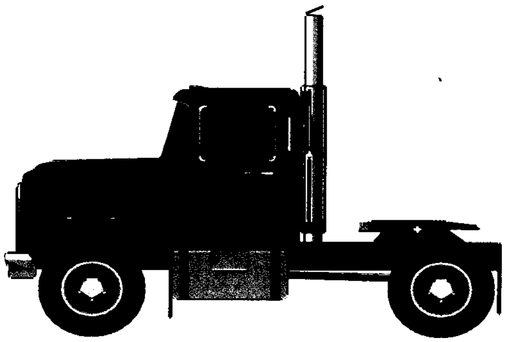
California Environmental Protection Agency

Air Resources Board

Staff Review of the Emission Benefits of California's Diesel Fuel Program



March 2003

Fuels Section
Criteria Pollutants Branch
Stationary Source Division
California Air Resources Board
1001 I Street, Sacramento, California

DRAFT

Staff Review of the Emission Benefits of California's Diesel Fuel Program

March 2003

Fuels Section
Criteria Pollutants Branch
Stationary Source Division
California Air Resources Board
1001 I Street, Sacramento, California

Table of Contents

I. Summary

In 1988, the Air Resources Board (ARB) staff estimated the benefits of the then-proposed regulations on the sulfur and aromatic hydrocarbon contents of motor-vehicle diesel fuel. The estimates, based on transient-cycle emission testing of only two engines, were 25-percent reduction in particulate matter (PM) emissions and seven-percent reduction in oxides of nitrogen (NOx) emissions. Also, sulfur-compound emissions would be reduced by the same percentage as the fuel sulfur reduction, assumed to be at least 80 percent.

The ARB staff has reviewed and analyzed the results of 35 different emission studies, involving 300 fuels and 73 engines, that have been conducted since the original estimates of the emission benefits were made. We find the original estimates continue to be valid, and are in close agreement with the estimates based on results of currently available emission studies. Our review determined that 31 studies were complete enough to be analyzed for PM and NOx reduction. Based on these studies the predicted emission reductions associated with California diesel fuel averaged about 26 percent and six percent, respectively for PM and NOx. Sulfur-compound emission reductions are now estimated to be at least 95 percent.

The results of these studies are quite consistent. In each study and for every engine configuration analyzed, emissions were predicted to decrease when fuel complying with the California diesel fuel regulations was used instead of conventional diesel fuel. These studies indicate that reducing sulfur content, aromatic hydrocarbon content, and specific gravity and increasing cetane number reduces PM emissions. They also show that reducing aromatic hydrocarbon content and specific gravity and increasing cetane number reduces NOx emissions from diesel engines.

The California diesel fuel regulations reduce emissions of PM and NOx because they limit the sulfur and aromatic hydrocarbons content of diesel or require changes to other properties that produce equivalent emission benefits. The studies reviewed confirm that this flexibility is possible because emission benefits accrue not only from the reduction in the content of sulfur and aromatic hydrocarbons in diesel fuel, but also from lower specific gravity and higher cetane number of complying diesel fuel. This interrelationship of multiple diesel fuel properties that affect emissions enables fuel producers to employ considerable flexibility in formulating California diesel fuel, so long as their alternative formulations provide the same environmental benefits.

II. Introduction

A. CALIFORNIA REGULATIONS

Motor vehicle diesel fuel sold in California must meet pollution-cutting specifications established by the Air Resources Board (ARB/Board). These specifications have resulted in California diesel fuel being the cleanest burning diesel in the United States. The ARB's diesel fuel regulations were adopted in 1988 and took effect in 1993. California diesel fuel results in significantly lower emissions than conventional diesel from diesel-powered vehicles and equipment: greater than 80 percent reduction in sulfur dioxide (SO_2), a 25 percent reduction in diesel PM, and a seven percent reduction in NO_x. California diesel fuel also reduces emissions of several toxic substances other than diesel particulate matter, including benzene and poly-nuclear aromatic hydrocarbons.

California's diesel fuel regulations contain two general provisions:

- A sulfur limit of 500 ppmw. This reduces emissions of both SO_2 and directly emitted particulate matter.
- An aromatic hydrocarbon content of ten percent for large refiners and 20 percent for small refiners. The lower level of aromatics results in reductions in emissions of both PM and NO_x.

As part of the 1988 diesel fuel rulemaking, the ARB adopted provisions that allow alternatives to the aromatic content if refiners can demonstrate through independent testing that an alternative diesel formulation provides comparable emission benefits. Most refiners have taken advantage of the flexibility provided by the alternative formulation procedure to produce diesel formulations that provide the same air quality benefits at a lower production cost and which enable greater production volumes. In 1990, the certification procedure for alternative formulations of diesel was modified to provide safeguards against certification of an alternative fuel that is inferior to the ten or 20 percent aromatic diesel fuel.

The use of California diesel fuel has significantly reduced pollution from diesel engines in California. California diesel is part of the state's core strategy of reducing air pollution through the use of clean fuels, and lower-emitting motor vehicles and off-road equipment.

B. DIESEL FUEL QUALITY, ENGINE TECHNOLOGY, AND EMISSIONS

Diesel fuel quality is a qualitative term used to describe the combustion and emission performance of diesel fuel in a diesel engine. It is primarily a function of the fuel's sulfur content, aromatic hydrocarbon content, density (or specific gravity), and cetane number. Nitrogen content, poly-cyclic aromatic content, and distillation temperatures are additional diesel fuel quality characteristics. Generally, a fuel of superior fuel quality will be low in all of fuel quality properties except cetane number, which will be high. Cetane number indicates the readiness of a diesel fuel to ignite spontaneously. The higher the cetane number, the shorter the delay is between injection and ignition, and the lower the rate of pressure rise. Cetane number too low can result in poor combustion and high emissions under transient cycle engine operation. Any engine burning a fuel of superior quality will have lower emissions of NOx and PM relative to fuels of lesser quality burned in the same engine. Usually it is not too difficult to predict the relative NOx and PM emission behaviors of different diesel fuels, because the lower sulfur, lower aromatic hydrocarbon fuels, normally, have lower densities and higher cetane numbers.

Gaseous SO_2 and particulate sulfate emissions from diesel engines are directly proportional to the sulfur content of the fuel and the specific fuel consumption of the engine. An estimated 98 percent of the sulfur in diesel fuel is emitted from diesel engines as SO_2 and the remaining two percent is emitted as sulfate. Altogether, about 2.1 pounds of sulfur-containing compounds are emitted for every pound of sulfur in diesel fuel.[1] Sulfate emissions from diesel engines also contribute to the total PM emissions from diesel engines. The major portion of diesel PM emissions is comprised of carbonaceous material (soot) with the remainder comprised of condensed organic compounds, and sulfates, nitrates, and other condensed inorganic compounds. The sulfur content of diesel fuel has no direct impact on emissions other than sulfur-containing compounds from diesel engines. However, the refining processes of producing diesel fuel with lower sulfur content may result in other fuel composition and property changes, and the changes in these properties may cause the reduction of non-sulfur-containing emissions.

By design, an engine equipped with exhaust gas re-circulation (EGR) has lower NOx emissions than the same engine without EGR. This is true, regardless of the fuel burned. An undesirable effect of EGR is an increase in PM emissions, especially in high-load engine operation. For engines with EGR, our analysis of test data indicates that both NOx and PM are as sensitive to overall diesel fuel quality as for engines without EGR. As with PM emissions, gaseous hydrocarbon (HC) and carbon monoxide (CO) emissions also tend to decrease as the cetane number increases. For these reasons, the regulation of fuel quality will continue to be important in controlling emissions from advanced diesel engines of the future as well as being needed to maintain lower emissions from California's current motor-vehicle, stationary, marine, and other diesel engines.

