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The Effect of Cetane Number Increase Due to Additives on NOx Emissions from Heavy-Duty Highway Engines

Final Technical Report

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Final Technical Report

Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

NOTICE

This technical report does not necessarily represent final EPA decisions or positions. It is intended to present technical analysis of issues using data that are currently available. The purpose in the release of such reports is to facilitate the exchange of technical information and to inform the public of technical developments which may form the basis for a final EPA decision, position, or regulatory action.

Abstract

This report presents a technical analysis of the NOx emissions impacts of increases in cetane number brought about through the use of diesel fuel additives. The purpose of this technical report is to provide information to parties who may be evaluating the value, effectiveness, and appropriateness of the use of cetane improver additives. It was originally provided to the public in draft form so that interested parties could comment on the methodology, assumptions, and conclusions. Where deemed appropriate, modifications were made to the report on the basis of those comments. This technical report is now being released in final form.

The analysis described in this report uses statistical regression analysis to correlate diesel cetane number increases brought about through additives with NOx emissions from heavy-duty highway engines. It relies upon pre-existing data from publicly available sources. The result is that the effect of cetane improver additives on NOx emissions can be predicted for the in-use fleet using a correlation which is a function of the natural cetane number of the unadditized base fuel and the increase in cetane number brought about through additives. These NOx emission effects are also a function of the calendar year in order to account for lower cetane sensitivity of advanced technology engines. For instance, if cetane improvers are added to a national average base fuel so that the total cetane number is increased by 5 numbers, the percent reduction in NOx for calendar year 2003 is predicted to be 2.0 for highway engines. The correlations predict lower NOx benefits for future calendar years. Nonroad engines may exhibit slightly higher NOx benefits due to the slower introduction of cetane-insensitive technologies into the nonroad fleet.

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I. Context

A. Nature and purpose of this technical report

This report presents a technical analysis of the NOx emissions impacts of increases in cetane number brought about through the use of certain diesel fuel additives. It analyzes pre-existing data from various emissions test programs to investigate these effects. The conclusions drawn in this technical report represent the current understanding of this specific technical issue, and are subject to re-evaluation at any time.

The purpose of this technical report is to provide information to interested parties who may be evaluating the value, effectiveness, and appropriateness of the use of cetane improver additives. This report informs any interested party as to the potential air emission impacts of increases in cetane number brought about through use of these additives. It was originally provided to the public in draft form so that interested parties would have an opportunity to review the methodology, assumptions, and conclusions. The Agency also requested independent peer reviews on the draft technical report from experts outside the Agency.

This technical report is not a rulemaking, and does not establish any legal rights or obligations for any party. It is not intended to act as a model rule for any State or other party. This report is by its nature limited to the technical analysis included, and is not designed to address the wide variety of additional factors that could be considered by a State when initiating a fuel control rulemaking. For example, this report does not consider isues such as air quality need, cost, cost effectiveness, technical feasibility, fuel distribution and supply impacts, regional fleet composition, and other potentially relevant factors.

State or local controls on motor vehicle fuels are limited under the Clean Air Act (CAA) - certain state fuel controls are prohibited under the Clean Air Act, for example where the state control applies to a fuel characteristic or component that EPA has regulated (see CAA Section 211(c)(4)). This prohibition is waived if EPA approves the State fuel control into the State Implementation Plan (SIP). EPA has issued guidance describing the criteria for SIP approval of an otherwise preempted fuel control. See "Guidance on the Use of Opt-in to RFG and Low RVP Requirements in Ozone SIPs," (August, 1997) at: http://www.epa.gov/otaq/volatility.htm.

The SIP approval process, a notice and comment rulemaking, would also consider a variety of technical and other issues in determining whether to approve the State fuel control and what emissions credits to allow. An EPA technical report like this one can be of value in such a rulemaking, but the SIP rulemaking would need to consider a variety of factors specific to the area, such as fleet make-up, refueling patterns, program enforcement and any other relevant factors. Additional evidence on emissions effects that might be available could also be considered. The determination of emissions credits would be made when the SIP rulemaking is concluded, after considering all relevant information. While a technical report such as this may

be a factor in such a rulemaking, the technical report is not intended to be a determination of SIP credits for a State fuel program.

B. Public participation

This technical report was made available to the general public in draft form on June 17, 2002. A comment period was established during which reviewers could submit written comments on the analyses contained in the draft technical report. This comment period ended on July 15, 2002. We received comments from the following companies/organizations:

- Alliance of Automobile Manufacturers
- American Petroleum Institute
- American Trucking Association
- California Truckers Association
- Cummins, Inc.
- Defense Energy Support Center
- Ethyl Corporation
- Flint Hills Resources, LP
- Kern Oil & Refining Company
- National Petrochemical & Refiners Association

We also requested and received comments from EPA's Office of Research and Development.

We reviewed the comments received from stakeholders and updated this technical report accordingly. We also submitted a draft of this technical report to two outside experts to obtain independent peer review. Following the guidelines in EPA's Science Policy Council Handbook on Peer Review, we generated responses to all the recommendations provided by the peer reviewers and modified this technical report and the analyses contain herein where it was deemed appropriate.

Parties interested in the draft technical report, background materials, and support documents associated with this final technical report can find them at the following Web site:

http://www.epa.gov/otaq/models/analysis.htm

This Web site also contains copies of all comments received from our stakeholders, the reports generated by the independent peer reviewers, and our responses to the peer reviewers' recommendations.

II. Introduction

A. Background on cetane analysis

The control of diesel fuel properties as a means for reducing emissions of regulated pollutants continues to be of interest to parties interested in or charged with reaching various air quality goals. Previous test programs have shown various levels of benefits for changes to such fuel properties as cetane number, aromatics, density, sulfur, and distillation properties. For areas that are out of attainment for ozone or particulate matter, State air quality managers may consider changes to diesel fuel as one element of their overall strategy for meeting the National Ambient Air Quality Standards.

One example of a State that has implemented a diesel fuel approach as part of its overall strategy to reach attainment is Texas. When its Low Emission Diesel (LED) program was first proposed for Houston and Dallas in the fall of 2000, EPA determined that the NOx emission reduction benefits claimed by Texas were based on a small amount of outdated data. As a result we initiated an effort to evaluate the emission benefits of varying diesel fuel parameters. In July of 2001, we issued a Staff Discussion Document[1] with the preliminary results of this analysis.

Our process in conducting this evaluation involved reviewing existing engine emissions data rather than conducting new emissions tests. Where data was available, we used a regression model approach to analyze results and to develop a quantitative set of relationships between fuel parameters and emissions changes (in the remainder of this technical report, this work will be referred to as the Staff Discussion Document model). As part of our process, we met with numerous stakeholders to review our preliminary conclusions, beginning in May of 2001, and in response to requests from stakeholders, held a public workshop on August 28, 2001 to hear comments on our Staff Discussion Document and our analysis.

After reviewing the comments made at the workshop, we estimated the NOx emission factors for the Texas diesel fuel program based on this analysis. Our conclusions were summarized in a memorandum to EPA's Region VI[2]. In this memorandum, we limited the use of the draft NOx model presented in the Staff Discussion Document to the evaluation of the benefits of the Texas diesel fuel program. As a result, there currently exists no widely-applicable, EPA-approved model for estimating the emission impacts of more general changes in diesel fuel properties. At this time, EPA has no plans to pursue such a comprehensive model.

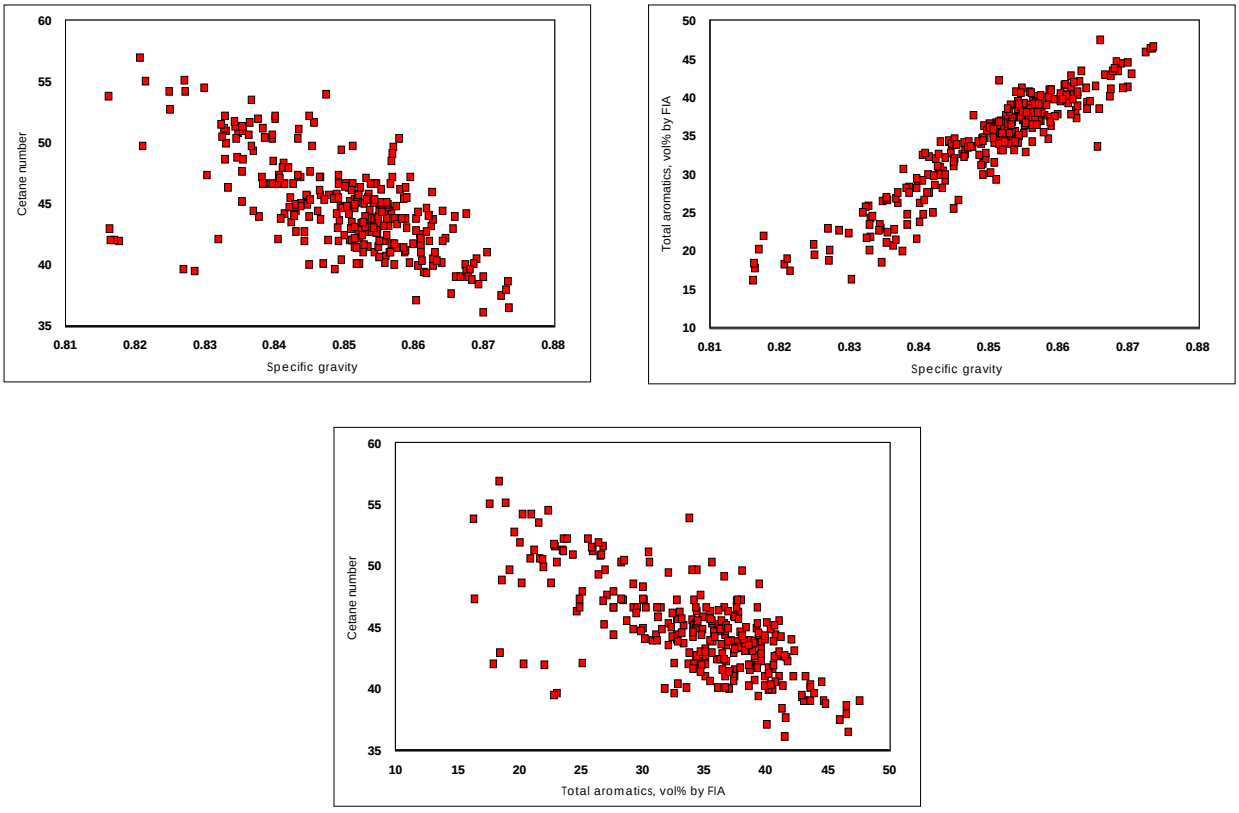
B. Cetane number as an emission control strategy

Of the various diesel fuel properties that could be controlled in order to produce emission benefits, cetane number holds the greatest interest, particularly with regard to NOx. Even in the absence of a more comprehensive model correlating all diesel fuel properties with emissions, some States are still considering implementing cetane control programs. In such cases, the

emission benefits might be based on results from various individual test programs that attempted to control cetane number. Since any NOx benefits claimed in a SIP as a result of cetane control must eventually be approved by EPA, we have determined that it is now appropriate to investigate the NOx benefits of cetane control in a comprehensive fashion to preclude the use of less robust estimates that may misrepresent benefits.

The cetane number of diesel fuel can be increased in two different ways: naturally, and via the use of additives. The "natural" approach involves the modification of various physical properties of diesel fuel, via changes to the concentration of various diesel fuel components. The result is that multiple properties/components may change at the same time. This "colinearity" is best illustrated for cetane, aromatics, and specific gravity, as shown in Figure II.B-1. The data in these graphs is drawn from a survey of in-use diesel fuels[3].

Figure II.B-1
Colinearities for natural cetane number



These graphs provide strong evidence that changes in one fuel property will generally be accompanied by concurrent changes in other fuel properties, confounding attempts to correlate any one fuel property with emissions.

