yes	Yes
C-E10	CRC-E10	-	-	-	No	Yes	Yes	-	-	Yes	No
C-E10	CRC-E15	-	-	-	No	Yes	Yes	-	-	Yes	No
D-E10	G-E10	-	Yes	-	No	Yes	Yes	-	Yes	Yes	Yes
D-E10	H-E10	-	No	-	No	No	No	-	No	No	No
D-E10	CRC-C	-	-	-	No	Yes	Yes	-	-	Yes	No
D-E10	CRC-E10	-	-	-	No	Yes	Yes	-	-	Yes	No
D-E10	CRC-E15	-	-	-	No	Yes	Yes	-	-	Yes	No
G-E10	H-E10	-	Yes	-	No	Yes	Yes	-	Yes	Yes	No
G-E10	CRC-C	-	-	-	No	Yes	Yes	-	-	Yes	Yes
G-E10	CRC-E10	-	-	-	No	Yes	Yes	-	-	Yes	No
G-E10	CRC-E15	-	-	-	No	Yes	Yes	-	-	Yes	No
H-E10	CRC-C	-	-	-	No	Yes	Yes	-	-	Yes	No
H-E10	CRC-E10	-	-	-	No	Yes	Yes	-	-	Yes	No
H-E10	CRC-E15	-	-	-	No	Yes	Yes	-	-	Yes	No
CRC-C	CRC-E10	-	-	No	No	No	No	-	-	No	Yes
CRC-C	CRC-E15	-	-	Yes	No	No	Yes	-	-	No	Yes
CRC-E10	CRC-E15	-	-	Yes	No	No	Yes	-	Yes	Yes	No

Table A3. Pairs of fuels for which the difference in mean PM is not statistically significant across multiple analyses represented in Table A2, along with associated values of AKI, EtOH, and PMI.

		Fuel 1				Fuel 2				Difference in			
Fuel 1	Fuel 2	Mean PM	AKI	EtOH	PMI	Mean PM	AKI	EtOH	PMI	Mean PM	AKI	EtOH	PMI
A	E	4.12	87.2	9.55	1.42	4.23	93.6	9.56	1.3	0.11	6.4	0.01	0.12
A	G-E10	4.12	87.2	9.55	1.42	3.84	96.4	9.75	1.17	0.28	9.2	0.20	0.25
C	G	3.14	87.9	0	1.42	3.05	93.8	0	1.27	0.09	5.9	0	0.15
C	C-E10	3.14	87.9	0	1.42	3.5	91.5	9.44	1.28	0.36	3.6	9.44	0.14
C	G-E10	3.14	87.9	0	1.42	3.84	96.4	9.75	1.17	0.70	8.5	9.75	0.25
D	F	7.13	88.2	0	2.65	7.01	93.7	9.51	2.55	0.12	5.5	9.51	0.10
E	G-E10	4.23	93.6	9.56	1.30	3.84	96.4	9.75	1.17	0.39	2.8	0.19	0.13
G	C-E10	3.05	93.8	0	1.27	3.5	91.5	9.44	1.28	0.45	2.3	9.44	0.01
H	D-E10	5.92	94.1	0	2.49	6.43	91.1	9.71	2.45	0.51	3.0	9.71	0.04
H	H-E10	5.92	94.1	0	2.49	5.99	96.0	9.88	2.32	0.07	1.9	9.88	0.17
C-E10	G-E10	3.50	91.5	9.44	1.28	3.84	96.4	9.75	1.17	0.34	4.9	0.31	0.11
D-E10	H-E10	6.43	91.1	9.71	2.45	5.99	96.0	9.88	2.32	0.44	4.9	0.17	0.13
CRC-C	CRC-E10	1.67	88.2	0	1.30	1.7	91.7	9.97	1.16	0.03	3.5	9.97	0.14
									Average =	0.30	4.8	5.28	0.13
									Standard Deviation =	0.20	2.28	4.95	0.07

Table A4. Pairs of fuels for which the difference in mean PM is statistically significant across multiple analyses represented in Table A2, along with associated values of AKI, EtOH, and PMI.