C. WORLD-WIDE FUEL CHARTER

The automobile and engine manufacturers have an interest in promoting improved fuel qualities for gasoline and diesel fuels. Without appropriate enabling fuel-quality properties, manufacturers state that they will not be able to meet future vehicle and engine emission standards. The automobile and engine manufacturers' World-Wide Fuel Charter (December 2002) calls for diesel fuel with a very low sulfur content, an aromatic hydrocarbon content of no greater than 15 percent by weight, and a density of

---

[1] The sulfur dioxide molecule weighs about 2 times as much as the sulfur atom, and the sulfate complex, assumed to be H_2SO_4:$7H_2O$, weighs about 7 times as much as the sulfur atom.

no greater than 840 kg/m^3. It also calls for a cetane number of no less than 55, and a cetane index of no less than 52. Cetane index is an indicator of natural cetane number. The manufacturers are advocating the production of high natural cetane-number fuel, where the cetane number has been only moderately increased by the use of cetane improvement additives.

The certification of emission-equivalent formulations under the California diesel fuel regulations supports the concept that high natural cetane number with only moderate use of additives defines a good quality fuel. This will be especially true for the next generation of advanced emission control technologies.

The Texas Commission on Environmental Quality has adopted a requirement for the use of California diesel fuel in 110 counties in Texas. The requirement becomes effective in 2005. Outside of California and Texas (in the future) the cleanest burning diesel fuel may be found in Europe, as shown in Table 1. The Swedish urban diesel fuel specifications are not required standards. Instead the fuels are sold with a tax reduction to offset the increased cost of production. The European Union (EU) diesel fuel specifications are directed standards. It appears that the cetane-number specifications for Swedish urban diesel fuel are superseded by the EU cetane-number requirement of 51 for on-road use. Also, sulfur-content specifications for Swedish urban diesel will be superseded by the future EU sulfur maximum of 10 ppmw for on-road use. With their applicability to all motor vehicle diesel fuel sold in California, the California fuel standards represent the cleanest burning diesel fuel in the world, required statewide for on- and off-road use.[2]

Table 1. European Clean Diesel Fuel Specifications

Country or Countries	Sweden	Sweden	European Union
Applicability	Urban Class 1	Urban Class 2	On-road
Implementation Date	1991	1991	2000
Cetane Number	≥ 50	≥ 47	≥ 51
Dens. (g/mL) or Sp. Grav.	0.800 to 0.820	0.800 to 0.820	≤ 0.845
Aromatic Content (vol.%)	≤ 5	≤ 20	(poly-) ≤ 11 (wt.%)
Sulfur Content (ppmw)	≤ 10	≤ 50	≤ 10*

*Sulfur content maximum is 350 ppmw until 2005. Zero-sulfur (maximum 10-ppmw) requirement is phased-in beginning in 2005 with full market penetration by 2011.

---

[2] The Texas regulations will also require California diesel fuel for on- and off-road use.

III. Diesel Fuel Programs

A. CALIFORNIA DIESEL FUEL CERTIFIED FORMULATIONS

California's basic requirements for motor vehicle diesel fuel are 500 parts-per-million-by-weight (ppmw) maximum sulfur content and ten percent-by-volume maximum aromatic hydrocarbon content. However, 13 CCR 2282(g), "Certified Diesel Fuel Formulations Resulting in Equivalent Emissions Reductions," allows for higher maximum aromatic hydrocarbon contents for fuels that have been shown to be emission-equivalent to a specified 10-percent-aromatic reference fuel[3], as determined through prescribed laboratory engine testing and statistical comparison. The engine emission tests are typically performed on a Detroit Diesel Corporation Series-60 engine over a transient operation cycle.

Almost all motor-vehicle diesel fuel sold in California today uses the emission-equivalent alternative formulation provision to comply with the aromatic hydrocarbon regulation. Most of this fuel contains 2-ethyl-hexyl nitrate or similar cetane-number improver. Each certification includes a minimum of five fuel-quality property specifications: (1) the maximum sulfur content (not to exceed 500 ppmw); (2) the maximum total aromatic hydrocarbon content; (3) the maximum poly-cyclic aromatic hydrocarbon content; (4) the maximum nitrogen content; and (5) the minimum cetane number.

Table 2. Typical Characteristics of California Certified Diesel Fuel Formulations

Characteristic	Reference Fuel	Average of Specifications for Certified Formulations
Sulfur Content (ppmw)	≤ 500	250
Aromatic Content (vol. %)	≤ 10	22
PAH Content (wt. %)	≤ 1.4	4
Cetane Number	(natural) ≥ 48	54

Based on the certification data for the alternative formulations, California diesel fuel has an ethyl-hexyl nitrate treatment ratio of about 0.10 percent-by-weight. This means that the additized (treated) cetane number of the certified California diesel is about five higher than its natural (untreated) cetane number. As discussed later, this amount of additive is less than the lowest level added to the Heavy-Duty Engine Working Group (HDEWG) test program fuels. It also means that the nitrogen added to the fuel with the EHN treatment is about 75 ppmw on average. This amount of added nitrogen should not be significantly detrimental to achieving future NOx emission standards, such as the 0.20-g/hp-hr standard for heavy-duty diesel engines (HDEs). Overall, the cetane improvement, along with reduced aromatic hydrocarbon content and specific gravity,

---

[3] Small refiners are allowed a 20 percent-by-volume maximum aromatic hydrocarbon content or emission-equivalent formulation to a specified 20-percent-aromatic reference fuel.

should make the future PM emission standards, such as the 0.01-g/hp-hr standard for HDEs, easier to meet. Additional sulfur reduction, combined with catalytic after-treatment, will likely be the means of achieving future PM standards. The lower engine-out emissions of both NOx and PM due to the use of California diesel fuel should provide an additional compliance margins; which, in turn, should provide flexibility to engine and emission-control equipment designers to meet the NOx standards more easily.

B. CALIFORNIA DIESEL FUEL PROPERTIES

Estimated average diesel fuel properties, for both California and National (non-California, non-Alaska) on-road fuel were used in the work described in the next section to predict the emission benefits of the California diesel fuel regulations. The fuel properties, as presented in Table 3, are generally the same as those used by the United States Environmental Protection Agency (U.S. EPA) as California and on-highway non-California (non-Alaska) diesel fuel properties[4]. The additional properties of mono- and poly-cyclic aromatic contents were also estimated for these fuels. Overall, the estimated average fuel properties are similar to average fuel properties before and after implementation of the California diesel fuel regulations, determined from the Alliance of Automobile Manufacturer's (AAM)[5] fuel survey data for Los Angeles, as summarized in Table 4. The average properties of pre-1993 California diesel fuel are also shown in Table 3. A sulfur content of 2800 ppmw was used for pre-1993 California fuel. For comparison, Table 5 lists the fuel property values used in 1988 for predicting the future emission benefits of the California diesel fuel regulations.