This colinearity can also be seen in variance inflation factors. Variance inflation factors

are based on the r^2 value (coefficient of determination) resulting from a least-squares regression in which one fuel property is made a function of all other fuel properties. The formula for variance inflation factors (VIF) is:

$$VIF = 1 / (1 - r^2)$$

A value close to 1 indicates that no correlation exists. A value higher than 5 indicates a moderately strong correlation, while values approaching 10 indicate very strong correlations. A listing of variance inflation factors is shown in Table II.B-1 for the same in-use survey data shown in Figure II.B-1.

Table II.B-1
Variance inflation factors for in-use survey data

Natural cetane	7.1
Additized cetane[α]	1.1
Sulfur	1.3
Aromatics	10.0
T10	4.8
T50	11.1
T90	4.2
Specific gravity	16.7

[α] "Additized cetane" is the increase in total cetane number brought about through the addition of cetane improver additives.

From this table it is clear that natural cetane is highly correlated with many other fuel properties. In addition, the high VIFs for aromatics and specific gravity indicate that these three properties are highly correlated with one another (the distillation properties are primarily correlated with each other). However, since fuels in test programs are sometimes the product of more carefully designed blending that might avoid some of these correlations between fuel properties, the values in Table II.B-1, based on a survey of in-use fuels, may be misleading. We therefore repeated the calculation of VIFs for the Staff Discussion Document model database. The result was that the VIFs were indeed lower than the values in Table II.B-1, but not significantly.

Finally, a correlation matrix is another way to investigate colinearities between fuel properties. Using our emissions database, we generated a correlation matrix by standardizing all of the fuel property measurements (by subtracting the mean from every observation and dividing by the standard deviation), multiplying the fuels matrix by its transpose, and normalizing the results. The results for the primary fuel properties of interest are shown in Table II.B-2. The matrix is necessarily identical on either side of the diagonal.

Table II.B-2
Correlation matrix for diesel emissions database

	Natural Cetane	Additized cetane	Sulfur	Aro-matics	T10	T50	T90	Specific gravity
Natural Cetane	1							
Additized cetane	-0.35	1						
Sulfur	-0.04	-0.17	1					
Aromatics	**-0.57**	0.20	0.30	1				
T10	0.16	-0.08	0.01	0.13	1			
T50	0.26	-0.07	0.11	0.30	**0.69**	1		
T90	0.32	-0.10	0.10	0.23	0.30	**0.70**	1	
Specific gravity	**-0.61**	0.25	0.21	**0.75**	0.30	0.41	0.23	1

[α] "Additized cetane" is the increase in total cetane number brought about through the addition of cetane improver additives.

As the values in the correlation matrix approach 1 (or -1), the correlation between the two fuel properties in question approaches a perfect linear correlation. Thus the Table II.B-2 values can be viewed as correlation coefficients for one fuel property as a function of another fuel property. The highest values are for T50 as a function of the adjacent distillation properties T10 and T90, and the intercorrelation between natural cetane, aromatics and specific gravity. The correlation matrix also highlights the fact that colinearity between diesel fuel properties is more pronounced than for gasoline, likely due to the fact that gasoline is composed of 7-8 blending streams while diesel fuel is composed of 2-3 streams. For instance, the average of the values in Table II.B-2 (ignoring the diagonal and using the absolute values) is 0.28. By way of comparison, the average correlation coefficient for the fuels used in developing the Complex Model[4] for the reformulated gasoline program was 0.15. Although the selection of fuel properties of interest is somewhat arbitrary in both cases, we can conclude that the degree of colinearity between fuel properties in our diesel emissions database is significantly greater than that in our Complex Model database.

Given the strong colinearities between natural cetane and other fuel properties, it is not surprising that many stakeholders questioned the draft emissions model described in Section II.A. In particular, the NOx model contained no natural cetane term, despite the fact that many test programs had shown a strong correlation between natural cetane and NOx emissions. On closer examination, the absence of a natural cetane term appears to be a result of "aliasing". The NOx model contained both an aromatics and a specific gravity term, and it is likely that these two

terms were sufficient to describe the combined effect of aromatics, specific gravity, and natural cetane on NOx emissions. The natural cetane effect on NOx was, therefore, included in the effects exhibited by aromatics and specific gravity. This concept is supported by the fact that our estimate of NOx benefits for the Texas diesel fuel program was the same regardless of whether we used the NOx model proposed in our Staff Discussion Document (the model which did not contain a natural cetane term) or an alternative model that contained a total cetane term representing the sum of natural and additized cetane.

The model proposed in our Staff Discussion Document could still be used to predict the NOx impacts of changes in natural cetane so long as there existed a means for translating natural cetane changes into the aromatics and specific gravity changes that would likely occur collinearly. Although currently there is no commonly accepted way to do this, we were fortunate in the case of the Texas LED program to have survey data for fuels sold in California. Since Californian diesel fuel was deemed a reasonable representation of fuels that would be produced under the Texas LED program, we could use them to estimate the benefits of the Texas program. The result was that the colinearities between natural cetane and other fuel properties were inherent in the California survey data, and we could place confidence in the resulting predictions from the Staff Discussion Document model.

There exists an alternative way to estimate the impact of changes in cetane number on NOx emissions, one that avoids the complication of colinearity between fuel properties. This approach uses additized cetane as the independent variable instead of natural cetane. Additized cetane is here defined as increases in the total cetane number brought about through the use of small quantities (~1 vol% or less) of compounds designed to specifically and solely bring about this result. Examples of such cetane improver additives include 2-ethylhexylnitrate and di-tertiary butyl peroxide. Other bulk blending components that could increase the natural cetane number of conventional diesel fuel but which would generally be added at significantly larger concentrations, such as biodiesel or Fischer-Tropsch diesel, would not be considered to be cetane improver additives nor as sources of "additized cetane" for the purposes of this analysis, since they always affect other fuel properties in addition to cetane number.

Additized cetane is largely uncorrelated with other diesel fuel properties, as shown by the low variance inflation factor in Table II.B-1. This result is expected since the additives used to increase cetane generally are used in concentrations of 1 volume percent or less. These low additive concentrations mean that the other components of diesel fuel are not diluted in any measurable way. Also, the non-cetane properties of the additives themselves are not so extreme that physical properties of diesel fuel such as distillation properties or specific gravity are affected. Table II.B-2 indicates that the correlation coefficient between natural and additized cetane is -0.35, a value that may appear to be non-negligible. However, this degree of colinearity is due to human intervention and the need to enhance fuels with poor natural cetane by using additives to meet minimum cetane requirements. It does not reflect properties inherent in the fuel makeup as is the case for other fuel property pairs. As described in more detail in Section III.A below, the colinearity between natural and additized cetane is reduced substantially when

the database is limited to those observations for which both an additized fuel and its associated unadditized base fuel were tested.

There is good reason to believe that additized cetane and natural cetane describe identical, or at least similar, combustion mechanisms, since both additized and natural cetane are measures of a fuel's propensity to auto-ignite. Any differences in NOx impacts between additized and natural cetane may be related to the aromatics and specific gravity effects that are inherent with natural cetane. That is, natural cetane increases accompanied by typical reductions in aromatics and specific gravity might be expected to produce somewhat larger NOx benefits than additized cetane alone. However, we have insufficient information at this time to quantify any potential differences between natural and additized cetane effects on NOx, excluding the inherent effects of aromatics and specific gravity.

As a result of our review of colinearities between diesel fuel properties and our current understanding of the impacts of increased cetane number on combustion activity, we have determined that correlating additized cetane with NOx emissions is an appropriate means for providing inventory impact information to anyone considering the use of higher cetane diesel fuel. The remainder of this technical report describes the analyses we conducted to investigate additized cetane effects on NOx emissions.

III. Analytical approach

A. Database preparation

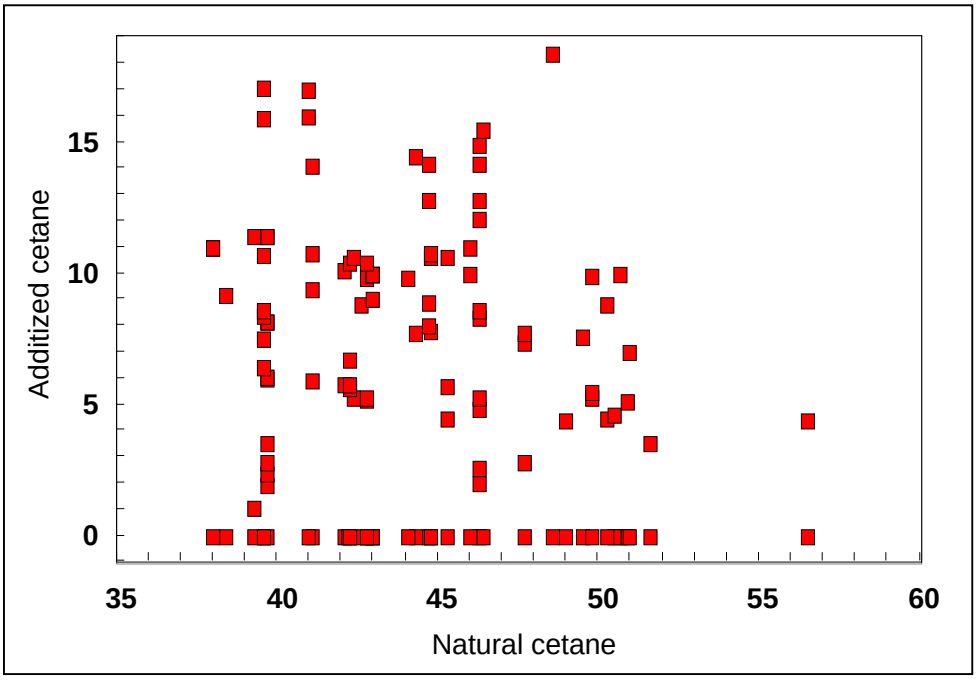
The data that we used for our analysis was a subset of the database used to develop the Staff Discussion Document models (discussed in Section II.A). That database was composed of three portions covering engine characteristics, emission measurements, and fuel properties. The database included values for a fuel property titled "CETANE_DIF" which represented the increase in cetane number resulting from the addition of a cetane improver additive to conventional diesel fuel. CETANE_DIF is thus the same as "additized cetane" referred to in Section II. In order to use this database for the analysis of additized cetane effects on NOx emissions, we simply deleted (blanked out) any CETANE_DIF values in the fuel properties database for any test fuels that either did not contain a cetane improver additive, or were not the base fuel to which a cetane improver was added. Base fuels with CETANE_DIF values of zero were left intact. In the course of curve-fitting using SAS, any fuels with a missing value for CETANE_DIF were automatically dropped from the analysis. The result was a collection of fuels whose additized cetane values were essentially uncorrelated with other fuel properties. Although the correlation coefficients for additized cetane in Table II.B-2 were low, the data subset used for our analysis produced correlation coefficients that were even lower, as shown in Table III.A-1. A listing of the fuels that were retained for this analysis is given in the Appendix.

Table III.A-1
Correlation coefficients for additized cetane

	Full database	Subset of database used for additized cetane analysis
Natural Cetane	-0.35	-0.17
Additized cetane	1	1
Sulfur	-0.17	-0.07
Aromatics	0.20	0.01
T10	-0.08	-0.10
T50	-0.07	-0.12
T90	-0.10	-0.10
Specific gravity	0.25	0.04

The final database used in our analysis provided a wide range of measurements for additized cetane and natural cetane number. Figure III.A-1 shows the distribution of cetane values in the database and the lack of correlation between natural and additized cetane.

Figure III.A-1
Additized cetane versus natural cetane measurements



Although we eliminated all irrelevant fuels from the fuels dataset, doing so did not guarantee that every engine in the database was tested on both an additized fuel and its corresponding unadditized base fuel. Therefore, we took additional steps to ensure that every engine used in the analysis was tested on both an unadditized fuel and an additized fuel. The result was that all engines from the EPEFE study which received modifications to their injection timings were excluded. No other engines were excluded for this reason. Note that complete descriptions of the full database can be found in the July 2001 Staff Discussion Document.