		Fuel 1				Fuel 2				Difference in			
Fuel 1	Fuel 2	Mean PM	AKI	EtOH	PMI	Mean PM	AKI	EtOH	PMI	Mean PM	AKI	EtOH	PMI
A	B	4.12	87.2	9.55	1.42	8.59	87.1	9.56	2.64	4.47	0.1	0.01	1.22
A	C	4.12	87.2	9.55	1.42	3.14	87.9	0	1.42	0.98	0.7	9.55	0
A	D	4.12	87.2	9.55	1.42	7.13	88.2	0	2.65	3.01	1.0	9.55	1.23
A	F	4.12	87.2	9.55	1.42	7.01	93.7	9.51	2.55	2.89	6.5	0.04	1.13
A	G	4.12	87.2	9.55	1.42	3.05	93.8	0	1.27	1.07	6.6	9.55	0.15
A	H	4.12	87.2	9.55	1.42	5.92	94.1	0	2.49	1.80	6.9	9.55	1.07
A	D-E10	4.12	87.2	9.55	1.42	6.43	91.1	9.71	2.45	2.31	3.9	0.16	1.03
A	H-E10	4.12	87.2	9.55	1.42	5.99	96.0	9.88	2.32	1.87	8.8	0.33	0.9
A	CRC-C	4.12	87.2	9.55	1.42	1.67	88.2	0	1.30	2.45	1.0	9.55	0.12
A	CRC-E10	4.12	87.2	9.55	1.42	1.70	91.7	9.97	1.16	2.42	4.5	0.42	0.26
A	CRC-E15	4.12	87.2	9.55	1.42	1.30	92.8	14.85	1.08	2.82	5.6	5.3	0.34
B	C	8.59	87.1	9.56	2.64	3.14	87.9	0	1.42	5.45	0.8	9.56	1.22
B	D	8.59	87.1	9.56	2.64	7.13	88.2	0	2.65	1.46	1.1	9.56	0.01
B	E	8.59	87.1	9.56	2.64	4.23	93.6	9.56	1.30	4.36	6.5	0	1.34
B	F	8.59	87.1	9.56	2.64	7.01	93.7	9.51	2.55	1.58	6.6	0.05	0.09
B	G	8.59	87.1	9.56	2.64	3.05	93.8	0	1.27	5.54	6.7	9.56	1.37
B	H	8.59	87.1	9.56	2.64	5.92	94.1	0	2.49	2.67	7.0	9.56	0.15
B	C-E10	8.59	87.1	9.56	2.64	3.50	91.5	9.44	1.28	5.09	4.4	0.12	1.36
B	D-E10	8.59	87.1	9.56	2.64	6.43	91.1	9.71	2.45	2.16	4.0	0.15	0.19
B	G-E10	8.59	87.1	9.56	2.64	3.84	96.4	9.75	1.17	4.75	9.3	0.19	1.47
B	H-E10	8.59	87.1	9.56	2.64	5.99	96.0	9.88	2.32	2.60	8.9	0.32	0.32
B	CRC-C	8.59	87.1	9.56	2.64	1.67	88.2	0	1.30	6.92	1.1	9.56	1.34
B	CRC-E10	8.59	87.1	9.56	2.64	1.70	91.7	9.97	1.16	6.89	4.6	0.41	1.48
B	CRC-E15	8.59	87.1	9.56	2.64	1.30	92.8	14.85	1.08	7.29	5.7	5.29	1.56
C	D	3.14	87.9	0	1.42	7.13	88.2	0	2.65	3.99	0.3	0	1.23
C	E	3.14	87.9	0	1.42	4.23	93.6	9.56	1.30	1.09	5.7	9.56	0.12
C	F	3.14	87.9	0	1.42	7.01	93.7	9.51	2.55	3.87	5.8	9.51	1.13
C	H	3.14	87.9	0	1.42	5.92	94.1	0	2.49	2.78	6.2	0	1.07
C	D-E10	3.14	87.9	0	1.42	6.43	91.1	9.71	2.45	3.29	3.2	9.71	1.03
C	H-E10	3.14	87.9	0	1.42	5.99	96.0	9.88	2.32	2.85	8.1	9.88	0.9
C	CRC-C	3.14	87.9	0	1.42	1.67	88.2	0	1.30	1.47	0.3	0	0.12
C	CRC-E10	3.14	87.9	0	1.42	1.70	91.7	9.97	1.16	1.44	3.8	9.97	0.26
C	CRC-E15	3.14	87.9	0	1.42	1.30	92.8	14.85	1.08	1.84	4.9	14.85	0.34
D	E	7.13	88.2	0	2.65	4.23	93.6	9.56	1.30	2.90	5.4	9.56	1.35
D	G	7.13	88.2	0	2.65	3.05	93.8	0	1.27	4.08	5.6	0	1.38
D	H	7.13	88.2	0	2.65	5.92	94.1	0	2.49	1.21	5.9	0	0.16
D	C-E10	7.13	88.2	0	2.65	3.5	91.5	9.44	1.28	3.63	3.3	9.44	1.37
D	G-E10	7.13	88.2	0	2.65	3.84	96.4	9.75	1.17	3.29	8.2	9.75	1.48
D	H-E10	7.13	88.2	0	2.65	5.99	96.0	9.88	2.32	1.14	7.8	9.88	0.33
D	CRC-C	7.13	88.2	0	2.65	1.67	88.2	0	1.30	5.46	0	0	1.35
D	CRC-E10	7.13	88.2	0	2.65	1.70	91.7	9.97	1.16	5.43	3.5	9.97	1.49
D	CRC-E15	7.13	88.2	0	2.65	1.30	92.8	14.85	1.08	5.83	4.6	14.85	1.57
E	F	4.23	93.6	9.56	1.30	7.01	93.7	9.51	2.55	2.78	0.1	0.05	1.25
E	G	4.23	93.6	9.56	1.30	3.05	93.8	0	1.27	1.18	0.2	9.56	0.03
E	H	4.23	93.6	9.56	1.30	5.92	94.1	0	2.49	1.69	0.5	9.56	1.19