C. FEDERAL PROGRAM

The U.S. EPA regulation (40 CFR 80.29) prohibits the sale or supply of diesel fuel for use in on-road motor vehicles, unless the diesel fuel has a sulfur content, by weight, no greater than 500 parts per million (ppmw). Beginning June 1, 2006 the sulfur limit is 15 ppmw. The lowering of the sulfur limit is intended to enable the use of catalytic exhaust after-treatment devices for controlling PM and NOx emissions. In addition, the regulation requires on-road motor vehicle diesel fuel to have a cetane index of at least 40 or have an aromatic hydrocarbon content of no greater than 35 percent by volume (vol. %). All on-road motor-vehicle diesel fuel sold or supplied in the United States, except in Alaska, must comply with these requirements. As previously stated, the average diesel fuel properties for national on-road diesel fuel sold outside of California and Alaska is shown in Table 3.

---

[4] Averages of Alliance of Automobile Manufacturers (AAM) annual-average fuel property data across years 1995 through 2000. California data actually represents Los Angeles only.

[5] Formerly known as the American Automobile Manufacturers' Association (AAMA).

Table 3. Average California and National Diesel Fuel Properties

Property	California Average		National Average w/o CA and AK
	Pre-1993	1995-2000	1995-2000
Sulfur, ppmw	2800*	130	330
Cetane No.	45	52	45
Mono Aromatics, Wt.%	**	17	26
Poly Aromatics, Wt.%	**	6	10
Total Aromatics, Vol.%	36	22	34
Specific Gravity	0.856	0.837	0.850

* 500 ppmw or less in the South Coast Air Basin and Ventura County, effective January 1, 1985

** Not available

Table 4. AAM National Diesel Fuel Survey Data for Los Angeles

Before Implementation				After Implementation			
Period	Cet. No.[1]	Aromatic	Sp. Grav[2]	Period	Cet. No.[1]	Aromatic	Sp. Grav[2]
Win. '87	44.0	26.7	0.8545	Win. '94	51.5	23.5	0.8422
Sum. '87	47.0	37.2	0.8549	Sum. '94	52.4	24.2	0.8430
Win. '89	46.6	29.1	0.8559	Win. '95	53.2	23.7	0.8392
Sum. '89	45.9	30.0	0.8572	Sum. '95	53.6	23.4	0.8409
Win. '91	44.0	43.0	0.8587	Win. '97	50.8	20.1	0.8384
Sum. '91	46.1	41.2	0.8582	Sum. '97	53.8	20.4	0.8309
Win. '93	44.6	40.6	0.8590	Sum. '98	51.9	20.7	0.8333
Sum. '93	43.8	35.6	0.8571	Sum. '99	52.0	22.5	0.8353
Average	**45**	**36**	**0.856**	Average	**52**	**22**	**0.838**

[1] Cetane Number

[2] Specific Gravity

Table 5. California Diesel Fuel Properties Used in 1988

Property	Pre-1993	Post-1993
Sulfur	2800	500
Total Aromatics, Vol. %	31	10/20*

* 10 percent for fuel produced by large refiners and 20 percent for fuel produced by small refiners

IV. Studies and Results

A. REVIEWED EMISSION STUDIES

The PM and NO_x emission reductions associated with California's regulation of the sulfur and aromatic hydrocarbon contents of diesel fuel were estimated in 1988, based on transient cycle testing of two different heavy-duty diesel engines. We have recently reviewed the emission reduction estimates relative to California's pre-regulation diesel fuel, using emission and fuel property data from 31 different test programs, involving a total of 67 different diesel engines and 282 different fuels. Table 6 summarizes the engines tested. The individual test-programs and study results are summarized in the Appendix.

B. Overall Emission Results

ARB staff has performed a "mixed-modeling" statistical analysis of emission data from the test programs to estimate the benefits of California diesel fuel. Based on data from each study and average California diesel fuel properties before and after regulation, the NO_x emission reduction estimates from each study's data vary from 0.3 to 15 percent, with an overall average of 6 percent ± 1 percent. The PM emission reduction estimates from each study's data vary from 1.8 to 88 percent, with an overall average of 26 percent ± 9 percent. Details are presented in Table 7.

The studies show that fuels with lower aromatic hydrocarbon content and specific gravity, and higher cetane number result in lower NOx emissions. Similarly, the studies showed that fuels with lower sulfur content, aromatic hydrocarbon content and specific gravity, and a higher cetane number result in lower PM emissions.

C. HEAVY-DUTY ENGINE WORKING GROUP TEST PROGRAM

1. Description

In 1995, the U.S. EPA established a Heavy-Duty Engine Working Group (HDEWG) that consisted of the U.S. EPA, state agencies, oil and engine companies, academics, and other stakeholders. The main goal of the group was to assess the effect of diesel fuel properties on heavy-duty diesel engine exhaust emissions. Southwest Research Institute (SwRI) was in charge of conducting the experiment.

Overall, the experiment called for a fuel matrix design of 14 blends by controlling four fuel properties: cetane, density, mono- and poly-aromatic contents. The test engine was a Caterpillar 3176 heavy-duty diesel engine at the SwRI lab. This engine was equipped with an EGR in an attempt to simulate a 2004 prototype engine that meets the 2.5 gr/hp-hr NOx emissions standard. The engine was run in four configurations: EGR,

Table 6. Reviewed Studies: List of Engines

STUDY ID.	NO. OF FUELS	NUMBER OF ENGINES STUDIED						MODEL YEARS
		TOTAL	DETROIT	CUMMINS	CATERPILLAR	NAVISTAR	OTHER	
ACEA	5	1	1	0	0	0	0	1991
CARB-LOCO	3	1	1	0	0	0	0	1991
CARB-TOXIC	3	1	0	1	0	0	0	1993
EPEFE	11	12	0	0	0	0	12	1996
HDEWG II	19	4	0	0	4	0	0	1994, 2004
SAE1999-01-1117	7	1	0	0	0	1	0	1994
SAE1999-01-1478	22	1	1	0	0	0	0	1993
SAE1999-01-3606	2	1	0	1	0	0	0	1993
SAE2000-01-2890	10	4	1	3	0	0	0	1995, 1996, 2004
SAE790490	5	2	1	0	1	0	0	1979
SAE852078	6	1	0	0	1	0	0	1988
SAE881173	3	1	0	0	0	0	1	1988
SAE902172	11	1	0	0	0	1	0	1991
SAE902173	18	1	1	0	0	0	0	1991
SAE910735	5	3	3	0	0	0	0	1986
SAE912425	7	1	1	0	0	0	0	1991
SAE922214	8	2	0	0	0	0	2	1989, 1991
SAE922267	12	1	0	0	0	1	0	1993
SAE932685	12	1	0	0	0	0	1	1991
SAE932731	2	1	1	0	0	0	0	1991
SAE932734	14	1	1	0	0	0	0	1991
SAE932767	3	1	1	0	0	0	0	1991
SAE932800	5	1	0	1	0	0	0	1994
SAE942019	12	1	1	0	0	0	0	1991
SAE942053	4	3	1	0	0	2	0	1994
SAE961973	2	1	0	1	0	0	0	1990
SAE961974	6	3	3	0	0	0	0	1995
SAE970758	10	4	1	1	0	0	2	1991, 1994
SAE971635	9	3	0	0	0	0	3	1996
SAE972894	5	1	0	0	0	0	1	1996
SAE972898	7	1	1	0	0	0	0	1991
SAE972904	6	3	3	0	0	0	0	1993
VE 10	23	5	3	0	0	2	0	1994, 1998
VE-1_PHASE I	10	3	1	1	0	1	0	1987, 1988
VE-1_PHASE II	13	1	1	0	0	0	0	1991
TOTALS	**300**	**73**	**28**	**9**	**6**	**8**	**22**	