As in the development of the Staff Discussion Document model, we excluded all data collected on the Japanese 13-mode cycle as being unrepresentative of the federal FTP, since the overall loads in this steady-state cycle are too low in comparison to the FTP. We also included all repeat emission measurements (i.e. the same fuel tested on the same engine and cycle multiple times) in the database without averaging those repeats or limiting their inclusion in the database to some maximum number of observations.

1. Representativeness of fuels

The goal of our analysis was to determine the impact on NOx emissions of increases in cetane number brought about through additives. Generally the amounts of the additive required is small, one percent or less, so that the impacts on fuel properties other than cetane number is negligible. Since only one fuel property changes when cetane improver additives are used, we

have assumed that the other fuel properties play no role in the effect that increased cetane number has on emissions. The one exception to this assumption is the base (natural) cetane number, which was taken into account explicitly in our analysis as described in Section III.B.

However, to ensure that fuel properties other than cetane would not bias the emission effects we estimated, we reviewed the composition and properties of the base fuels in the database to determine the degree to which they could be said to represent in-use fuels. In this comparison we made use of survey data collected by the Alliance of Automobile Manufacturers in 2000. We created distributions for each fuel property and placed the results from the base fuels in our database side-by-side with distributions created from the in-use survey data. The results are shown in Figures III.A.1-1 through III.A.1-6.

Figure III.A.1-1
Comparison of base fuels from database to in-use fuels for sulfur content

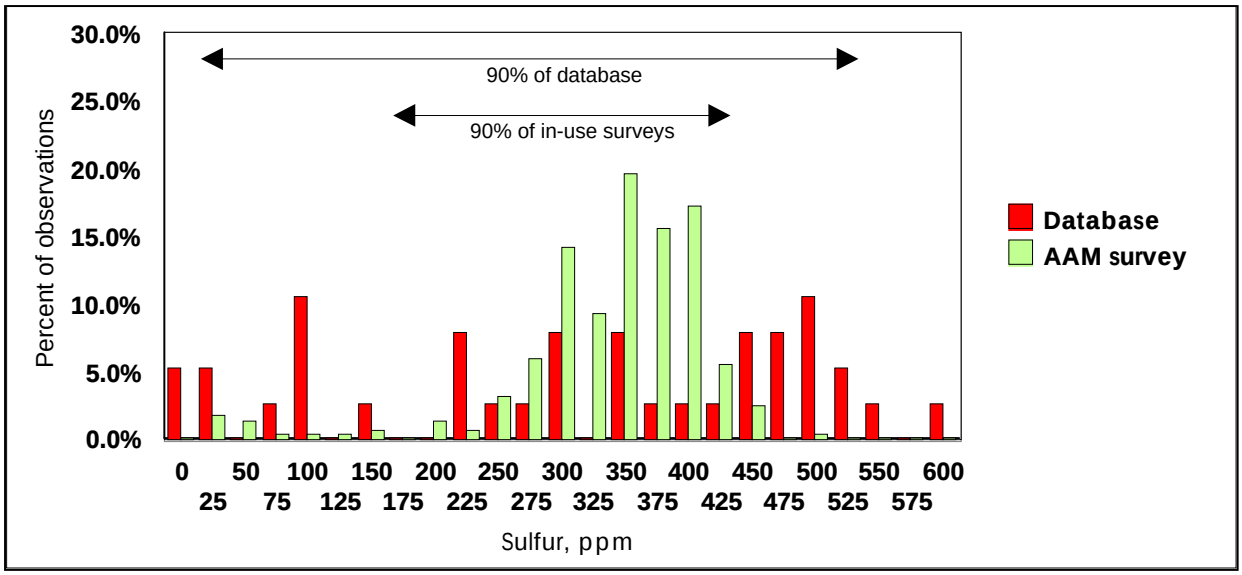


Figure III.A.1-2
Comparison of base fuels from database to in-use fuels for natural cetane

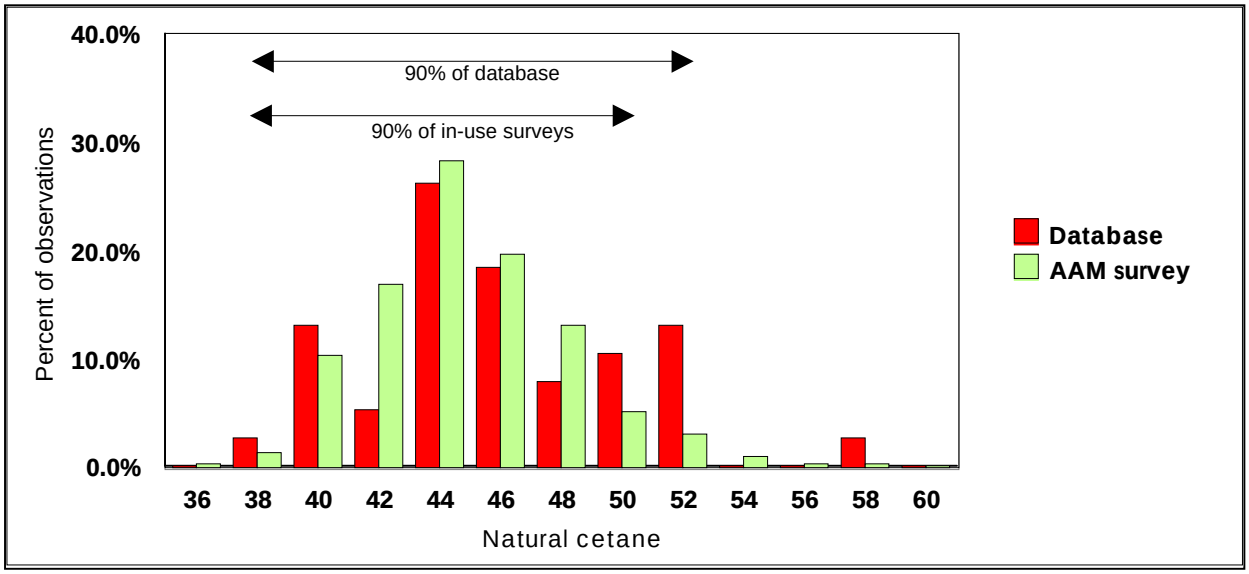


Figure III.A.1-3
Comparison of base fuels from database to in-use fuels for aromatics content

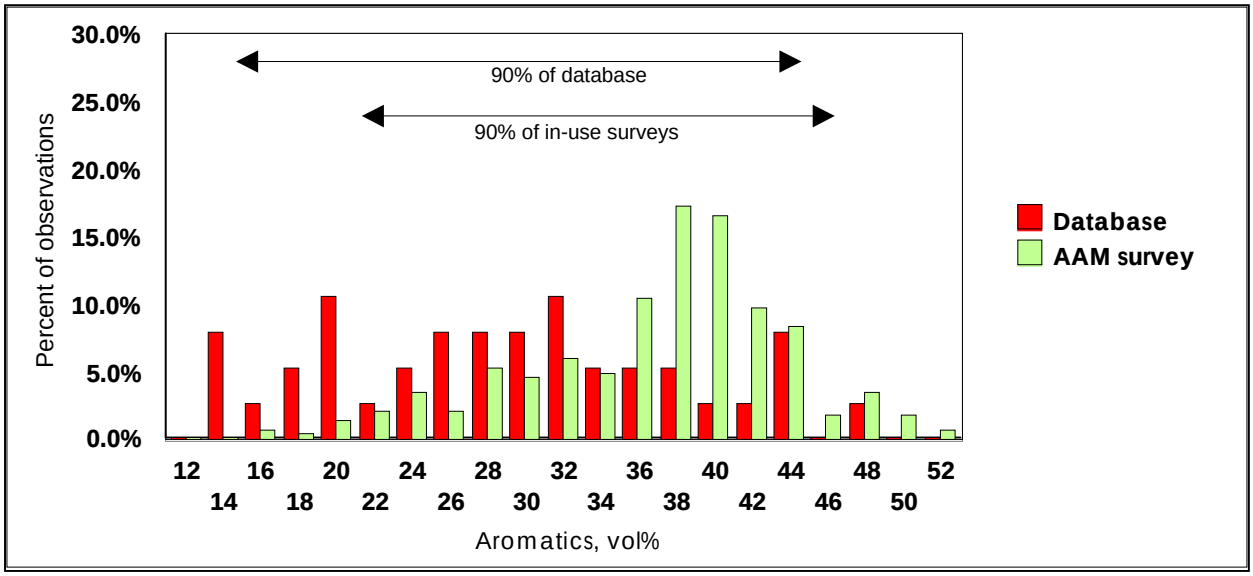


Figure III.A.1-4
Comparison of base fuels from database to in-use fuels for specific gravity