E	C-E10	4.23	93.6	9.56	1.30	3.50	91.5	9.44	1.28	0.73	2.1	0.12	0.02
E	D-E10	4.23	93.6	9.56	1.30	6.43	91.1	9.71	2.45	2.20	2.5	0.15	1.15
E	H-E10	4.23	93.6	9.56	1.30	5.99	96.0	9.88	2.32	1.76	2.4	0.32	1.02
E	CRC-C	4.23	93.6	9.56	1.30	1.67	88.2	0	1.30	2.56	5.4	9.56	0
E	CRC-E10	4.23	93.6	9.56	1.30	1.70	91.7	9.97	1.16	2.53	1.9	0.41	0.14
E	CRC-E15	4.23	93.6	9.56	1.30	1.30	92.8	14.85	1.08	2.93	0.8	5.29	0.22
F	G	7.01	93.7	9.51	2.55	3.05	93.8	0	1.27	3.96	0.1	9.51	1.28
F	H	7.01	93.7	9.51	2.55	5.92	94.1	0	2.49	1.09	0.4	9.51	0.06
F	C-E10	7.01	93.7	9.51	2.55	3.50	91.5	9.44	1.28	3.51	2.2	0.07	1.27
F	G-E10	7.01	93.7	9.51	2.55	3.84	96.4	9.75	1.17	3.17	2.7	0.24	1.38
F	H-E10	7.01	93.7	9.51	2.55	5.99	96.0	9.88	2.32	1.02	2.3	0.37	0.23
F	CRC-C	7.01	93.7	9.51	2.55	1.67	88.2	0	1.30	5.34	5.5	9.51	1.25
F	CRC-E10	7.01	93.7	9.51	2.55	1.70	91.7	9.97	1.16	5.31	2.0	0.46	1.39
F	CRC-E15	7.01	93.7	9.51	2.55	1.30	92.8	14.85	1.08	5.71	0.9	5.34	1.47
G	H	3.05	93.8	0	1.27	5.92	94.1	0	2.49	2.87	0.3	0	1.22
G	D-E10	3.05	93.8	0	1.27	6.43	91.1	9.71	2.45	3.38	2.7	9.71	1.18
G	G-E10	3.05	93.8	0	1.27	3.84	96.4	9.75	1.17	0.79	2.6	9.75	0.1
G	H-E10	3.05	93.8	0	1.27	5.99	96.0	9.88	2.32	2.94	2.2	9.88	1.05
G	CRC-C	3.05	93.8	0	1.27	1.67	88.2	0	1.30	1.38	5.6	0	0.03
G	CRC-E10	3.05	93.8	0	1.27	1.70	91.7	9.97	1.16	1.35	2.1	9.97	0.11
G	CRC-E15	3.05	93.8	0	1.27	1.30	92.8	14.85	1.08	1.75	1.0	14.85	0.19
H	C-E10	5.92	94.1	0	2.49	3.50	91.5	9.44	1.28	2.42	2.6	9.44	1.21
H	G-E10	5.92	94.1	0	2.49	3.84	96.4	9.75	1.17	2.08	2.3	9.75	1.32
H	CRC-C	5.92	94.1	0	2.49	1.67	88.2	0	1.30	4.25	5.9	0	1.19
H	CRC-E10	5.92	94.1	0	2.49	1.70	91.7	9.97	1.16	4.22	2.4	9.97	1.33
H	CRC-E15	5.92	94.1	0	2.49	1.30	92.8	14.85	1.08	4.62	1.3	14.85	1.41
C-E10	D-E10	3.50	91.5	9.44	1.28	6.43	91.1	9.71	2.45	2.93	0.4	0.27	1.17
C-E10	H-E10	3.50	91.5	9.44	1.28	5.99	96.0	9.88	2.32	2.49	4.5	0.44	1.04
C-E10	CRC-C	3.50	91.5	9.44	1.28	1.67	88.2	0	1.30	1.83	3.3	9.44	0.02
C-E10	CRC-E10	3.50	91.5	9.44	1.28	1.70	91.7	9.97	1.16	1.80	0.2	0.53	0.12
C-E10	CRC-E15	3.50	91.5	9.44	1.28	1.30	92.8	14.85	1.08	2.20	1.3	5.41	0.2
D-E10	G-E10	6.43	91.1	9.71	2.45	3.84	96.4	9.75	1.17	2.59	5.3	0.04	1.28
D-E10	CRC-C	6.43	91.1	9.71	2.45	1.67	88.2	0	1.30	4.76	2.9	9.71	1.15
D-E10	CRC-E10	6.43	91.1	9.71	2.45	1.70	91.7	9.97	1.16	4.73	0.6	0.26	1.29
D-E10	CRC-E15	6.43	91.1	9.71	2.45	1.30	92.8	14.85	1.08	5.13	1.7	5.14	1.37
G-E10	H-E10	3.84	96.4	9.75	1.17	5.99	96.0	9.88	2.32	2.15	0.4	0.13	1.15
G-E10	CRC-C	3.84	96.4	9.75	1.17	1.67	88.2	0	1.30	2.17	8.2	9.75	0.13
G-E10	CRC-E10	3.84	96.4	9.75	1.17	1.70	91.7	9.97	1.16	2.14	4.7	0.22	0.01
G-E10	CRC-E15	3.84	96.4	9.75	1.17	1.30	92.8	14.85	1.08	2.54	3.6	5.1	0.09
H-E10	CRC-C	5.99	96.0	9.88	2.32	1.67	88.2	0	1.30	4.32	7.8	9.88	1.02
H-E10	CRC-E10	5.99	96.0	9.88	2.32	1.70	91.7	9.97	1.16	4.29	4.3	0.09	1.16
H-E10	CRC-E15	5.99	96.0	9.88	2.32	1.30	92.8	14.85	1.08	4.69	3.2	4.97	1.24
									Average =	3.09	3.57	5.34	0.83
									Standard Deviation =	1.57	2.59	4.91	0.56