Table 7. Reviewed Studies: Estimated Effects of Fuel Properties on Emissions

SUMMARY OF REVIEWED STUDIES ON DIESEL ENGINE EMISSIONS AND THE EFFECTS OF FUEL PROPERTIES				AVE. CA FUEL vs. AVE. PRE-REG. CA FUEL**	
STUDY ID.	NUMBER OF FUELS	FUEL PARAMETERS	NUMBER OF ENGINES	PREDICTED CHANGE	
				PM (%)	NOx (%)
ACEA	5	cet.no, S, arom, dist.Ts, sp.grav.	1	-43.4	-3.3
CARB-LOCO	3	cet.no, S, arom, dist.Ts, sp.grav.	1	-21.7	-6.2
CARB-TOXIC	3	cet.no, S, arom, dist.Ts, sp.grav.	1	-18.2	-4.1
EPEFE	11	cet.no, S, arom, dist.Ts, sp.grav.	12	-49.2	-6.0
HDEWG II	19	cet.no, S, arom, dist.Ts, sp.grav.	4	Not Meas'd	-5.3
SAE1999-01-1117	7	cet.no, S, arom, sp.grav.	1	-50.4	-4.2
SAE1999-01-1478	22	cet.no, S, arom, dist.Ts, sp.grav.	1	-3.9	-5.1
SAE1999-01-3606	2	cet.no, S, arom, dist.Ts, sp.grav.	1	-21*	-5.1
SAE2000-01-2890	10	cet.no, S, arom, dist.Ts, sp.grav.	4	-23.2	-5.4
SAE790490	5	cet.no, S, arom, dist.Ts, sp.grav.	2	-13.5	-5.7
SAE852078	6	cet.no, S, arom, dist.Ts, sp.grav.	1	-58.7	-5.3
SAE881173	3	cet.no, S, arom, dist.Ts, sp.grav.	1	Not Meas'd	Not Meas'd
SAE902172	11	cet.no, S, arom, dist.Ts, sp.grav.	1	-18.7	-6.4
SAE902173	18	cet.no, S, arom, dist.Ts, sp.grav.	1	-4.8	-5.8
SAE910735	5	cet.no, S, arom, dist.Ts, sp.grav.	3	-20.9	-0.3
SAE912425	7	cet.no, S, arom, dist.Ts, sp.grav.	1	-22.0	Not Meas'd
SAE922214	8	cet.no, S, arom, dist.Ts, sp.grav.	2	-68.3	-10.2
SAE922267	12	cet.no, S, arom, dist.Ts, sp.grav.	1	-73.3	-8.8
SAE932685	12	cet.no, S, arom, dist.Ts, sp.grav.	1	-88.3	-5.9
SAE932731	2	cet.no, S, arom, dist.Ts, sp.grav.	1	Aromatic Dif. Insignificant	
SAE932734	14	cet.no, S, arom, dist.Ts, sp.grav.	1	-11.8	-3.6
SAE932767	3	cet.no, S, arom, dist.Ts, sp.grav.	1	-1.8	-3.3
SAE932800	5	cet.no, S, arom, dist.Ts, sp.grav.	1	-71.7	-5.2
SAE942019	12	cet.no, S, arom, dist.Ts, sp.grav.	1	-14.6	-4.7
SAE942053	4	cet.no, S, arom, dist.Ts, sp.grav.	3	-2.5	-5.8
SAE961973	2	cet.no, S, arom, dist.Ts, sp.grav.	1	-5.8	-8.4
SAE961974	6	S	3	Identical Comp. Except S	
SAE970758	10	cet.no, S, arom, dist.Ts, sp.grav.	4	-17.0	-7.7
SAE971635	9	cet.no, S, arom, dist.Ts, sp.grav.	3	-5.4	-15.1
SAE972894	5	cet.no, S, arom, dist.Ts, sp.grav.	1	-7.7	-4.8
SAE972898	7	cet.no, S, arom, dist.Ts, sp.grav.	1	-6.8	-5.6
SAE972904	6	cet.no, S, arom, dist.Ts, sp.grav.	3	-5.2	-9.4
VE 10	23	cet.no, S, arom, dist.Ts, sp.grav.	5	-10.2	-6.7
VE-1_PHASE I	10	cet.no, S, arom, dist.Ts, sp.grav.	3	-31.7	-6.4
VE-1_PHASE II	13	cet.no, S, arom, dist.Ts, sp.grav.	1	-2.8	-6.8
TOTALS	**300**		**73**	**-25.6**	**-6.0**

* Average of extrapolations for cetane no., aromatic content, and sp. gravity

** See Table 2 for average fuel properties

EGR with fuel injection timing retarded, EGR with advanced timing, and no EGR. It should be noted that the EGR-equipped engine could not be tuned to meet the 2.5 g/hp-hr NOx emission standard in a transient FTP test cycle. However, the engine could meet the NOx standard in steady-state operation. Therefore, all test runs were performed at 8 different steady-state operational modes instead of the transient test cycle.

2. Results

The HDEWG Program found NOx emissions to be sensitive to both aromatic hydrocarbon content and fuel density when the test engine was operated with EGR. NOx emissions were found to decrease as aromatic hydrocarbon content decreased and as fuel density decreased. These results are typical of the results of other diesel fuel effects studies. Aromatic and other high-density hydrocarbons tend to burn hotter due to lower product mass and specific heat, hence lower product heat capacity, than for the lighter hydrocarbons. Higher peak combustion temperatures result in higher specific NOx emissions, given a constant thermal efficiency.[6]

Since aromatic hydrocarbon content and fuel density are physically related properties, these fuel properties are normally strongly correlated among diesel fuels, density decreasing with decreasing aromatic hydrocarbon content. Also, natural cetane number is highly correlated to fuel density, natural cetane number increasing with decreasing density. This is why cleaner burning diesel fuels tend to have relatively low aromatic hydrocarbon contents and lower densities and relatively high natural cetane numbers. However, the program found that NOx emissions stayed the same or increased mildly with the addition of the cetane improver, 2-ethyl-hexyl nitrate (EHN),[7] as aromatic content and other properties stayed the same. Since EHN contains nitrogen, which contributes to NOx emissions, albeit an undetermined amount, it is difficult to draw any conclusions regarding the impact of cetane number on NOx emissions for these tests.

Enough nitrogen was added through cetane improvers to the natural fuels to influence and reverse the sign of the NOx emission results as a function of cetane number. However, it should be noted that for the additized test fuels, all additive amounts were greater than the amounts typically added to California diesel fuel.

Unfortunately, the HDEWG Program did not study PM emissions. Steady-state testing does not provide an accurate prediction of transient test results for PM emissions.[8] However, the results of the HDEWG Program do verify the reduction of HC and CO

---

[6] 2544 Btu/hp-hr / Specific Fuel Consumption (lbs/hp-hr) / Lower Heating Value (Btu/lb)

[7] The five base fuels with natural cetane numbers of 42.1 to 42.8 were improved with two different levels of EHN, creating five 47.7 to 48.1 cetane-number fuels at 0.14 to 0.20 percent-by-weight EHN and five 52.2 to 53.2 cetane-number fuels at 0.56 to 0.63 percent-by-weight EHN.

[8] PM emissions are more sensitive to fuel quality under transient operation.

emissions with increasing cetane number. Also, other studies indicate the increase in PM emissions with EGR and the sensitivity of PM emissions to fuel quality.