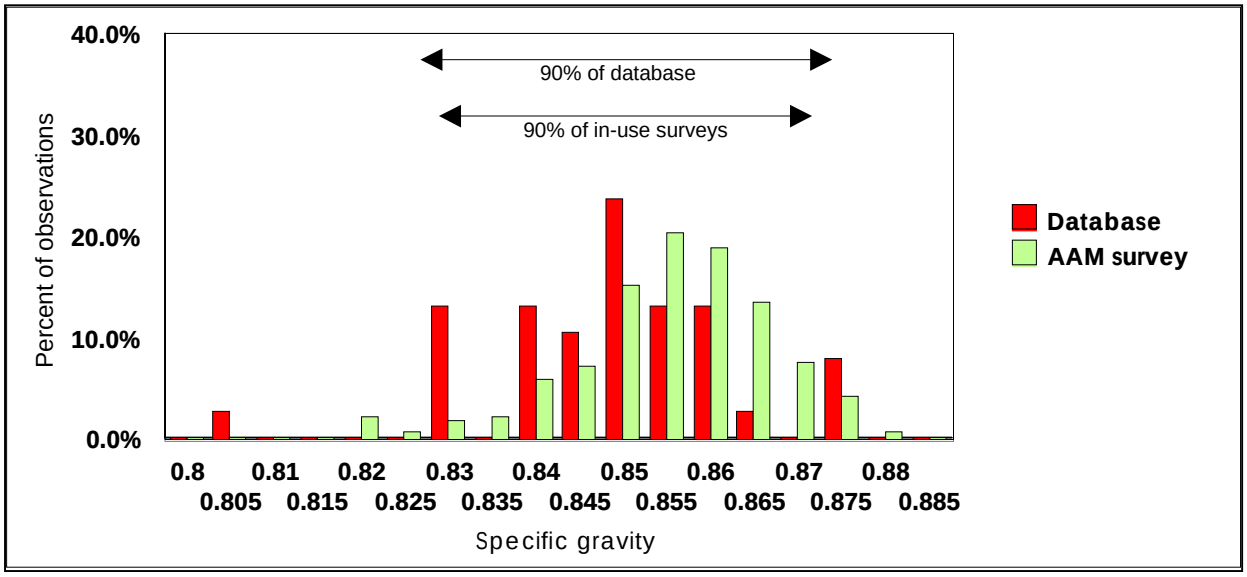


Figure III.A.1-5
Comparison of base fuels from database to in-use fuels for T50

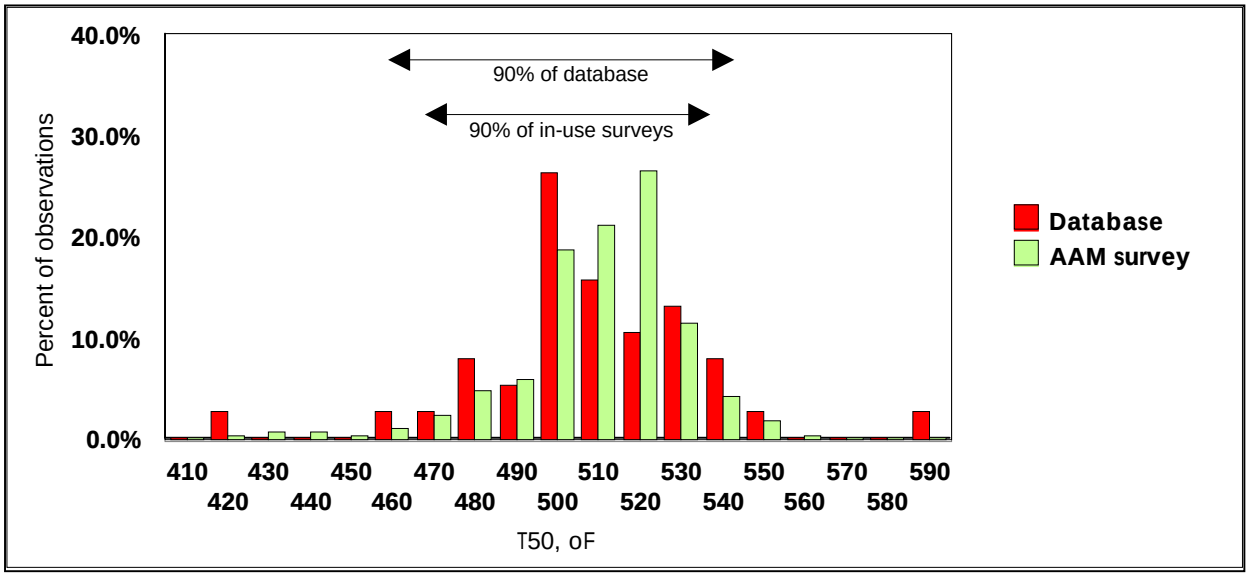
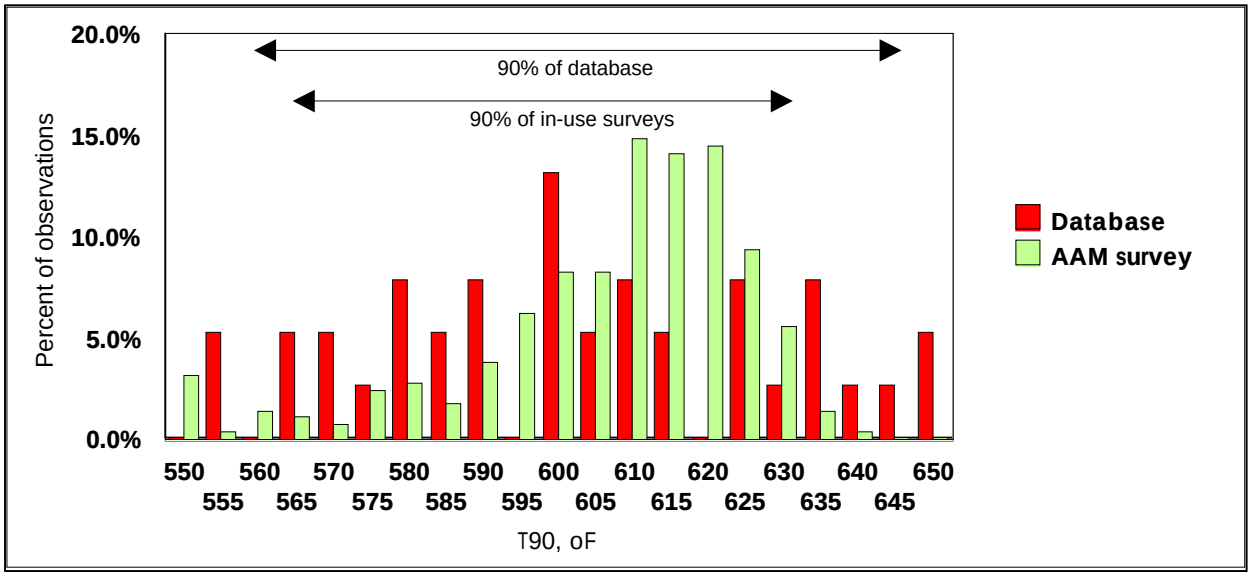


Figure III.A.1-6
Comparison of base fuels from database to in-use fuels for T90

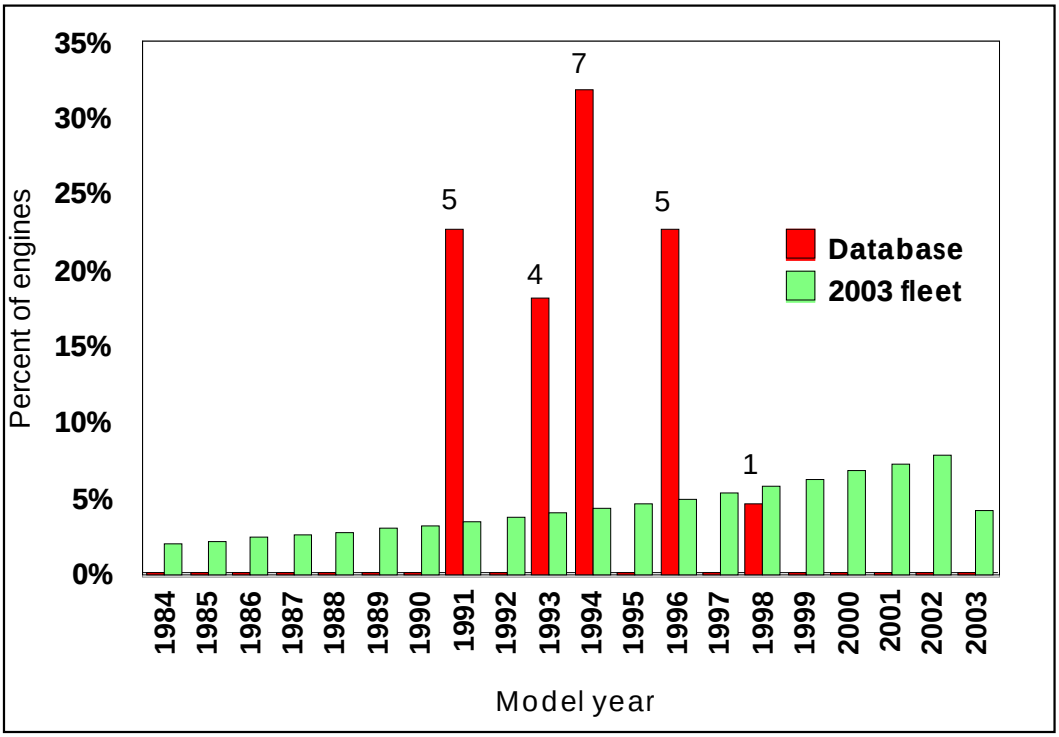


With the possible exception of aromatics, the range of property values for base fuels in the database encompases the range of values for in-use fuels. This result ensures that NOx emission effects that we estimate for additized cetane will not be unduly influenced by other fuel properties, and thus can be used to represent the NOx emission effects that would be expected in the field. For aromatics, the database range substantially overlaps the in-use survey range, and extends to lower aromatics levels which may be more representative of clean diesel fuel such as that required in California. Thus we believe that our database is fully representative of in-use fuels.

2. Representativeness of engines

The degree to which we can apply the results of our analysis to the in-use fleet of heavy-duty engines also depends on the degree to which engines in our database are representative of in-use engines. To evaluate this issue, we focused on the distribution of model years among engines in our database. Since we excluded all 2-stroke and EGR-equipped engines as described in Section III.B below, all engines used in our analysis were built in the 1990's. Figure III.A.2-1 shows the distribution of model years for these engines.

Figure III.A.2-1
Distribution of engine model years in the database



(numbers above bars represent the actual number of engines in the database)

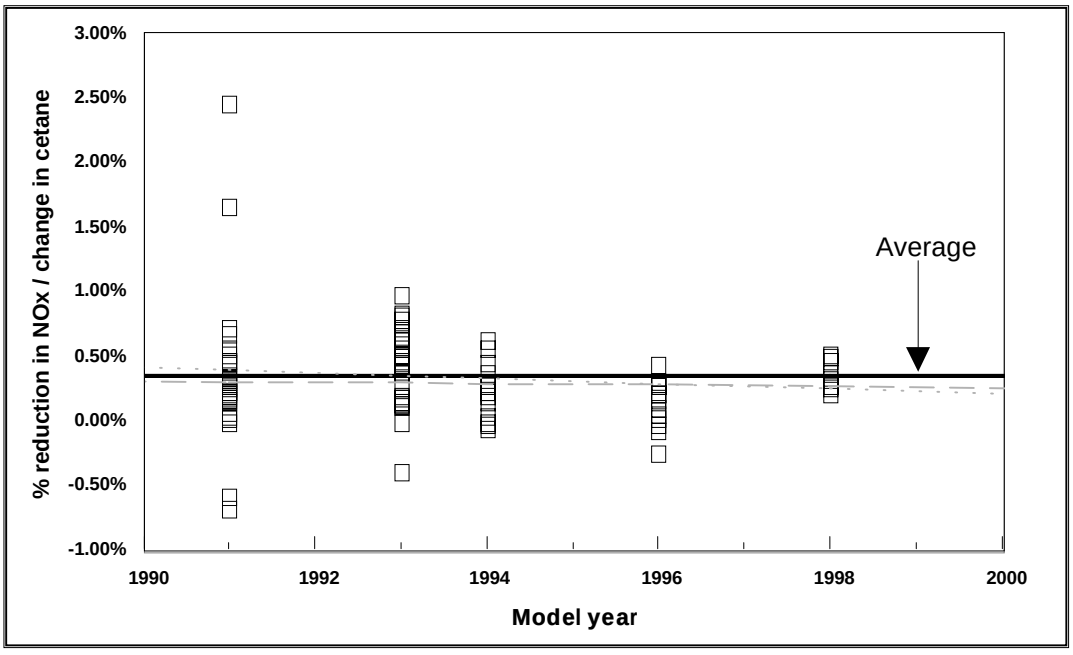
The distribution of model years is more broad for the in-use 2003 fleet than for the database. However, the current in-use fleet is comprised primarily of engines built in the 1990's, consistent with the database. Also, the average model year for the database is 1994, compared to an average of 1996 for the in-use 2003 fleet. We do not consider this difference to be significant in the context of estimating the impact of cetane on NOx emissions. Finally, engines built after 1999 will not constitute a majority of the highway engine NOx inventory for several more years. Thus we have determined that the distribution of model years in our database is sufficient to represent the current fleet for the purposes of our analysis.

As time goes on and the fleet turns over, however, it is possible that the emission effects estimated in our analysis will become less representative of effects exhibited by the in-use fleet. One step we have taken to account for this possibility is to assume that all engines built after 2002 will be equipped with EGR and will, as a result, exhibit no benefits from higher cetane (see Section IV.C for details). This is a conservative assumption, since there are indications that some manufacturers will not use EGR in their 2002+ engines. For those manufacturers that do use EGR, early indications are that EGR will continue to be used on engines built to meet the 2007 standards.

We also investigated the degree to which engines built in the later 1990's were less responsive to higher cetane than engines built in the early 1990's. There has been some limited

information suggesting that the more frequent use of injection rate-shaping and diffusion burning could mute the impact that cetane has on NOx emissions by reducing the amount of pre-mix burning and thus raising the adiabatic flame temperature. To do this analysis, we calculated engine-specific NOx effects for every unique pair of base fuel and its additized counterpart. For each engine in the database, the average % change in NOx was calculated from all repeat emission measurements on a given base fuel and its associated additized counterpart. The average % change in NOx was then divided by the change in cetane brought about through additives to produce an estimate of the % reduction in NOx for a unit increase in cetane number. We then plotted these effects by model year. To determine if engines were becoming less responsive to higher cetane over the course of the last decade, we conducted a least-squares regression on these values, with model year as the independent variable. We also conducted a least-squares regression that included dummy variables for the engines. The results are shown in Figure III.A.2-2.