Table A5. Association between average difference in mean PM and average difference in PMI. (A) Results based on sorting Table A4 by the difference in mean PM, and (B) Results based on sorting Table A4 by the difference in PMI.

(A)

Range of Difference in Mean PM	Number of Differences	Average Difference in Mean PM	Average Difference in PMI
Diff < 1	3	0.83	0.04
1 ≤ Diff < 2	21	1.47	0.31
2 ≤ Diff < 3	28	2.55	0.70
3 ≤ Diff < 4	10	3.51	1.26
4 ≤ Diff < 5	12	4.46	1.27
5 ≤ Diff < 6	10	5.43	1.38
Diff ≥ 6	3	7.03	1.46

(B)

Range of Difference in PMI	Number of Differences	Average Difference in Mean PM	Average Difference in PMI
Diff < .1	11	1.59	0.03
.1 ≤ Diff < .2	13	1.73	0.14
.2 ≤ Diff < .3	15	2.00	0.23
.3 ≤ Diff <. 4	4	2.10	0.33
.4 ≤ Diff <. 5	0	N/A	N/A
.5 ≤ Diff <. 6	0	N/A	N/A
.6 ≤ Diff <. 7	0	N/A	N/A
.7 ≤ Diff <. 8	0	N/A	N/A
.8 ≤ Diff <. 9	0	N/A	N/A
.9 ≤ Diff < 1.0	2	2.36	0.90
1.0 ≤ Diff < 1.1	8	2.71	1.04
1.1 ≤ Diff < 1.2	10	3.24	1.16
1.2 ≤ Diff < 1.3	13	3.83	1.25
1.3 ≤ Diff < 1.4	13	4.45	1.36
1.4 ≤ Diff < 1.5	6	5.12	1.47
Diff ≥ 1.5	2	6.56	1.57

Appendix B: Additional Investigation of the PM-DHA Relationship

As suggested in the main body of the report, the extent to which DHA results inform the analysis of PM data requires additional consideration. Results of two different analyses—one based on the recorded Wgt% values of PM for individual fuels and the other based on the ranks assigned to the Wgt% values of individual DHA constituents associated with the same corresponding fuels—are summarized in Table A2 of Appendix A, Columns F and L. Comparisons are presented in Tables 60 and 61 of the main report. Note that neither analysis considers program-to-program or vehicle-to-vehicle differences and that mean PM is "averaged over" vehicles and tests.

In an effort to further investigate the results of the two different analyses, differences in AKI, EtOH, PMI, and the total Wgt% of all constituent values associated with C_9 thru C_{12} were computed for each of the 105 fuel pairs and aligned with the corresponding differences in mean PM and sum (or, equivalently, mean) of the DHA constituent ranks. Table B1 provides a partial listing of the resulting data.

Table B1. Partial listing of differences in mean PM, mean of ranks assigned to the Wgt% values of DHA constituents, AKI, EtOH, PMI, and Wgt% values of C_9 thru C_{12} for all pairs of fuels.

Fuel 1	Fuel 2	Difference in Mean PM	Difference in Mean Ranks Assigned to DHA Constituents	Difference in PMI	AKI	EtOH	C9	C10	C11	C12
A	B	4.47	162	1.22	0.1	0.01	5.711	3.893	1.572	0.670
A	C	0.98	58	0	0.7	9.55	1.175	0.379	0.193	0.129
A	D	3.01	8	1.23	1.0	9.55	2.076	3.496	1.652	0.751
A	E	0.11	34	0.12	6.4	0.01	4.536	0.168	0.059	0.277
A	F	2.89	75	1.13	6.5	0.04	0.254	3.897	1.669	0.533
A	G	1.07	129	0.15	6.6	9.55	2.946	0.785	0.074	0.263
A	H	1.80	1	1.07	6.9	9.55	0.156	3.567	1.750	0.466
A	C_E10	0.62	127	0.14	4.3	0.11	0.009	0.819	0.079	0.166
A	D_E10	2.31	37	1.03	3.9	0.16	1.017	2.891	1.232	0.675
A	G_E10	0.28	174	0.25	9.2	0.20	1.756	1.142	0.053	0.268
A	H_E10	1.87	45	0.9	8.8	0.33	1.035	2.652	1.509	0.433
A	CRC_C	2.45	33	0.12	1.0	9.55	2.520	0.145	0.508	0.063
A	CRC_E10	2.42	90	0.26	4.5	0.42	3.320	0.726	0.253	0.045
A	CRC_E15	2.82	114	0.34	5.6	5.30	3.641	0.922	0.160	0.065
B	C	5.45	220	1.22	0.8	9.56	4.536	4.272	1.379	0.799
B	D	1.46	170	0.01	1.1	9.56	3.635	0.397	0.080	0.081
B	E	4.36	128	1.34	6.5	0	1.175	4.061	1.513	0.947
B	F	1.58	87	0.09	6.6	0.05	5.457	0.004	0.097	0.137
B	G	5.54	291	1.37	6.7	9.56	2.765	4.678	1.498	0.933
B	H	2.67	161	0.15	7.0	9.56	5.555	0.326	0.178	0.204
B	C_E10	5.09	289	1.36	4.4	0.12	5.720	4.712	1.651	0.836
B	D_E10	2.16	199	0.19	4.0	0.15	4.694	1.002	0.340	0.005
B	G_E10	4.75	336	1.47	9.3	0.19	3.955	5.035	1.625	0.938
B	H_E10	2.60	207	0.32	8.9	0.32	6.746	1.241	0.063	0.237
B	CRC_C	6.92	129	1.34	1.1	9.56	8.231	4.038	1.064	0.607
B	CRC_E10	6.89	252	1.48	4.6	0.41	9.031	4.619	1.319	0.715
B	CRC_E15	7.29	276	1.56	5.7	5.29	9.352	4.815	1.412	0.735