D. THE EFFECTS OF CETANE IMPROVERS

The studies reviewed indicate that there is a diminishing returns relationship between increased cetane improver concentrations and reductions in the emissions of NOx. In fact, at very high concentrations of cetane improver, with more nitrate additive, the nitrogen in the cetane improver may actually lead to increasing NOx emissions. However, these levels are significantly beyond any levels used in CARB diesel.

One study was specifically designed to examine the relationship between emissions and cetane improvers. The study report, entitled "The Effects of 2-Ethylhexyl Nitrate and Di-tertiary-butyl Peroxide on the Exhaust Emissions from a Heavy-Duty Engine," was published by the Society of Automotive Engineers (SAE 1999-01-1478). This study also examined whether the nitrogen in the (2-ethylhexyl nitrate, or EHN) cetane improvement additive contributes to NOx emissions. The study concluded, "the nitrogen in EHN does not contribute to NOx emissions at typical treat rates. [At the highest treat rate[9],] while not statistically significant, there was on average slightly more NOx emitted from EHN compared to DTBP treated fuels. Even at this high treat rate NOx emissions were still significantly lower than with unadditized fuel." This study indicates that, while the NOx emission benefits of cetane improvement are limited, increasing cetane number alone does result in lower NOx emissions.

---

[9] 0.75 percent-by-volume ≈ 0.85 percent-by-weight

V. NOx Emission Models

A. HDEWG PROGRAM MODEL

As part of the HDEWG Program described earlier, a mathematical model for NOx, was developed assuming a linear function of fuel properties, based on the data from the engine configured with EGR and normal injection timing. The independent variables are mono- and poly-cyclic aromatic hydrocarbon contents, density (kg/m^3), and cetane number. The mono- and poly-cyclic aromatic coefficients are about the same, the poly-cyclic coefficient being only 18 percent higher than the mono-cyclic coefficient.

As expected, the model predicts NOx emissions to decrease with decreasing aromatic hydrocarbon content and fuel density. The cetane number coefficient is positive, meaning increasing NOx emissions with increasing cetane number, which is the opposite of what is indicated by most other studies on NOx emissions and fuel property effects. This may be partly due to the nitrogen content of the cetane additive and the high concentration of additive used as described in section IV.C.2. This may also be partly due to the database being too limited as described below in section V.D. Table 8 summarizes the model coefficients, replacing the density coefficient with a specific gravity coefficient[10].

The HDEWG model may have limited applicability, because it is based on data from only one engine operated in one prototype configuration. Nevertheless, the model estimates about a 5-percent reduction in NOx emissions due to the use of California diesel fuel.

Table 8. Property Coefficients for NOx Emission Models

Model	Intercept	Mono-AHC	Poly-AHC	Total AHC	Sp. Grav.	Cetane No.	T50
		(wt. %)	(wt. %)	(vol. %)			(°F)
HDEWG[1]	-1.334	0.00646	0.00763	[3]	4.13	0.00337	[3]
EPA[2]	0.50628	[3]	[3]	0.002922	1.3966	[4] -0.002779	-0.0004023
EPA EGR[2]	-0.13383	[3]	[3]	0.002922	1.3966	[4] 0.001172	-0.0004023

[1] NOx (g/hp-hr) = Intercept + Σ(Coefficient * Fuel Property)
[2] NOx (g/hp-hr) = $e^{[\text{Intercept} + \Sigma(\text{Coefficient} * \text{Fuel Property})]}$
[3] Fuel property not used in model.
[4] For EPA models, the fuel property is (Cetane Number - Natural Cetane Number).

---

[10] Fuel Density (kg/m^3) @ 15 °C ≈ 1000 * Specific Gravity @ 60 °F/60 °F.

B. U.S. EPA UNIFIED MODEL

The EPA developed NOx emission models for five different engine technology groups. For predicting the emission benefits that the implementation of California diesel fuel regulation will have in Texas, the five models were then simplified into a single "default" model for engines without EGR and a model for engines with EGR. Total aromatic hydrocarbon content, specific gravity, cetane number difference[11], and 50-percent distillation temperature[12] (T50) are the independent variables in EPA's NOx models.

The EPA modeling estimates a 6-percent NOx reduction for engines without EGR and a 5-percent NOx reduction for engines with EGR, due to the use of California diesel fuel.[13]

C. U.S. EPA CETANE NUMBER MODEL

A recent analysis of data from NOx studies on additized fuels indicates that NOx response to cetane number boost is nonlinear. NOx emission reductions flatten out or, for high natural cetane-number fuels, begin to diminish at extremely high additized cetane improvement. This analysis is documented in the US EPA's draft technical report, *The Effect of Cetane number Increase Due to Additives on NOx Emissions from Heavy-Duty Highway Engines.*

EPA's cetane number (CN) model for NOx is

$$\begin{aligned}\ln(\text{NOx, g/hp-hr}) = {} & 1.79883 - 0.015151*(\text{CN-Natural CN}) + 0.000169*(\text{CN-Natural CN})^2 \\ & - 0.006014*(\text{Natural CN}) + 0.000223*(\text{CN-Natural CN})*(\text{Natural CN}).\end{aligned}$$

A linear model of emissions with cetane number improvement should only apply over a limited range of cetane number boost, no more than 5 or 6 cetane numbers. The HDEWG program's emission modeling does not adequately define the relationship between NOx emissions, natural cetane number, and additized cetane improvement. Superimposing a linear relationship over a range where the response is inherently non-linear may lead to results that are very difficult to interpret.

---

[11] Cetane Number Difference = Cetane Number - Natural (Unadditized) Cetane Number.

[12] The temperature at which 50 percent of the fuel volume is distilled

[13] With cetane number differences of 0.8 and 4.4, and T50s of 505 °F and 502 °F, for national on-road and California diesel fuels, respectively

D. ARB STAFF ANALYSIS OF U.S EPA DATABASE

The regression coefficients for the NOx model in the HDEWG study were generated from the test data that were based on one engine using different EGR and fuel injection timing configurations. The test data show a good relationship between NOx emissions, as the dependent variable, and all independent variables but cetane number. The results show that NOx emissions increase with increasing cetane number. This seemingly contradictory result may arise when the model building efforts are limited to a small number of fuels and only a single test engine. Correlation among fuel properties, particularly with those that were not controlled in the experiment, and insufficient data to account for engine-to-engine variation in emission response to fuel properties of lesser significance may be to blame. If the fuel properties are correlated, then it may be very difficult to properly interpret individual responses. Simply put, in a mathematical model designed to best fit an array of known values of a dependent variable, if one of two or more correlated independent variables becomes an under-estimator; then, another variable must become an over-estimator. For a relatively weak independent variable (e.g., cetane number) the model may reverse the sign of the actual physical effect. Furthermore, if there are latent variables, influential properties that are not included as part of the analysis, the individual fuel property effects could be influenced and lead to misleading interpretations.

To better understand how the results from the engine in the HEDWG study compares to engines from other studies the staff used the U.S. EPA Diesel Fuel Effects database to generate a model for each engine in the database. Regression coefficients were estimated using the log of the data and using a modeling approach similar to the one used in the HDEWG study. The HDEWG study evaluated density, cetane, and mono- and poly-cyclic aromatics. Since most studies included in the U.S. EPA Diesel Fuel Effects database did not separate mono- and poly-cyclic aromatics, total aromatics were used as a replacement. Estimates for each regression coefficient for each engine are presented in Table 8. From Table 8 it is evident that the aromatic hydrocarbon coefficients are consistently greater than zero and, for the majority of engines studied, the cetane number coefficients are negative and the specific gravity coefficients are positive.