Figure III.A.2-2
Effects of increased cetane on NOx by model year



The graph shows that the least-squares regressions result in lines that are very similar to the flat average. Although the slope was negative for both regression lines, suggesting that more recent engines may indeed exhibit less NOx sensitivity to cetane than older engines, in both cases the curve was not statistically significant at the $p = 0.10$ level. The regression coefficients and p-values are shown in Table III.A.2-1

Table III.A.2-1
Correlations between model year and % reduction in NOx/change in cetane

	Coefficient	p-value
Overall regression	-0.000209	0.11
Regression including dummy variables for engines	-0.000062	0.35

Based on this investigation, it is reasonable to assume that the effects of cetane on NOx are the same for all engines built in the 1990's. In addition, since we do not have conclusive data to the contrary, it appears reasonable to assume that these effects are also representative of model years 1999 - 2002.

B. Summary of analysis

In correlating additized cetane with NOx emissions, we generally followed the approach described in our July 2001 Staff Discussion Document. This included using the procedure "proc mix" in the statistical analysis package SAS to permit the simultaneous treatment of cetane number as a continuous independent variable and engines as random effects. We included all repeat emission measurements in the database without averaging those repeats or limiting their inclusion in the database to some maximum number of observations. The SAS curve-fitting procedure "proc mix" treats these repeat observations in a manner that precludes them from overweighting the results.

We chose to use the natural logarithm of NOx emissions to mitigate the heteroscedastic nature of the NOx measurements. We also standardized the independent variables by subtracting the mean and dividing by the standard deviation. The means and standard deviations are shown in Table III.B-1. Standardization removes the scale differences between fuel terms, and also reduces some of the colinearity between first and second-order terms.

Table III.B-1
Means and standard deviations used for standardizing independent variables

	Mean	Standard deviation
Additized cetane	5.03963	4.94910
Natural cetane	45.13889	4.27954

In our earlier work, we found that technology groups B and L produced different cetane/NOx relationships than other engine technology groups (see Table III.B.3-2 in the Staff Discussion Document). Technology group B represents 2-stroke engines, while technology group L represents engines equipped with exhaust gas recirculation (EGR). For our analysis of

additized cetane effects, we chose to exclude all technology group B data. Two-stroke engines currently represent approximately 1 percent of the heavy-duty highway fleet[5], and are expected to become an even smaller part of the fleet in the future. As a result we do not believe that excluding the group B data from our analysis materially affected the applicability of the results to the in-use fleet.

We also chose to exclude all group L data from our analysis. There are essentially no EGR-equipped engines in the current fleet, but they are expected to become a significant portion of the fleet over the next decade. The Heavy-Duty Engines Workgroup[6] is our primary source for data on the effects of additized cetane on an EGR-equipped engine, and that data suggests that these engines exhibit no discernable NOx response to cetane. The July 2001 Staff Discussion Document did conclude that a group L model adjustment term was statistically significant, but its magnitude was very similar to the overall term and of opposite sign. The result was that the predicted effect of cetane on NOx for group L engines was nearly zero (the correlation predicted a very small increase in NOx for EGR-equipped engines). However, the adjustment term was significant only because EGR-equipped engines could not be assigned the same NOx effect as non-EGR engines. When we attempted to generate an independent model for EGR-equipped engines, the effect on NOx was not significant, consistent with the findings of the Heavy-Duty Engines Workgroup. Therefore, the NOx impacts of additized cetane that resulted from the analyses described below are expected to apply to the entire fleet except EGR-equipped engines, as described more fully in Section IV.C.

Engines were identified in proc_mix as categorical random variables in our modeling. This is equivalent to specifying dummy variables for each engine in a fixed model, except that tested engines are treated as a random sample of engines drawn from the full population of engines in the fleet. We also recognized and accounted for two other types of random effects in our modeling. The first is the cetane/NOx relationship that is specific to every test engine, and the second is the effect of the unadditized base fuel on NOx emissions for each engine. By controlling for these types of random effects, we believe that the overall estimated effect of additized cetane on NOx can be confidently applied to the in-use fleet.

The primary independent variable included as a fixed effect in our model was additized cetane, defined as the increase in cetane number brought about through the addition of a cetane improver to conventional diesel fuel. We made no distinction between different types of cetane improver additives since we were not concerned with the effectiveness of a given additive in terms of cetane increase per unit concentration of additive. Instead we treated a given increase in cetane number as having the same effect on NOx regardless of the specific additive used to bring about that cetane number increase. This approach is consistent with conclusions reached in several previous studies[7,8,9]. To account for potential nonlinear effects we also included a squared additized cetane term.

Based on past studies of additized cetane effects on emissions, we had some evidence that increases in cetane brought about through the use of additives produced diminishing NOx

impacts as the base (natural) cetane number of the diesel fuel increased. Thus, for instance, an increase in cetane number from 45 to 50 might be expected to produce larger NOx impacts than an increase in cetane number from 50 to 55. To account for this possibility, we introduced a term into the model that represented the interaction of additized cetane and natural cetane number. Figure III.A-1 shows that there is good separation between additized cetane values and natural cetane values, i.e. no correlation exists between the two, which is an important prerequisite for investigating interactive terms. Since the inclusion of an interactive term meant that the natural cetane number was now represented in the model, we decided to also investigate the need for linear and squared natural cetane number terms. The complete list of five terms investigated in this analysis are given in Table III.B-2.

Table III.B-2
Independent variables investigated
in correlation between cetane number and NOx

Additized cetane
Additized cetane^2
Natural cetane
Natural cetane^2
Additized cetane × natural cetane

Only those terms that were statistically significant at the $p = 0.05$ level were retained using a backwards stepwise approach. Once all the remaining terms were statistically significant, we identified outliers as any data points whose residual exceeded four standard deviations from the predicted effect, removed them, and regenerated the model.

IV. Conclusions

A. SAS modeling results

The initial modeling run indicated that the squared natural cetane number term was not statistically significant. After it was dropped and the model regenerated, the remaining terms were all significant. Four outliers were then identified out of 540 total observations. These outliers are listed in Table IV.A-1 by the labels used in the database.

Table IV.A-1
Outliers excluded from final model

Study	Engine	Fuel	NOx, g/bhp-hr
SAE902173	902173-1	A3	3.66
SAE902173	902173-1	A3	3.67
SAE902173	902173-1	B2	4.38
SAE902173	902173-1	D1	4.63

Once the outliers were excluded, the model was regenerated a final time. The coefficients for the standardized variables and the associated P-values are given in Table IV.A-2.

Table IV.A-2
SAS proc mix output for final model

Variable	Coefficient	P-value
Intercept	1.5060	< 0.0001
Additized cetane	-0.01677	< 0.0001
Additized cetane ^{2}	0.004139	< 0.0001
Natural cetane	-0.02093	0.0057
Additized cetane × natural cetane	0.004720	< 0.0001

Using the mean and standard deviation for the standardized independent variables (Table III.B-1), we converted the coefficients back into unstandardized form. The fixed effects portion of the resulting model is shown below:

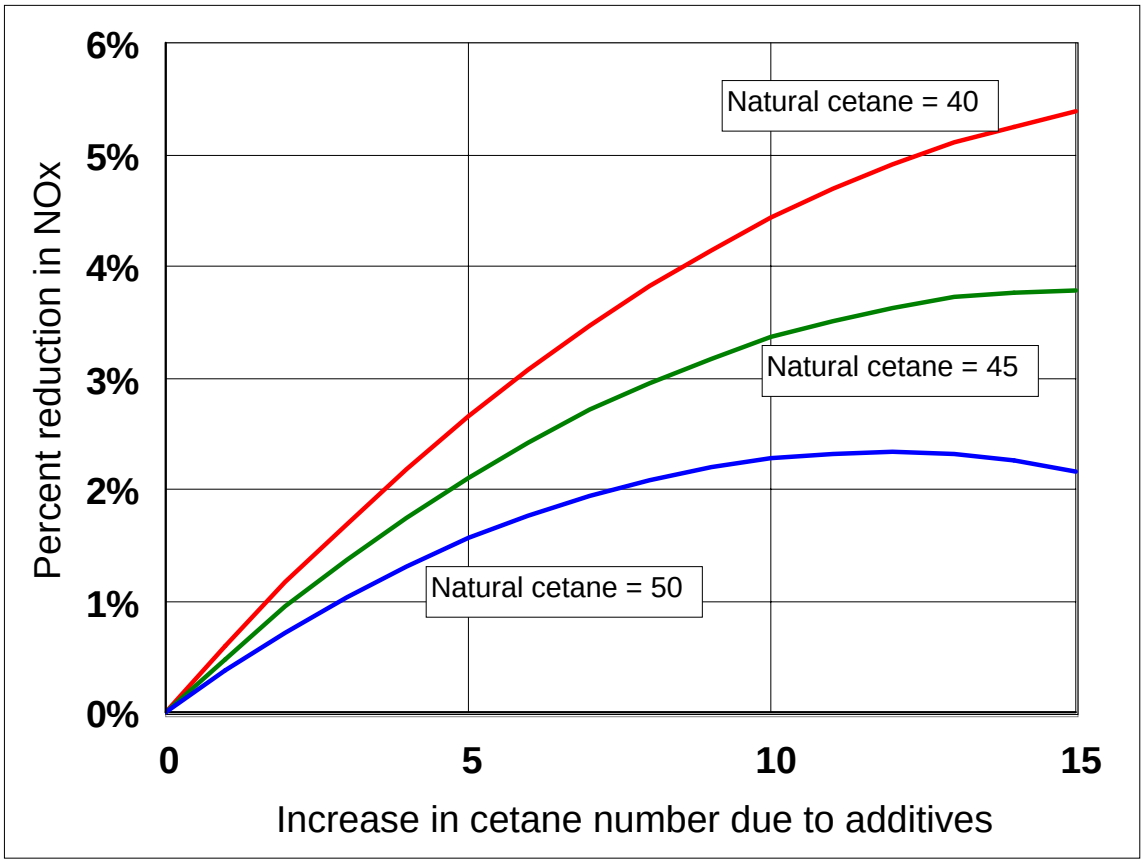
$$\ln(\text{NOx, g/bhp-hr}) = 1.79883 - 0.015151 \times (\text{additized cetane}) + 0.000169 \times (\text{additized cetane})^2 - 0.006014 \times (\text{natural cetane}) + 0.000223 \times (\text{additized cetane}) \times (\text{natural cetane}) \quad (1)$$

We can convert this equation into one that provides a percent change in NOx emissions as a function of additized cetane and natural cetane. During this conversion, the natural cetane term drops out since natural cetane is the same for the base fuel and the additized fuel. The constant also drops out for the same reason. If the base fuel is assumed to contain no cetane improver additives, the resulting equation is:

$$\%\ \text{change in NOx} = \{\exp[- 0.015151 \times (\text{additized cetane}) + 0.000169 \times (\text{additized cetane})^2 + 0.000223 \times (\text{additized cetane}) \times (\text{natural cetane})] - 1 \} \times 100\% \quad (2)$$

The predicted NOx impacts are shown graphically in Figure IV.A-1.

Figure IV.A-1
Predicted effect of additized cetane on NOx for all heavy-duty highway engines
except 2-strokes and those equipped with EGR



The predicted NOx impact of a given increase in cetane number brought about through the use of additives diminishes as the natural cetane increases, consistent with expectations. If the average natural cetane number in a particular area happens to be close to 40, the use of cetane improver additives will have a substantially larger benefit than would be produced in areas with an average natural cetane number close to 50. Thus regional differences in base fuel properties can and should be taken into account when using equation (2). There is also a possibility that natural cetane numbers nationwide will increase with the introduction of ultra-low sulfur highway diesel fuel in 2006, since the hydrogenation typically used to remove sulfur tends also to increase natural cetane. Although we do not have the means at present to quantify this effect, early indications are that any increase in natural cetane number will be quite small.