*Mean PM is "averaged over" all vehicles and tests within each fuel.

Pairwise correlations were then computed among the nine "difference variables" for five different sets of fuel pairs identified in Table B2. The five sets of fuel pairs are associated with the comparative results of the two different analyses described above and which are presented in Tables 60 and 61 of the main report. The pairwise correlations are displayed in Table B3. Blue shaded cells indicate correlations that are ≥.5 in absolute value.

Table B2. Identification of the five sets of fuel pairs associated with the pairwise correlations displayed in Table B3.

Set	Number of Observations (Pairs of Fuels)	Description
A	105	All pairs of fuels encompassed by the analyses represented by each of Columns F and L in Table A2.
B	11	Pairs of fuels for which the difference in mean PM (Table A2, Column F) and the corresponding difference in sum (or mean) of ranks (Table A2, Column L) are both statistically significant.
C	66	Pairs of fuels for which neither the difference in mean PM (Table A2, Column F) nor the corresponding difference in sum (or mean) of ranks (Table A2, Column L) are statistically significant.

D	22	Pairs of fuels for which the difference in mean PM (Table A2, Column F) is not statistically significant but the corresponding difference in sum (or mean) of ranks (Table A2, Column L) is.
E	6	Pairs of fuels for which the difference in mean PM (Table A2, Column F) is statistically significant but the corresponding difference in sum (or mean) of ranks (Table A2, Column L) is not.

Discussion of Panel (A)

Panel (A) of Table B3 suggests that when considering all 105 pairs of fuels, the difference in mean PM is weakly positively correlated with the difference in the Wgt% value of C_9, and moderately positively correlated with the difference in the Wgt% values of C_{10}, C_{11}, and C_{12}. These results parallel and underscore those presented in Table 43, Figure 21, and Figure 22. Further, the difference in mean PM is strongly positively correlated with the difference in PMI. This relationship is suggested in Figure 4, Figure 9, and Figure 13 in the main report. However, from the analytical perspective described here, the relationship is stronger than that suggested in Table 20, and stronger than the discussion of information contained in Table 54 and Table 56 would indicate.

Panel (A) of Table B3 also indicates a strong relationship between the difference in PMI and the difference in the Wgt% values of C_{10}, C_{11}, and C_{12}, a finding which has not heretofore been reported.

Panel (A) further indicates that, among the 105 pairs of fuels, differences in mean PM values and differences in means of ranks assigned to DHA constituents are positively, but not strongly, correlated, and that there is no notable correlation between differences in means of ranks and differences in any of the other variables. Taken on whole, this would suggest a lack of correspondence between the two analytical approaches, and by extension, that DHA results are relatively non-informative with regard to PM. The additional discussion below may shed further light on this observation.

Discussion of Panel (B)

Panel (B) of Table B3 suggests that, when considering only the 11 pairs of fuels for which both analyses indicate statistical significance, the difference in mean PM is strongly positively corelated with the difference in Wgt% values of C_9. This finding is somewhat counter to the corresponding result when all 105 pairs of fuels are considered. In the present case, the correlation is .84, but in the former case it is only .4. Also, in Panel (A), the correlation between the difference in mean PM and the difference in C_{11} is .67, but here the corresponding correlation is -.67, a completely opposite result. Further, Panel (A) indicates a positive correlation between differences in mean PM and differences in C_{10} and C_{12}, but Panel (B) indicates there is essentially no correlation.

As in the case of Panel (A), Panel B indicates there is positive but weak correlation between differences in mean PM values and differences in means of ranks assigned to DHA constituents, but that the differences in mean ranks themselves are moderately positively correlated with differences in PMI and AKI, and with differences in C_{10} and C_{12}. By comparison, in Panel (A) the correlation between the difference in mean ranks and differences in all other factors is weak.