Based on staff's analysis of the pooled data, as summarized in Table 9, the new cetane number regression coefficients for the HDEWG data are negative with respect to NOx emissions. This is different from the HDEWG results where the signs of the coefficients where not consistent. A benefit to this type of analysis is that it allows estimates to be generated for the other HDEWG engine operating configurations. It should be noted that all of the EGR engine configurations resulted in relatively high aromatic hydrocarbon and specific gravity coefficients, as indicated in Table 8. It should also be noted that, when the HDEWG engine was operating with EGR and either timing advanced or retarded, the cetane number improvement effect was strongly beneficial for NOx.

Table 9. Diesel Model Random Effect Standardized Coefficients

By Study and Engine

Study Id.	Engine*	Intercept	Cetane Number	Total Aromatic	Spec. Gravity	% NOx Change**	
ACEA	DDC-SWRI	1.4696	-0.0069	0.0458	-0.0158	-5.0	
CARB-LOCO	06RE001123	1.5000	-0.0124	0.0270	0.0126	-5.6	
CARB-TOXIC	34705128	1.5374	-0.0061	0.0293	0.0097	-4.9	
EPEFE	V_-2	1.4523	-0.0147	0.0186	0.0265	-5.9	
	V_+2	1.7403	-0.0133	0.0186	0.0207	-5.3	
	V_STD	1.6225	-0.0108	0.0226	0.0177	-5.3	
	X_-2	1.4930	-0.0116	0.0251	0.0161	-5.5	
	X_+2	1.7696	-0.0060	0.0318	0.0009	-4.5	
	X_STD	1.6140	-0.0102	0.0213	0.0200	-5.2	
	Y_-2	1.5275	-0.0056	0.0328	0.0046	-4.9	
	Y_+2	1.6988	-0.0053	0.0320	0.0024	-4.6	
	Y_STD	1.6209	-0.0056	0.0383	-0.0062	-4.7	
	Z_-2	1.4409	-0.0090	0.0248	0.0185	-5.4	
	Z_+2	1.8003	-0.0047	0.0359	-0.0060	-4.3	
	Z_STD	1.6171	-0.0069	0.0393	-0.0083	-4.8	
HDEWG II	HDEWG EGR	0.9077	-0.0011	0.0284	0.0266	-5.6	
	HDEWG EGR T2	1.0392	-0.0192	0.0249	0.0239	-6.9	HDEWG Ave. -6.5%
	HDEWG EGR T3	0.8195	-0.0214	0.0301	0.0197	-7.4	
	HDEWG No EGR	1.3486	-0.0071	0.0255	0.0199	-5.4	
SAE1999-01-1478	1999-01-1478-1	1.5424	-0.0114	0.0225	0.0188	-5.4	
SAE2000-01-2890	04 SWRI/CAT 10.3	0.8730	-0.0173	0.0299	0.0201	-7.0	w/ EGR
	95 CAT 3406E	1.6116	-0.0131	0.0220	0.0179	-5.5	
	95 CUMMINS N14	1.7669	0.0070	0.0445	-0.0152	-3.3	
	96 SERIES 50	1.8639	-0.0067	0.0313	-0.0004	-4.5	
SAE902172	DTA466 PROTO	1.5612	-0.0183	0.0253	0.0121	-6.0	
SAE902173	902173-1	1.3998	-0.0097	0.0259	0.0174	-5.5	
SAE910735	AIR RESTRICTION	2.1797	0.0091	0.0342	-0.0073	-2.5	
	BASELINE	2.3171	0.0087	0.0245	0.0052	-2.4	
	THROTTLE DELAY	2.3188	0.0031	0.0264	0.0006	-2.8	
SAE922214	3	1.8095	-0.0188	0.0135	0.0259	-5.8	
SAE922267	922267-1	1.5594	-0.0264	0.0231	0.0138	-6.8	
SAE932685	932685-1	1.7146	-0.0107	0.0276	0.0074	-5.1	
SAE932731	S60 PROTO	1.3901	-0.0088	0.0404	-0.0055	-5.3	
SAE932734	932734-1	1.4149	-0.0081	0.0318	0.0078	-5.3	
SAE932767	932767-1	1.3883	-0.0176	0.0255	0.0158	-6.2	
SAE932800	932800-N14	1.4263	-0.0138	0.0333	0.0031	-5.7	
SAE942019	S60 PROTO	1.4594	-0.0131	0.0217	0.0214	-5.7	
SAE970758	A	1.6292	-0.0061	0.0234	0.0177	-4.9	
	B	1.6349	-0.0078	0.0205	0.0219	-5.1	
SAE971635	8460.41-10	1.6165	-0.0137	0.0153	0.0288	-5.6	
	8460.41-8.7	1.5462	-0.0110	0.0274	0.0113	-5.4	
	8460.41-9.2	1.5763	-0.0083	0.0232	0.0183	-5.1	
SAE972894	972894-1	1.5165	-0.0087	0.0296	0.0091	-5.2	
SAE972898	S60-0/98	1.5286	-0.0129	0.0151	0.0308	-5.7	
SAE972904	S60-0	1.5101	-0.0231	0.0165	0.0259	-6.6	
	S60-3	1.3457	-0.0286	0.0186	0.0245	-7.3	
	S60-5	1.2701	-0.0352	0.0223	0.0180	-7.9	
VE 10	VE_10_1	1.5695	-0.0103	0.0277	0.0105	-5.3	
	VE_10_2	1.3757	-0.0143	0.0229	0.0212	-6.0	
	VE_10_3	1.5328	-0.0140	0.0174	0.0268	-5.7	
	VE_10_4	1.4196	-0.0217	0.0165	0.0283	-6.6	
	VE_10_5	1.3925	-0.0214	0.0187	0.0255	-6.6	
VE-1_PHASE I	DDC 60	1.5605	-0.0204	0.0325	0.0003	-6.1	
	NIC 7.3	1.5092	-0.0031	0.0568	-0.0324	-4.5	
	NTCC 400	1.5032	-0.0025	0.0463	-0.0160	-4.5	
VE-1_PHASE II	6R-510/6067G740	1.4995	-0.0254	0.0294	0.0048	-6.7	

*Not all engines used, as some had insufficient data

**Computed as NOx emissions difference between CARB and pre-CARB diesels, relative to pre_CARB fuel, in percent

VI. Predicted NOx Emission Benefits

In order to put the new U.S. EPA regression equations in a better perspective, staff estimated the NOx emission benefits of the HDEWG engine for each of its four different operating configurations along with engines from other studies. Table 8 also presents the predicted NOx emission percent change associated with the use of a California diesel fuel relative to a pre-1993 diesel fuel, for each engine of each study. The first column lists the engines of each study in the pooled data, followed by linear regression coefficients as shown in the next three columns, as noted earlier. The last column shows the predicted NOx emission changes in percent. The range in predicted NOx emission benefits of California diesel fuel is 2 to 8 percent. As shown (highlighted) in the table, the HDEWG engine, operated in four different configurations, would produce an average NOx emission reduction of about 7 percent. This compares to the simple analysis in chapter III, which gave an estimate of about 6 percent for the NOx reduction.