We note that there are certain conditions under which a "turnover" appears in the predicted effects in Figure IV.A-1. For instance, when the natural cetane is 50, the slope of the additized cetane curve changes from positive to negative at a value of approximately 11.8 . We do not believe that these turnovers represent real impacts of additized cetane on NOx emissions, but rather are artifacts of the squared additized cetane term that we used to represent nonlinear

effects. We believe it would be appropriate to insert a flat-line extrapolation at the point of any turnover, so that additional increases in cetane number brought about through additives would cause no additional changes in NOx emissions. To do this, we derived a formula that identifies the location of all turnovers as a function of the natural cetane number. This formula is shown below:

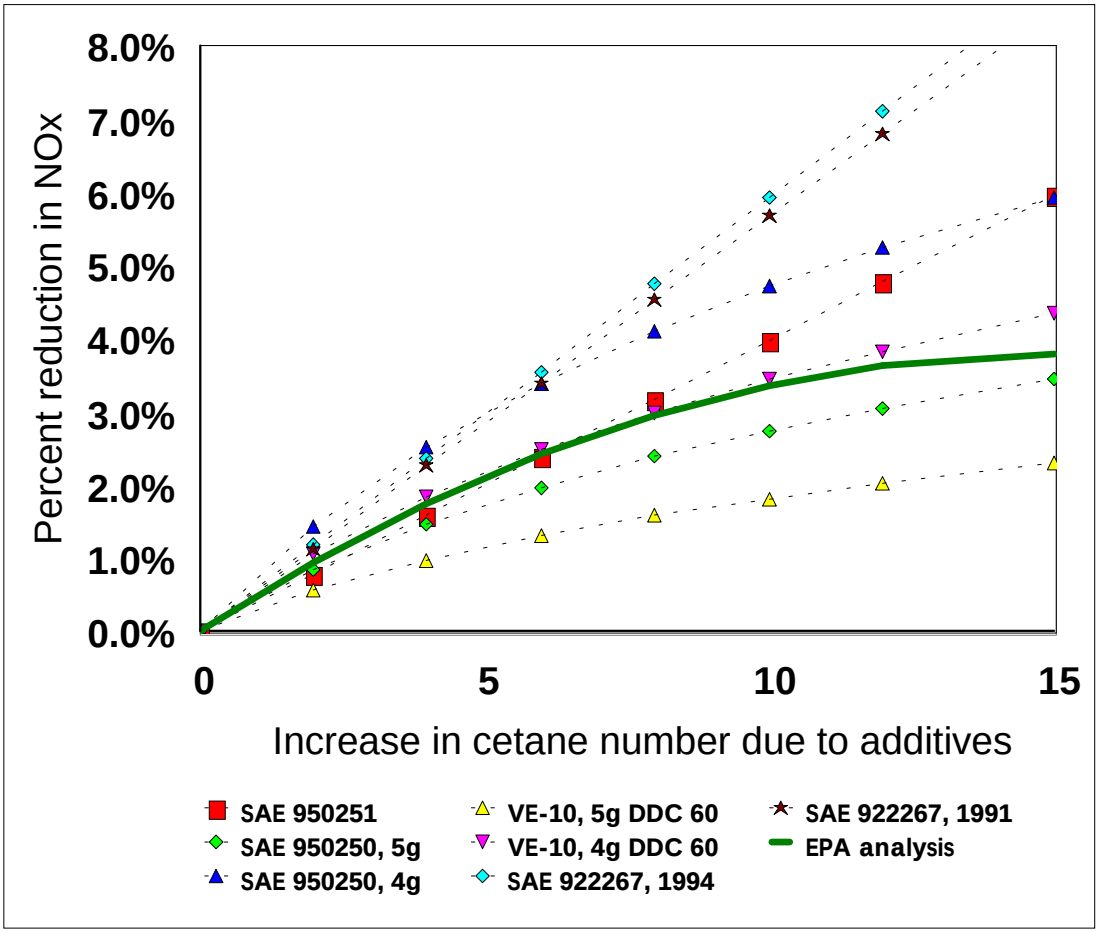
$$\text{Turnover in additized cetane} = 44.83 - 0.6598 \times (\text{natural cetane}) \qquad (3)$$

Thus for any values of the additized cetane that are larger than the value calculated from equation (3), the predicted NOx impact should be the value calculated from equation (2) using the additized cetane value calculated using equation (3). In practice, however, we do not believe that this flat-line extrapolation will be necessary. Cetane improver additives are rarely used to increase the cetane number of fuels that already have natural cetane numbers above 55, and even in these cases the additive would have to add more than 8 cetane numbers (for a total cetane number of more than 63) before the turnover would be reached and the extrapolation would be necessary. Far more common is for cetane improver additives to be added to fuels having a natural cetane number in the range of 40 - 50, and then only to raise the total cetane number 5 - 10 numbers. Within these ranges, no turnovers are encountered.

B. Confirmation of explanatory power

Although we did not have an independent set of emissions data with which to validate the model due to the fact that we used all the available data to construct the model, we were able to confirm the explanatory power of the correlations described in Section IV.A using two alternative approaches. First, we compared equation (2) with regression equations generated by other researchers. A review of the literature produced seven different regression models from four different studies, each of which included either an additized cetane term or a total cetane (natural + additized) term. For natural cetane and other fuel properties present as independent variables in some of the models, we used the nationwide average values given in Table III.D-1 of the July 2001 Staff Discussion Document. Figure IV.B-1 presents this comparison.

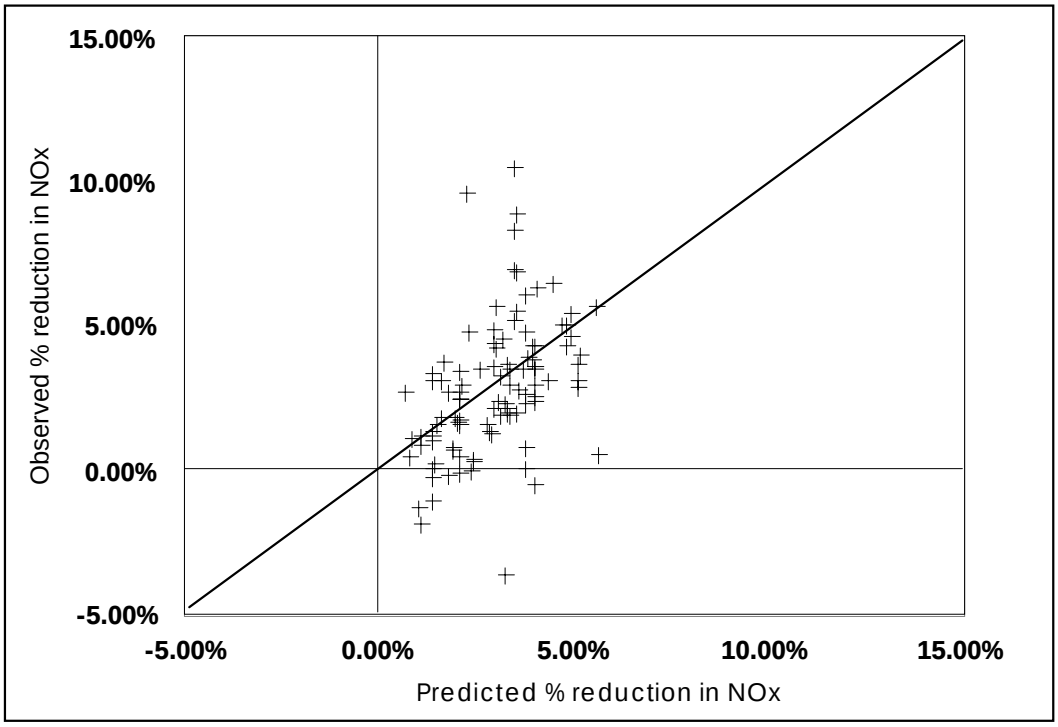
Figure IV.B-1
Comparison of EPA correlation to those from other researchers



Our correlation falls in the middle of the range of effects estimated via regression analysis from other researchers. In addition, our correlation predicts that cetane improver additives pro0duce less NOx benefit as the cetane number increases. Most other models are strictly linear, suggesting that our correlation provides a more conservative prediction at higher values of additized cetane.

We also compared predictions from our model to the individual observations in our database. To do this, we first had to convert the emission measurements in the database into % change values. Since repeat emission measurements sometimes made it difficult to match specific base fuel measurements with specific additized fuel measurements, we first averaged any repeat emission measurements of a given fuel on a given engine. We then calculated a % change in NOx value for every unique pair of base fuel and its additized counterpart. Equation (2) was then used to predict a % change value for each fuel pair. Finally, the predicted and observed values were plotted against one another. The results are shown in Figure IV.B-2.

Figure IV.B-2
Comparison of predicted and observed impacts of additized cetane

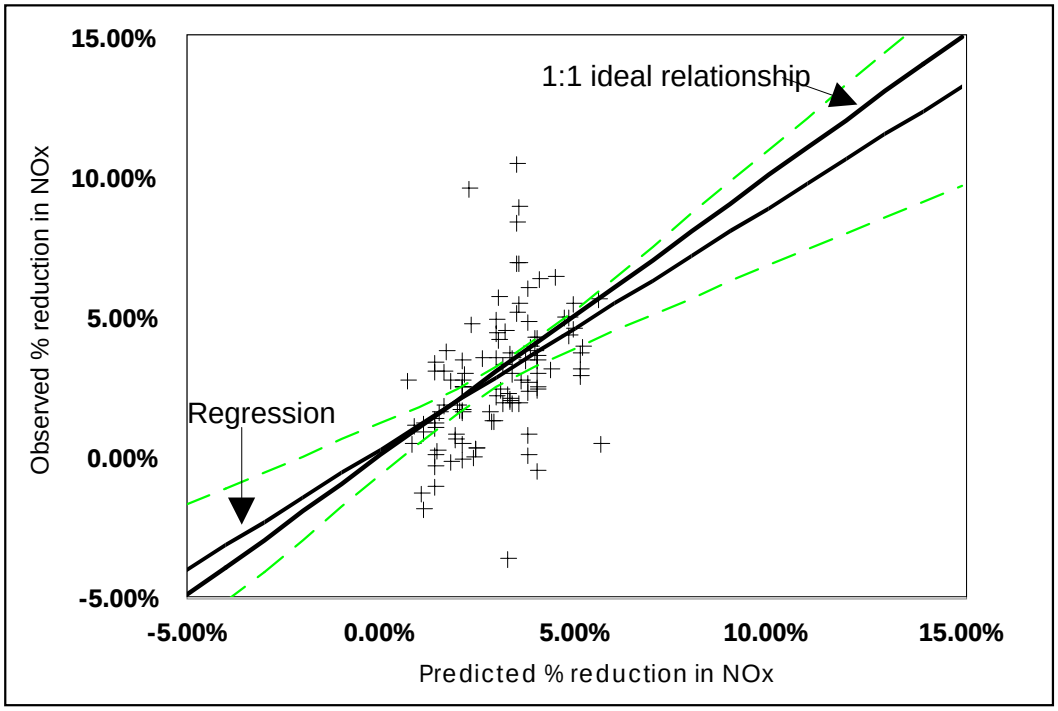


If the model perfectly predicted all the data, all the observations would fall exactly on the diagonal. The fact that the observations are distributed around the diagonal can be explained by measurement variability. For instance, 9% of the observations in the database indicated that NOx emissions actually increased when a cetane improver additive was added to a base fuel (the observations below the horizontal line in Figure IV.B-2). But this same result could be predicted from a knowledge of NOx measurement variability and an expected cetane improver NOx benefit of 2%[1]. These NOx increases do not change the fact that the fleet-wide effect of cetane improver additives is to lower NOx in a statistically significant way.