Panel (B) shows a positive correlation between differences in PMI and differences in C_9 and C10, (although the values are not as strong as in Panel (A)), but essentially no correlation with differences in C_{11} and C_{12}. Again, this is contrary to the evidence presented in Panel (1) that shows a strong correlation between differences in PMI and differences in C_{10}, C_{11}, and C_{12}, but essentially no correlation with differences in C_9.

From these observations it may concluded that the 11 fuel pairs for which the difference in mean PM and the difference in mean ranks are both deemed to be statistically significant represent a category that is different from the entire group of fuel pairs on whole. However, the small number of observations involved must be considered.

Discussion of Panel (C)

Panel (C) presents results associated with the 66 fuel pairs for which neither differences in mean PM nor differences in mean ranks assigned to the Wgt% values of DHA constituents are statistically significant. The correlation structure is nearly identical to the correlation structure for Panel (A).

Discussion of Panel (D)

Panel (D) contains pairwise correlations among the nine difference variables associated with the 22 fuel pairs for which the difference in mean PM is not statistically significant but the corresponding difference in the mean of the ranks assigned to Wgt% values of DHA constituents is. This represents one of the two mismatch situations. In this case, the correlation structure is largely consistent with that of Panel (A). The most noteworthy contrast is the stronger correlation between differences in mean PM and differences in mean ranks (.58 here, versus .35 in Panel (A)). Among all five panels, this is the strongest correlation between these two quantities. Additionally, the correlation between differences in mean PM and differences in PMI (.68) is the smallest value reported among the five panels.

Discussion of Panel (E)

Panel (E) presents the corresponding correlation results for the six fuel pairs for which the difference in mean PM is statistically significant but the corresponding difference in the mean of

the ranks assigned to the Wgt% values of DHA components is not. This is the second of the two mismatch categories.

In this case, differences in mean PM are moderately to strongly correlated with differences in PMI, C_9, C_{10}, C_{11}, and C_{12}, all in the positive direction. The correlation between differences in mean PM and differences in PMI (.98) is the highest among all five panels.

Differences in mean PM and differences in mean ranks are effectively uncorrelated, but differences in mean ranks are moderately positively correlated with differences in AKI and EtOH. Differences in PMI are moderately to strongly positively correlated with differences in the Wgt% values of all four carbons, and AKI is moderately negatively correlated with differences in C_{12}.

Again, all Panel (E) results must be tempered by the fact that only six observations are involved in the correlation computations.

Overall Observations

The following broad observations can be made about the correlation results presented in Panels (A) thru (E) of Table B3.

- The is little evidence of relationship between the differences in mean PM and the differences in the mean ranks assigned to Wgt% values of DHA constituents. This may suggest that, at the macro level, DHA constituent data does not directly inform PM. It may be the case that the constituent level data are too granular to detect any consistent effect or impact.
- Differences in mean PM are consistently shown to be moderately to strongly correlated with difference in the Wgt% values of C_9, C_{10}, C_{11}, and C_{12}, a finding that parallels similar results reported elsewhere in the main report. The strength of the evidence varies depending on how fuel pairs are grouped, but it seems clear that these four carbons are important to the production of PM, with greater weight being given to C_{10} thru C_{12}.

Table B3. Pairwise correlations among nine “difference variables” for five different sets of fuel pairs. Descriptions provided in Table B2.

(A)

Difference in / Difference in

	Mean PM	Mean Ranks	PMI	AKI	EtOH	C9	C10	C11	C12
Mean PM	1								
Mean Ranks	0.35	1							
PMI	0.81	0.25	1						
AKI	-0.07	0.14	-0.06	1					
EtOH	-0.01	-0.15	-0.07	-0.03	1				
C9	0.40	0.23	0.02	-0.09	-0.01	1			
C10	0.78	0.36	0.98	-0.05	-0.09	-0.03	1		
C11	0.67	0.22	0.93	-0.07	-0.08	-0.10	0.95	1	
C12	0.68	0.25	0.91	-0.01	-0.11	0.01	0.90	0.88	1

(B)

Difference in / Difference in

	Mean PM	Mean Ranks	PMI	AKI	EtOH	C9	C10	C11	C12
Mean PM	1								
Mean Ranks	0.31	1							
PMI	0.78	0.52	1						
AKI	0.23	0.54	0.26	1					
EtOH	-0.11	-0.17	-0.34	0.03	1				
C9	0.84	0.27	0.62	0.04	-0.37	1			
C10	0.20	0.65	0.68	0.39	-0.10	-0.03	1		
C11	-0.67	0.35	-0.17	0.06	-0.27	-0.50	0.35	1	
C12	-0.12	0.78	-0.05	0.42	0.25	-0.13	0.28	0.41	1

(C)

Difference in / Difference in

	Mean PM	Mean Ranks	PMI	AKI	EtOH	C9	C10	C11	C12
Mean PM	1								
Mean Ranks	0.24	1							
PMI	0.79	0.26	1						
AKI	-0.04	-0.01	-0.05	1					
EtOH	-0.03	-0.18	-0.10	-0.08	1				
C9	0.13	-0.12	-0.13	-0.16	0.09	1			
C10	0.74	0.32	0.98	-0.06	-0.12	-0.22	1		
C11	0.65	0.21	0.93	-0.05	-0.13	-0.21	0.95	1	
C12	0.65	0.22	0.89	-0.07	-0.16	-0.05	0.88	0.85	1