Appendix A. SUMMARY OF STUDY RESULTS

STUDY ID	Reference	Summary [illegible]
ACEA	Kleinschek, G., K. Richter, A. Roj, M. Signer, H.J. Stein, "Influence of Diesel Fuel Quality on Heavy-Duty Diesel Engine Emissions," ACEA Heavy-Duty Diesel Truck Manufacturers, March 20, 1997, BE/ACEA/30	
CARB-LOCO	Fritz, S.G., "Diesel Fuel Effects on Locomotive Exhaust Emissions," Southwest Research Institute Final Report, prepared for California Air Resources Board in October, 2000.	For EMD and GE locomotives, CARB fuel reduced composite NOx emissions by an average of 3% and 4% from levels for on-highway fuel, respectively. Compared to the high-sulfur, nonroad diesel fuel, average composite NOx emissions were 6-7 percent lower with CARB fuel.
CARB-TOXIC	Treux, Timothy J., J.M. Norbeck, M.R. Smith, "Evaluation of Factors That Affect Diesel Exhaust Toxicity," report sponsored by the California Air Resources Board, July 24, 1998	Reductions in NOx emission rates with the low aromatic (Aromatic HC-Vol% of 10 max) and reformulated fuels (Aromatic HC-Vol% of 20-25) range from 2.6 to 7.6% compared to the pre-1993 fuel (Aromatic HC-Vol% of 33).
EPEFE	Signer, M., P. Heinze, R. Mercogliano, H. J. Stein, "European Programme on Emissions, Fuels and Engine Technologies (EPEFE) – Heavy-Duty Diesel Study," SAE 961074.	Fuel density was the most influential property to reduce NOx (3.6%). Other fuel properties contributed also: T95 (1.7%), polyaromatics (1.7%) and cetane number (0.6%). Polyaromatics was the only fuel property to reduce PM (3.6%).
HDEWG II	Matheaus, Andrew C., T. W. Ryan III, R. Mason, G. Neely, R. Sobotowski, "Gaseous Emissions from A Caterpillar 3176 (With EGR) Using A Matrix of Diesel Fuels (Phase 2)," Final Report under EPA Contract Number 68-C-98-169, September, 1999.	NOx decreases with decreases in either density or aromatic content. Cetane number has very little effect on NOx emissions.
SAE1999-01-1117	Clark, Nigel N., C. M. Atkinson, G. J. Thompson, R. D. Nine, "Transient Emissions Comparisons of Alternative Compression Ignition Fuels," SAE 1999-01-1117.	The biodiesel fuel and blends showed the ability to reduce PM markedly, but NOx rose slightly. The addition of isobutanol to the MG reduced PM further, but raised CO and HC albeit to levels still well below regulatory limits.
SAE1999-01-1478	Schwab, Scott D., G. H. Guinther, T.J. Henly, K. T. Miller, "The Effects of 2-Ethylhexyl Nitrate and Di-Teritary-Butyl Peroxide on the Exhaust Emissions from a Heavy-Duty Diesel Engine," SAE 1999-01-1478.	Cetane improvers EHN and DTBP lowered CO, NOx, and particulate emissions.
SAE1999-01-3606	Cheng, A. S., R. W. Dibble, "Emissions Performance of Oxygenate-in-Diesel Blends and Fischer-Tropsch Diesel in a Compression Ignition Engine," SAE 1999-01-3606.	Results showed that all test fuels with blends of DMM and DEE of 5, 10, 15, and 30% by volume, reduced PM when data was averaged across the nine engine operating modes.
SAE2000-01-2890	Mitchell, K., "Effects of Fuel Properties and Source on Emissions from Five Different Heavy-Duty Diesel Engines," SAE 2000-01-2890.	NOx emissions from three engines showed the same relative decrease with decrease in total aromatics. The effect of cetane number on NOx emissions was not consistent amongst the engines.

STUDY ID	Reference	Summary
SAE790490	Hare, C. T., R. L. Bradow, "Characterization of Heavy-Duty Diesel Gaseous Particulate Emissions, and Effects of Fuel Composition," SAE 790490.	Regulated gaseous emissions (HC; CO, NOx,) from the two test engines differed from each other in a relatively consistent manner. Limited fuel effects were apparent in emissions from both engines, mostly between the No. 2 fuels as a group and the No. 1 fuel
SAE852078	Barry, E. G., L. J. McCabe, D. H. Gerke, J. M. Perez, "Heavy-Duty Diesel Engine/Fuels Combustion Performance and Emissions – A Cooperative Research Program," SAE.	Polycylic Aromatic Hydrocarbon levels increased with increasing fuel aromatic content, but changes below 35%aromatic were not significant as compared to changes up to 50%.
SAE881173	Knuth, Hans Walter, Hellmut Garthe, "Future Diesel Fuel Compositions – Their Influence on Particulates," SAE 881173.	The gaseous emissions, particularly CO and HC, are unfavorably influenced by low cetane numbers being associated with increased aromaticity in the diesel fuel. The emission of particulates is increased by low cetane numbers.
SAE902172	Sienocki, E., R. E. Jass, W. J. Slodowsky, C. I. McCarthy, A. L. Krodel, "Diesel Fuel Aromatic and Cetane Number Effects on Combustion and Emissions from a Prototype 1991 Diesel Engine, " SAE 902712.	Increasing cetane number and reducing aromatic content resulted in lower emissions of hydrocarbons and NOx. HC emissions were reduced by reducing fuel aromatic content or by increasing cetane number. A 10 cetane number increase was equivalent to either a 2 vol% reduction in poly-aromatics, or an estimated 4 vol% reduction in total aromatics.
SAE902173	Cunningham, Lawrence J., Timothy J. Henly, Alexander M. Kulinowski, "The Effects of Diesel Ignition Improvers in Low-Sulfur Fuels on Heavy-Duty Diesel Emissions," SAE 902173.	Cetane imporvers lower HC and CO emissions and, in some cases NOx and particulate emissions. CO and HC emissions decreased as cetane number increased.
SAE910735	Ullman, Terry L., David M. Human, "Fuel and Maladjustment Effects on Emissions from a Diesel Bus Engine," SAE 910735.	Except for HC emissions, regulated emissions were affected more by state-of-tune than by variation in test fuel properties. However, fuel properties did have significant effects on regulated properties, such that lower emissions were generally favored when the fuel had a low 90% boiling point, low aromatic content, high cetane number, and low sulfur level.
SAE912425	Lange, W. E. "The Effects of Fuel Properties on Particulates Emissions in Heavy-Duty Truck Engines Under Transient Operating Conditions," SAE 912425.	Increasing fuel sulfur content and/or fuel density increases total particulate mass. Increasing ignition quality did not have any effect on particulates emissions in this engine
SAE922214	Asaumi, Y., M. Shintani, Y. Watanabe, "Effects of Fuel Properties on Diesel Engine Exhaust Emissions Characteristics," SAE 922214	Engine test results show that reducing the fuel sulfur content decreases particulate levels. Enriching aromatic content in fuel causes an increase in NOx, CO, and THC emissions.