In addition, a least-squares regression on the data in Figure IV.B-2 does produce a slope that is close to 1.0 (actual value was 0.86, with an associated p-value of <0.0001). This regression line, along with the 90% confidence interval around the regression line, is shown in Figure IV.B-3. Note that the 1:1 diagonal falls entirely within the confidence interval, providing another indication that equation (2) provides a good explanation of the observed values.

[1] We assumed a NOx measurement standard deviation of 0.037 g/bhp-hr based on repeat measurements presented in the July 2001 Staff Discussion Document, and a mean NOx emission level of 3.7 g/bhp-hr, representing a 1997 engine. Under these conditions, a large sample of emission measurements on additized and unadditized fuels would result in approximately 91% of paired observations exhibiting a reduction in NOx and 9% of observations exhibiting an increase in NOx.

Figure IV.B-3
Least-squares regression of predicted versus observed impacts
of additized cetane, including 90% confidence limits



For multi-parameter regression equations of the sort generated by our maximum likelihood curve-fitting approach, there is no straightforward mechanism for combining term-specific standard error estimates into confidence limits around equation (2). The SAS procedure "proc mix" employed in our analysis does have the capability of generating confidence intervals around every observation in the database, but this falls short of confidence limits around the regression equation itself. In order to generate a quantitative measure of uncertainty for equation (2), we used the predicted and observed % reduction values to calculate the standard error associated with the residuals, where the residuals were simply the difference between predicted and observed values for every observation. These values were calculated for several different ranges of values for natural cetane and additized cetane. Although this approach provides only an estimate of uncertainty in the regression equation at several discrete points on the curve, it is useful to illustrate the potential uncertainty in the predicted effects. The results are shown in Table IV.B-1.

Table IV.B-1
Standard errors and number of observations for % change residuals

Natural cetane range		Additized cetane range		
		2.5 to 7.5	7.5 to 12.5	12.5 to 17.5
		Median = 5	Median = 10	Median = 15
37.5 to 42.5	Median = 40	0.357 (35)[α]	0.271 (43)	0.468 (14)
42.5 to 47.5	Median = 45	0.553 (21)	0.310 (72)	0.267 (24)
47.5 to 52.5	Median = 50	0.269 (44)	0.285 (54)	1.722 (2)

[α] Values in parentheses are the number of observations

The standard errors for the residuals were then converted into confidence intervals by multiplying the standard errors by the appropriate value of t (from Student's t-distribution):

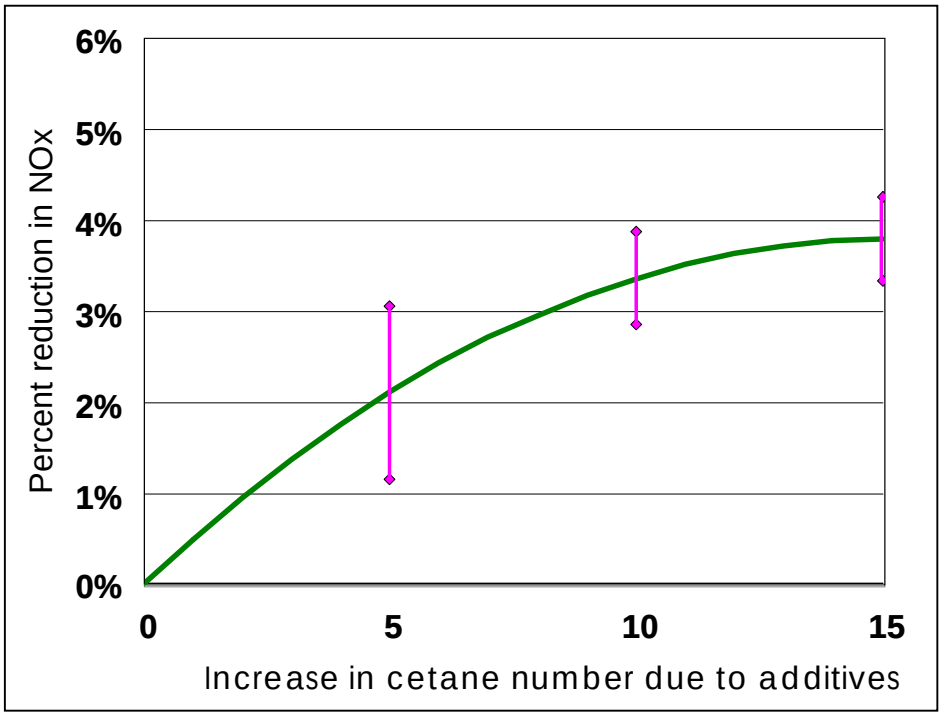
Confidence interval = mean predicted effect ± t × standard error

Table IV.B-2 presents the t × standard error values assuming a 90% confidence band, while Figure IV.B-4 shows how the confidence intervals would appear for the case of a base fuel with natural cetane of 45.

Table IV.B-2
90% t × standard error values about predicted % reduction values

Natural cetane range		Additized cetane range		
		2.5 to 7.5	7.5 to 12.5	12.5 to 17.5
		Median = 5	Median = 10	Median = 15
37.5 to 42.5	Median = 40	0.60	0.46	0.83
42.5 to 47.5	Median = 45	0.95	0.52	0.46
47.5 to 52.5	Median = 50	0.45	0.48	10.87

Figure IV.B-4
Predicted effect of additized cetane on NOx with 90% confidence intervals
for base fuel with natural cetane of 45



C. Application to the in-use fleet

As described in Section III.B, we excluded 2-stroke and EGR-equipped engines from our analysis. As a result, equation (2) does not predict NOx effects for these types of engines. For 2-stroke engines we do not believe that this result presents a hindrance to the application of equation (2) to the in-use fleet. There were no heavy-duty 2-stroke diesel engines certified for highway use for model years 1998 and 1999, and we expect that this trend will continue in the future. As described in Section III.B, 2-stroke diesel engines currently account for approximately 1% of the heavy-duty highway fleet, so the application of equation (2) to the entire (non-EGR) highway fleet for future years should introduce only negligible error.

Engines equipped with EGR, however, are expected to become an increasingly important part of the highway fleet beginning this year. EGR-equipped engines are expected to exhibit no discernable NOx response to cetane, based on testing done by the Heavy-Duty Engines Workgroup under the auspices of the Mobile Source Technical Review Subcommittee. This test program did not include an evaluation of the impacts of injection rate-shaping or other combustion management techniques that some contend are the primary, or possibly additional, reasons for the cetane-insensitivity of future engines. However, for our purposes it is not necessary to identify the specific reasons for cetane-insensitivity of future engines if we make the simplifying assumption that all future engines will employ cetane-insensitive technologies.

Thus our approach to estimating fleet-wide NOx effects of cetane improver additives was to use a weighted combination of equation (2), representing engines without cetane insensitive technologies, and the zero effect attributable to cetane-insensitive engines. Because the relative NOx inventories between these two categories of engines change over time, these weighting factors would be dependent on calendar year.

To estimate these weighting factors, one might use NOx inventories that represent the specific areas where the cetane improver additives are intended to be used. For the purposes of generating example weighting factors, we used the nationwide inventory modeling done in the context of our rulemaking setting new standards for heavy-duty engines beginning in 2007 [66 FR 5002]. Using this modeling, we determined how the NOx inventory will be distributed among the various model years in the nationwide fleet[10]. We assumed that all 2003 and later heavy-duty diesel engines will employ EGR or some other cetane-insensitive technology despite the fact that this may be not true for all manufacturers. Lacking a robust means for estimating the fraction of new engine sales that will employ cetane-insensitive technologies in the future, this assumption assures that we are not overestimating NOx benefits of cetane control via additives for future years. From this information we were able to estimate the fraction of the NOx inventory that derived from cetane-sensitive engines for any calendar year. These fractions are given in Table IV.C-1.

Table IV.C-1
Potential yearly weighting factors 'k' for additized cetane model

	Fraction of diesel highway NOx inventory which comes from cetane-sensitive engines
2003	0.93
2004	0.84
2005	0.77
2006	0.70
2007	0.65
2008	0.61
2009	0.57
2010	0.55
2011	0.54
2012	0.53
2013	0.51
2014	0.50
2015	0.48
2016	0.46
2017	0.44
2018	0.41
2019	0.39
2020	0.36

Using the values in Table IV.C-1, equation (2) could be modified to represent the entire in-use fleet of heavy-duty diesel highway engines. The result is shown below:

$$\%\ \text{change in NOx} = k \times 100\% \times \{\exp[\ -0.015151 \times (\text{additized cetane}) + 0.000169 \times (\text{additized cetane})^2 + 0.000223 \times (\text{additized cetane}) \times (\text{natural cetane})\ ] - 1\ \} \quad (4)$$

There were no nonroad engines in the database we used to evaluate the effects of additized cetane on NOx emissions. However, most nonroad engines (excluding locomotive engines) use technologies similar to those found in highway engines, although in a given year the highway vehicle technology is generally more advanced. Since our previous modeling showed few technology-specific effects of cetane on NOx, and many of those distinctions have been accounted for in our current analysis by excluding technology groups B and L, any differences between highway and nonroad technology may not be important for additized cetane effects on NOx. As a result, it might be appropriate to apply equation (2) to heavy-duty nonroad engines, excluding locomotives. This approach is consistent with the conclusion drawn by the American Petroleum Institute in a letter to the Ozone Transport Commission[11], in which API concluded that nonroad engines would exhibit NOx responses to cetane that were "similar" to highway engine

effects. However, we caution that there exists no robust set of data to validate the use of equation (2) for nonroad, and the concerns we raised in Section VII.B.6 of our Staff Discussion Document regarding this type of extrapolation have not yet been fully addressed. Thus the decision to apply equation (2) to nonroad in any particular context may be dependent on the availability of supporting data or other relevant factors.

Finally, we discussed in Section II.B how natural and additized cetane are related, and the fact that additized cetane is more easily analyzed since it can be disassociated from changes in other fuel properties. Based on our current understanding of diesel ignition properties, natural and additized cetane likely represent overlapping effects on combustion and thus on NOx. Although we do not at this time have sufficient information to quantify the differences in NOx effects between natural and additized cetane, preliminary analyses suggest that changes in natural cetane, if accompanied by the collinear changes in aromatics and specific gravity shown in Figure II.B-1, would produce larger NOx benefits than equivalent changes in additized cetane. If so, then equation (4) would provide environmentally conservative predictions of changes in NOx due to changes in natural cetane. Equation (4) can be modified for application to changes in natural cetane to produce the following:

$$\%\ \text{change in NOx} = k \times 100\% \times \{\exp[\ -0.015151 \times (NATCET_f - NATCET_i) + 0.000169 \times (NATCET_f - NATCET_i)^2 + 0.000223 \times (NATCET_f - NATCET_i) \times (NATCET_i)\ ] - 1\ \} \quad (5)$$

where

k = Factor from Table IV.C-1 representing engines without EGR
$NATCET_i$ = Initial value of natural cetane number
$NATCET_f$ = Final value of natural cetane number

Equation (5) would be relevant for changes in natural cetane brought about through conventional means, namely lowering aromatics content or other refinery-based changes to the composition of the fuel. It would not be appropriate to use equation (5) to represent changes in natural cetane brought about through the additional of high cetane bulk blending components, such as biodiesel or Fischer-Tropsch fuels, to conventional diesel fuel.

The only alternatives to equation (5) that we considered for correlating natural cetane with NOx emissions were those in the Staff Discussion Document. Since that analysis showed that the effects of natural cetane on NOx could actually be better represented by aromatics and density alone, equation (5) permits one to directly predict the NOx impact of changes in natural cetane instead of inferring the impacts through changes in aromatics and density.