(D)

Difference in / Difference in

	Mean PM	Mean Ranks	PMI	AKI	EtOH	C9	C10	C11	C12
Mean PM	1								
Mean Ranks	0.58	1							
PMI	0.68	0.48	1						
AKI	0.23	0.37	0.22	1					
EtOH	-0.20	-0.30	-0.15	-0.10	1				
C9	0.24	0.05	-0.41	0.01	-0.20	1			
C10	0.66	0.53	0.99	0.18	-0.19	-0.43	1		
C11	0.65	0.46	0.95	0.14	-0.05	-0.43	0.96	1	
C12	0.70	0.41	0.95	0.34	-0.14	-0.34	0.93	0.92	1

(E)

Difference in / Difference in

	Mean PM	Mean Ranks	PMI	AKI	EtOH	C9	C10	C11	C12
Mean PM	1								
Mean Ranks	-0.14	1							
PMI	0.98	-0.06	1						
AKI	-0.28	0.51	-0.35	1					
EtOH	0.02	0.78	0.00	0.88	1				
C9	0.64	0.46	0.61	0.09	0.46	1			
C10	0.96	-0.13	0.99	-0.31	-0.01	0.49	1		
C11	0.90	-0.09	0.96	-0.42	-0.09	0.42	0.98	1	
C12	0.73	0.04	0.85	-0.60	-0.22	0.37	0.83	0.92	1

- On the other hand, the results presented in Panel (B) are noteworthy because of the absence of correlation between differences in mean PM and differences in C_{10} and C_{12}, plus the moderately strong negative correlation with C_{11}. Since Panel (B) represents the 11 fuel pairs for which differences in mean PM and differences in mean ranks are both statistically significant, this likely identifies the fuels that are clearly different and signals that the differences are due to contrasting effects among the four carbons and PMI. Note that seven of the 11 fuel pairs involve Fuel B, the other four involve Fuel F, and that five of them involve one of the E-129 fuels. Fuels B and F have two of the three highest PM values, whereas Fuels CRC-C, CRC-ETOH10, and CRC-ETOH15 have the lowest PM values.
- The relationship between differences in PMI and differences in the four carbons is noteworthy. The weakest correlations appear in Panel (B) which, again, represents the 11 fuel pairs that are deemed to have statistically significant differences under both analytical regimes and may be the most clearly different fuel pairs.
- As indicated elsewhere in the main report, AKI and EtOH do not appear to play a significant role overall.

Appendix C. Evolution of the Detailed Hydrocarbon Analysis

The detailed hydrocarbon analyses (DHA) used in this report were conducted at Southwest Research Institute (SwRI) using an updated version of their customized ASTM D6729 method. Therefore, the DHA results of the E-94-2, E-94-3 and E-129-1 fuels in the present report do not exactly match the original results that have been previously reported in the corresponding projects conducted at SwRI. These updated DHA data are also used in other ongoing CRC projects to stay consistent with data analysis. Additionally, the same fuels were also tested at Separation Systems, Inc. (SSI) using its extended library and techniques to reduce the percentage of unidentified high molecular weight aromatics, and to determine if a more accurate particulate matter index (PMI) value could be constructed. The SSI method is documented in the appendix of ASTM D6730. The combined DHA file is provided as supplementary material to this report. Table C1 contains the calculated PMI values using both SwRI and SSI DHA analyses and Figure C1 shows the results from using the two techniques plotted against each other to illustrate how they compare. The difference between the two techniques is most pronounced at higher PMI values, due to the greater number of high-PMI components identified by the SSI DHA method.

Table C1. Summary of PMI Values for SwRI and SSI.

CRC Report	Fuel	Fuel Description	AKI Fuel Description	PMI Fuel Description	SWRI Reprocessed Chromatograms (2020)	SSI-Enhanced DHA (2018)
E-94-2	Fuel A	Match E10	LOW AKI	LOW PMI	1.42	1.43
E-94-2	Fuel B	Match E10	LOW AKI	HIGH PMI	2.64	3.01
E-94-2	Fuel C	Match E0	LOW AKI	LOW PMI	1.36	1.32
E-94-2	Fuel D	Match E0	LOW AKI	HIGH PMI	2.59	2.97
E-94-2	Fuel E	Match E10	HIGH AKI	LOW PMI	1.30	1.25
E-94-2	Fuel F	Match E10	HIGH AKI	HIGH PMI	2.55	2.83
E-94-2	Fuel G	Match E0	HIGH AKI	LOW PMI	1.27	1.23
E-94-2	Fuel H	Match E0	HIGH AKI	HIGH PMI	2.20	2.78
E-94-3	Fuel C	Match E0	LOW AKI	LOW PMI	1.42	1.32
E-94-3	Fuel C-E10	Splash E10	LOW AKI	LOW PMI	1.28	1.3
E-94-3	Fuel D	Match E0	LOW AKI	HIGH PMI	2.65	2.97
E-94-3	Fuel D-E10	Splash E10	LOW AKI	HIGH PMI	2.45	2.75
E-94-3	Fuel G	Match E0	HIGH AKI	LOW PMI	1.27	1.23
E-94-3	Fuel G-E10	Splash E10	HIGH AKI	LOW PMI	1.17	1.15
E-94-3	Fuel H	Match E0	HIGH AKI	HIGH PMI	2.49	2.78
E-94-3	Fuel H-E10	Splash E10	HIGH AKI	HIGH PMI	2.32	2.46
E-129	Fuel C	Match E0	LOW AKI	LOW PMI	1.37	1.22
E-129	10% EtOH	Splash			1.21	1.10
E-129	15% EtOH	Splash			1.16	1.04
E-129	16% Isobutanol	Splash			1.11	1.02
E-129	24% Isobutanol	Splash			1.02	0.94
E-129	19% MTBE	Splash			1.14	0.97
E-129	29% MTBE	Splash			1.00	0.87