STUDY ID	Reference	Summary
SAE922267	McCarthy, Christopher I., Warren J. Slodowsky, Edward J. Sienicki, Richard E. Jass, "Diesel Fuel Property Effects on Exhaust Emissions from a Heavy-Duty Diesel Engine that Meets 1994 Emissions Requirements," SAE 922267.	Reducing aromatic content reduced NOx and particulate emissions, but had no effect on HC or CO emissions. Increasing cetane number reduces all regulated diesel emissions species.
SAE932685	Lange, W. W., A. Schafer, A. Le'Jeune, D. Naber, A. A. Reglitzky, M. Gairing, "The Influence of Fuel Properties on Exhaust Emissions from Advanced Mercedes Benz Diesel Engines," SAE 932685.	Increasing cetane number reduced NOx emissions whereas total aromatics content had no influence on NOx emissions. Mono-aromatics content, distillation and cetane number did not affect particulates emissions.
SAE932731	Gonzalez D., Manuel A. Guillermo, G. Rodriguez, Roberto Galiasso, Edilberto Rodriguez, "A Low Emission Diesel Fuel: Hydrocracking Production, Characterization and Engine Evaluations," SAE 932731.	Fuel H (10 wt% aromatics), as compared to the high sulfur and high aromatics diesel fuel A, (37.5 wt% aromatics) showed lower HC, CO and NOx emissions.
SAE932734	Liotta, Jr., Frank J., Daniel M. Montaivo, "The Effect of Oxygenated Fuels on Emissions from a Modern Heavy-Duty Diesel Engine," SAE 93274.	The addition of an oxygenate to the fuel reduces CO and HC emissions. Non-regulated aldehyde and ketone emissions are also reduced with the addition of an oxygenate.
SAE932767	Liotta, Jr., Frank J., "A Peroxide Based Cetane Improvement Additive with Favorable Fuel Blending Properties," SAE 932767.	The peroxide based additive used to added to the fuels, reduced HC, CO, NOx and particulate matter emissions. Aldehyde and ketone emissions were also reduced. The peroxide additive lowered NOX emissions mores than the 2-ethlhexl nitrate cetane improvement additive.
SAE932800	Rosenthal, M. Lori, Tracy Bendinsky, "The Effects of Fuel Properties and Chemistry on the Emissions and Heat Release of Low-Emission Heavy-Duty Diesel Engines," SAE 932800.	The results of this study clearly show that aromatic content is the dominant fuel property that can be used to reduce emission levels.
SAE942019	Nandi, Manish K., David C. Jacobs, Frank J. Liotta, Jr., H. S. Kesling, Jr., "The Performance of a Peroxide Based Cetane Improvement Additive in Different Diesel Fuels," SAE 942019.	HC, CO, PM, and NOx are reduced significantly by treating a variety of fuels with either of cetane additives tested in this study.
SAE942053	Mitchell, K., D. E. Steere, J. A. Taylor, B. Manicom, J. E. Fisher, E. J. Sienicki, C. Chiu, P. Williams, "Impact of Diesel Fuel Aromatics on Particulate, PAH and Nitro-PAH Emissions," SAE 942053.	A catalyst lowered PAH emissions form 62%-76%. The Catalyst also Reduced HC by an average of 33% and CO by an average of 4%. The catalyst had no effect on NOx emissions
SAE961973	Geiman, Richard A., Patrick B. Cullen, Peter R. Chant, Philip N. Carlson, Venkatesh Rao, "Emission Effects on Shell LOW NOX Fuel on a 1990 Model Year Heavy Heavy-Duty Diesel Engine," SAE 961973.	Transient testing showed that the Shell LOW NOX fuel lowers NOX, HC and CO emissions. At steady-state testing, using the non-road cycle, showed that it decreased PM and HC emissions. Again at steady-state testing with a generator Shell LOW NOX Fuel increased HC and CO emissions.

STUDY ID	Reference	Summary / [illegible]
SAE961974	Daniels, Teresa L., Robert L. McCormick, Michael S. Graboski, Philip N. Carlson, Venkatesh Rao, Gary W. Rich, "The Effect of Diesel Sulfur Content and Oxidation Catalysts on Transient Emissions at High Altitude from a 1995 Detroit Diesel Series 50 Urban Bus Engine," SAE 961974.	Lowering fuel sulfur from 500 to 5 ppm reduces total PM emissions by 6% without a catalyst. A larger PM reduction results from the use of an oxidation catalyst at 500 ppm sulfur than from lowering the sulfur in the fuel to 5 ppm.
SAE970758	Tamanouchi, Mitsuo, Jiroki Morihisa, Shigehisa Yamada, Jihei Lida, Takanobu Sasaki, Harufusa Sue, "Effects of Fuel Properties on Exhaust Emissions for Diesel Engines With and Without Oxidation Catalyst and High Pressure Injection," SAE 970758.	As cetane number increased, THC and CO levels decreased. Aromatic content and density exhibited a good correlation with NOx, with NOx levels exhibiting increase following corresponding increases in these two parameters.
SAE971635	Stradling, Richard, Paul Gadd, Meinrad Signer, Claudio Operti, "The Influence of Fuel Properties and Injection Timing on the Exhaust Emissions and Fuel Consumption of an Iveco Heavy-Duty Diesel Engine,"	To get a NOx reduction of 0.1 g/kWh a 0.3 degree crank retardation of the injection timing or a 6 kg/m^3 reduction in density or a 8.5% reduction in total aromatics can be done to achieve this goal.
SAE972894	Lange, W. W., J. A. Cooke, P. Gadd, H. J. Zurner, H. Schlogl, and K. Richter, "Influence of Fuel Properties on Exhaust Emissions from Advanced Heavy-Duty Engines Considering the Effect of Natural and Additive Enhanced Cetane Number," SAE 972894.	Increasing cetane number from 51 to 61 did not affect particulates or HC emissions over either test cycle, but reduced CO emissions by about 6-7%. The new test cycle showed improved emissions of NOx by about 1.6% NO emissions of about 0-8% were noticed due mainly to part load conditions in the test cycles.
SAE972898	Schabert, Paul W., Ian S. Myburgh, Jacobus J. Botha, Piet N. Roets, Carl L. Viljeon, Luis P. Dancuart, Michael E. Starr, "Diesel Exhaust Emissions Using Sasol Slurry Phase Distillate Process Fuels," SAW 972898.	HC, CO, and NOx emissions with the CARB fuel were lower by 40%, 14%, and 15% respectively, when compared to the US 2-D fuel. PM was the same with both fuels.
SAE972904	Starr, Michael E., "Influence on Transient Emissions at Various Injection Timings, Using Cetane Improvers, Bio-Diesel, and Low Aromatic Fuels," SAE 972904.	CARB fuel resulted in the highest NOx and PM levels at each timing in this study. CARB fuel had the lowest Nox level at each timing, but bio-diesel had the lowest PM.
VE 10	Spreen, Kent B., T. L. Ullman, R. L. Mason, "Effects of Fuel Oxygenates, Cetane Number, and Aromatic Content on Emissions From 1994 and 1998 Prototype Heavy-Duty Diesel Engines," CRC Contract No. VE-10. Project VE-10.	Increasing cetane number reduced HC, CO, and NOx. Reducing aromatic content lowered NOx. Oxygen in the fuel reduced CO and particulate emissions, but tended to slightly increase NOx emissions.
VE-1_PHASE I	Ullman, Terry L., "Investigation of the Effects of Fuel Composition and Injection and Combustion System Type on Heavy-Duty Diesel Exhaust Emissions," CRC Contract CAPE 32-80, Project VE-1.	Transient emissions of NOx, particulate matter, soluble organic fraction, and hydrocarbons increased as aromatic content increased from 10 percent to 40 percent. Emissions of NOx decreased as cetane number increased.
VE-1_PHASE II	Ullman, Terry L., R. L. Mason, D. A. Montalvo, "Study of Fuel Cetane Number and Aromatic Content Effects on Regulated Emissions from a Heavy-Duty Diesel Engine," CRC Contract No. VE-1, Project VE-1.	Reducing aromatic hydrocarbon content reduced transient emissions of NOx and particulate matter. Increasing cetane number reduced transient emissions of NOx, particulate matter, and hydrocarbons.