D. Some predicted NOx impacts of additized cetane

The predicted NOx impact of a given change in cetane number is a function of both the calendar year (Table IV.C-1) and the natural (or initial) cetane number of the base fuel. We can choose some representative years and base fuel cetane values to predict specific NOx impacts using equations (2) and (4). For instance, one of the primary years in which many current non-attainment areas must show attainment with the ozone standard is 2007. Thus we have made NOx predictions both for the next full calendar year 2003 and for 2007. In this example we also used the current national average cetane number to represent the base fuel for areas that have not implemented a clean diesel fuel program. According to survey data collected by the Alliance of Automobile Manufacturers, the current average cetane number is approximately 45. If we wanted to raise the cetane number of such base fuels to 50, equations (2) and (4) would predict the NOx impacts shown in Table IV.D-1.

Table IV.D-1
Examples of predicted NOx effects (% reduction in NOx)
Cetane number increased 5 numbers to 50
National average base fuel assumed

	2003	2007
Highway engines	2.0	1.4
Nonroad engines	2.1	2.1

The modest NOx reductions predicted by equation (4) suggest that cetane improver additives are, by themselves, an unlikely candidate for producing NOx emission reductions that are equivalent to those produced for clean diesel fuel in California or other areas with California-like fuel. For instance, the July 2001 Staff Discussion Document concluded that California diesel fuel produces NOx reductions of approximately 6.2 percent (see Table III.F-2 in the Staff Discussion Document). Assuming a natural cetane number of 45 as the base, Figure IV.A-1 shows that the NOx benefits of cetane improver additives could not exceed 4 percent even for large concentrations of additive. In fact, cetane improver additives are already used in California by many refiners under the equivalent formulation provision of that state's clean fuel regulations. On average, cetane improver additives are responsible for approximately one-third of the NOx reductions generated by California diesel fuel, with the remaining NOx reductions being generated by higher natural cetane, lower aromatics, and lower density.

Appendix
Database used in additized cetane analysis

All studies are listed by their database STUDY_ID label. See Appendix A of Staff Discussion Document for full citations for studies that comprise the full database.

Studies that contained no additized fuels are were therefore eliminated from the additized cetane analysis

ACEA	SAE 852078	SAE 942053
CARB-LOCO	SAE 881173	SAE 961973
CARB-TOXIC	SAE 922214	SAE 961974
SAE 1999-01-1117	SAE 932685	SAE 971635
SAE 1999-01-3606	SAE 932731	SAE 972898
SAE 2000-01-2890	SAE 932734	VE-1_PHASE I
SAE 790490	SAE 932800	

Studies/fuels included in the additized cetane analysis

FBATCH_ID	STUDY_ID	CETANE_NUM	CETANE_DIF	BASE FUEL
EPD1	EPEFE	51		
EPD10	EPEFE	58		
EPD11	EPEFE	57.1	7.6	EPD7
EPD2	EPEFE	50.2		
EPD3	EPEFE	50		
EPD4	EPEFE	50.3	0	BASE
EPD5	EPEFE	50.6		
EPD6	EPEFE	50.2		
EPD7	EPEFE	49.5	0	BASE
EPD8	EPEFE	54.8	4.5	EPD4
EPD9	EPEFE	59.1	8.8	EPD4
HDE-10N	HDEWG II	42.3	0	BASE
HDE-11	HDEWG II	48.1	5.8	HDE-10N
HDE-12	HDEWG II	52.7	10.4	HDE-10N
HDE-14N	HDEWG II	42.1	0	BASE
HDE-15	HDEWG II	47.9	5.8	HDE-14N
HDE-16	HDEWG II	52.2	10.1	HDE-14N
HDE-16N	HDEWG II	53.4		
HDE-18	HDEWG II	47.9		
HDE-1N	HDEWG II	42.8	0	BASE
HDE-2	HDEWG II	48	5.2	HDE-1N
HDE-3	HDEWG II	53.2	10.4	HDE-1N
HDE-4N	HDEWG II	42.2	0	BASE
HDE-5	HDEWG II	47.7	5.3	HDE-4N
HDE-6	HDEWG II	53	10.6	HDE-4N
HDE-7N	HDEWG II	42.8	0	BASE

HDE-8	HDEWG II	48.1	5.3	HDE-7N
HDE-8N	HDEWG II	48		
HDE-9	HDEWG II	52.6	9.8	HDE-7N
HDE-R	HDEWG II	46.9		
FUEL1	SAE1999-01-1478	39.7	0	BASE
FUEL1A	SAE1999-01-1478	42.1	2.4	FUEL1
FUEL1B	SAE1999-01-1478	43.2	3.5	FUEL1
FUEL1C	SAE1999-01-1478	45.8	6.1	FUEL1
FUEL1D	SAE1999-01-1478	47.9	8.2	FUEL1
FUEL1E	SAE1999-01-1478	51.1	11.4	FUEL1
FUEL1F	SAE1999-01-1478	41.6	1.9	FUEL1
FUEL1G	SAE1999-01-1478	42.5	2.8	FUEL1
FUEL1H	SAE1999-01-1478	45.7	6	FUEL1
FUEL1I	SAE1999-01-1478	47.9	8.2	FUEL1
FUEL1J	SAE1999-01-1478	51.1	11.4	FUEL1
FUEL2	SAE1999-01-1478	46.3	0	BASE
FUEL2A	SAE1999-01-1478	48.9	2.6	FUEL2
FUEL2B	SAE1999-01-1478	51.6	5.3	FUEL2
FUEL2C	SAE1999-01-1478	54.6	8.3	FUEL2
FUEL2D	SAE1999-01-1478	59.1	12.8	FUEL2
FUEL2E	SAE1999-01-1478	60.5	14.2	FUEL2
FUEL2F	SAE1999-01-1478	48.3	2	FUEL2
FUEL2G	SAE1999-01-1478	51.1	4.8	FUEL2
FUEL2H	SAE1999-01-1478	54.9	8.6	FUEL2
FUEL2I	SAE1999-01-1478	58.4	12.1	FUEL2
FUEL2J	SAE1999-01-1478	61.2	14.9	FUEL2
0	SAE902172	42.5		
1	SAE902172	39.9		
2	SAE902172	39.6	0	BASE
2A	SAE902172	47.1	7.5	2
2B	SAE902172	55.5	15.9	2
2S	SAE902172	39.6		
4	SAE902172	46.4	0	BASE
4B	SAE902172	61.9	15.5	4
5	SAE902172	48.6	0	BASE
5B	SAE902172	67	18.4	5
6	SAE902172	51.8		
A1	SAE902173	45.3	0	BASE
A2	SAE902173	49.8	4.5	A1
A3	SAE902173	51	5.7	A1
A4	SAE902173	55.9	10.6	A1
B1	SAE902173	39.6	0	BASE
B2	SAE902173	46	6.4	B1
B3	SAE902173	48	8.4	B1
B4	SAE902173	48.2	8.6	B1
B5	SAE902173	50.3	10.7	B1
B6	SAE902173	56.7	17.1	B1

C1	SAE902173	47.7	0	BASE
C2	SAE902173	50.5	2.8	C1
C3	SAE902173	55.1	7.4	C1
C4	SAE902173	55.4	7.7	C1
D1	SAE902173	49.8	0	BASE
D2	SAE902173	55.1	5.3	D1
D3	SAE902173	55.3	5.5	D1
D4	SAE902173	59.7	9.9	D1
C1	SAE910735	42		
C2	SAE910735	44.8	0	BASE
C2I	SAE910735	52.6	7.8	C2
C2S	SAE910735	43.8		
CR	SAE910735	50.8		
DD10	SAE912425	62.7		
DD11	SAE912425	53.1		
DD12	SAE912425	47		
DD4	SAE912425	50.7	0	BASE
DD5	SAE912425	60.7	10	DD4
DD8	SAE912425	50.2		
DD9	SAE912425	50.7		
A	SAE922267	51.6	0	BASE
B	SAE922267	55.1	3.5	A
C	SAE922267	54.6		
D	SAE922267	42.3	0	BASE
E	SAE922267	47.9	5.6	D
F	SAE922267	49	6.7	D
G	SAE922267	38.4	0	BASE
H	SAE922267	47.6	9.2	G
I	SAE922267	47.3		
J	SAE922267	52		
K	SAE922267	39.6		
L	SAE922267	50.4		
LS	SAE932767	43	0	BASE
LS-N	SAE932767	52	9	LS
LS-P	SAE932767	53	10	LS
A	SAE942019	46	0	BASE
A-DTBP	SAE942019	57	11	A
A-EHN	SAE942019	56	10	A
B	SAE942019	41	0	BASE
B-DTBP	SAE942019	58	17	B
B-EHN	SAE942019	57	16	B
C	SAE942019	38	0	BASE
C-DTBP	SAE942019	49	11	C
C-EHN	SAE942019	49	11	C
D	SAE942019	43	0	BASE
D-EHN	SAE942019	53	10	D
D-EHN/DTBP	SAE942019	53	10	D

A-1	SAE970758	56		
A-10	SAE970758	53	10	A-9
A-2	SAE970758	65		
A-3	SAE970758	43		
A-4	SAE970758	60		
A-5	SAE970758	58		
A-6	SAE970758	56		
A-7	SAE970758	51	0	BASE
A-8	SAE970758	58	7	A-7
A-9	SAE970758	43	0	BASE
MAN18	SAE972894	58.7		
MAN2	SAE972894	50.9	0	BASE
MAN2*	SAE972894	56	5.1	MAN2
MAN7	SAE972894	56.5	0	BASE
MAN7*	SAE972894	60.9	4.4	MAN7
A	SAE972904	44.8	0	BASE
B	SAE972904	50.5	0	BASE
C	SAE972904	54.7		
D	SAE972904	55.4	10.6	A
E	SAE972904	55.6	10.8	A
F	SAE972904	55.1	4.6	B
VE 10 A	VE 10	44.3	0	BASE
VE 10 AA	VE 10	41.1	0	BASE
VE 10 B	VE 10	52	7.7	VE 10 A
VE 10 BB	VE 10	47	5.9	VE 10 AA
VE 10 C	VE 10	58.8	14.5	VE 10 A
VE 10 CC	VE 10	50.5	9.4	VE 10 AA
VE 10 D	VE 10	50.8		
VE 10 DD	VE 10	51.9	10.8	VE 10 AA
VE 10 E	VE 10	51.5		
VE 10 EE	VE 10	55.2	14.1	VE 10 AA
VE 10 F	VE 10	51.4		
VE 10 FF	VE 10	44.7	0	BASE
VE 10 G	VE 10	50.5		
VE 10 GG	VE 10	52.7	8	VE 10 FF
VE 10 H	VE 10	54.2		
VE 10 HH	VE 10	53.6	8.9	VE 10 FF
VE 10 I	VE 10	59.4		
VE 10 II	VE 10	57.5	12.8	VE 10 FF
VE 10 J	VE 10	46.3		
VE 10 JJ	VE 10	58.9	14.2	VE 10 FF
VE 10 K	VE 10	54.3		
VE 10 KK	VE 10	51.7		
VE 10 L	VE 10	54.3		
VE-1A	VE-1_PHASE II	42.6	0	BASE
VE-1B	VE-1_PHASE II	51.4	8.8	VE-1A
VE-1C	VE-1_PHASE II	55.1		

VE-1D	VE-1_PHASE II	39.3	0	BASE
VE-1E	VE-1_PHASE II	40.4	1.1	VE-1D
VE-1F	VE-1_PHASE II	50.7	11.4	VE-1D
VE-1G	VE-1_PHASE II	49	0	BASE
VE-1H	VE-1_PHASE II	53.4	4.4	VE-1G
VE-1K	VE-1_PHASE II	44.1	0	BASE
VE-1L	VE-1_PHASE II	53.9	9.8	VE-1K
VE-1M	VE-1_PHASE II	48.6		
VE-1N	VE-1_PHASE II	38.5		
VE-1O	VE-1_PHASE II	49.2		

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