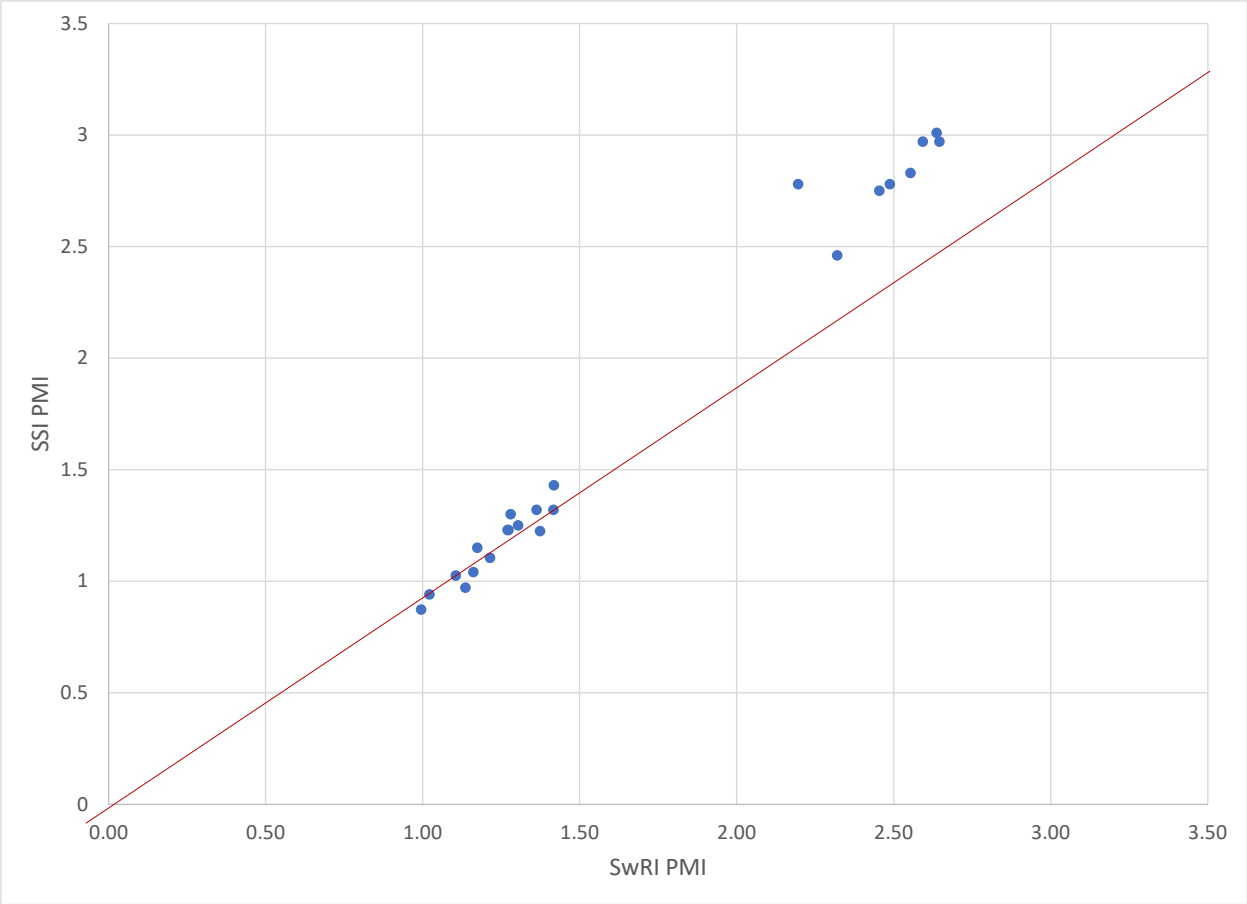

Figure C1. Plot of SSI PMI versus SwRI PMI DHA data from E-94-2, E-94-3 and E-129 reports. See Table C1.

Appendix D. DHA Master File

Prior to conducting any analyses of the DHA data relevant to the present report, a master file of the DHA results had to be constructed. The master file (an Excel workbook) is provided as supplementary material to this report on the CRC website as Appendix D. The file collects together in one place all the DHA results obtained by SwRI on each individual fuel at the carbon, group, and individual constituent levels. Also indicated are constituents that are absent in one or more fuels but present in others. Information about the AKI, EtOH and PMI values associated with each fuel is included, along with mean and median values of weighted PM.