

PEER REVIEW

PROPOSED DIESEL SULFUR REGULATIONS AND EMISSION BENEFITS OF CURRENT REGULATIONS

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INTRODUCTION

The California Air Resources Board (ARB) requested an independent peer review of (1) the proposed revisions to the California Diesel Fuel regulations, including a standard for lubricity, and (2) benefits quantified for the existing regulations.

Reviewers were provided with a copy of the staff report¹ for the proposed revisions to regulations. The report includes, as Appendix D, a staff review of the benefits of the existing regulations. Reviewers were also provided with copies of previous staff reports and a CD containing references cited in the staff report.

The regulation for reduced sulfur content of diesel fuel is consistent with regulations promulgated earlier by the U. S. Environmental Protection Agency (EPA) for sulfur content of diesel fuel intended for on-highway vehicles.² The EPA recently published a notice of proposed rulemaking for reduction of the sulfur content of offroad diesel fuel.³

In addition, EPA has recently reviewed studies regarding the effects of diesel fuel properties on emissions. This reviewed was initiated in response to EPA's concern about NOx emission reduction credits claimed by Texas for a state implementation plan (SIP) measure requiring low-emission diesel (LED) fuel similar to California diesel. In addressing this issue, EPA commissioned a contractor report by Southwest Research Institute (SwRI),⁴ and prepared a staff discussion document.⁵ EPA ultimately provided an estimate of the benefits of the Texas program, but declined to publish a general model for the effect of diesel fuel properties on emissions. Instead, EPA published a simpler correlation that dealt with the effects of cetane additives on NOx emissions.⁶

Thus, the issues addressed in this review can draw not only upon the technical literature but also upon previous analyses of such literature related to the regulatory issues considered in the staff report under review here.

The review is organized into two sections that address the two issues posed here: the proposed regulation amendments and the effect of the current regulations.

PROPOSED REVISIONS TO THE REGULATIONS

The proposed revisions modify existing regulations for diesel fuel sold in California. The current regulations require a maximum sulfur concentration of 500 parts per million by weight (ppmw) and a maximum aromatics content of 10 percent by volume (10%v). Refiners may produce alternative diesel fuels to comply with the 10%v aromatics limit if they show, by engine testing, that the alternative fuel provides the same emission benefits. Although low-sulfur diesel fuels are known to have reduced lubricity, compared to diesel fuels with higher sulfur, the current regulations do not have a lubricity standard. However, California refiners have voluntarily agreed to place additives in the fuel to provide adequate lubricity. Diesel fuel meeting the current regulations must be used in all motor vehicles.*

The main regulatory change proposed here is a reduction of the maximum sulfur content of diesel fuel from 500 ppmw to 15 ppmw. This limitation would be phased in starting on June 1, 2006. In addition to the sulfur limit, the proposed rule revisions would make the following changes.

- Set a lubricity standard to alleviate any effects of reduced lubricating properties of fuels with the reduced sulfur content.
- Change the allowable limit for sulfur in fuels that are used to certify new diesel engines.
- Provide a set of fuel specifications that refiners could use as an alternative to 10%v aromatics limit without doing actual engine tests.
- Make various changes in the procedures that refiners use to certify an alternative fuel that satisfies the 10%v aromatics requirement.
- Adopt an airborne toxic control measure (ATCM) requiring that that this fuel be used in nonvehicular engines, except those used in locomotives and marine vessels.
- Make various changes in definitions and test methods and exempt the military from use of this diesel fuel.

These individual elements of the rule are discussed below.

Reduced sulfur content

The major purpose for the rule revisions is based on the need for very low sulfur fuel to allow future emission control technologies – such as catalytic particulate filters and NO_x adsorbers – for diesel engines. ARB and EPA expect these technologies to be used for

* The ARB regulations apply to all diesel-fueled motor vehicles as defined in section 415 of the state vehicle code; these are self-propelled devices “by which any person or property may be propelled, moved, or drawn upon a highway, excepting a device moved exclusively by human power or used exclusively upon stationary rails or tracks.”

diesel emission standards in 2007 and later; these engine emission standards are already required by ARB (and EPA) rules.

In addition to the use of these technologies for new engines, ARB also seeks the use of the catalytic particulate filters for retrofit applications as part of its plan for reducing the risk from exposure to diesel particulate matter from existing engines. This need for low-sulfur fuel in advanced engine emission control technologies has been noted for several years now and EPA promulgated a rule for low sulfur fuel at the same time as it promulgated a rule for the new engine standards for 2007. The explanation for this need is appropriately expressed in the staff report and is consistent with references cited in the staff report and other sources.

The proposed 15 ppmw sulfur limit will also provide a proportionate reduction in gaseous SO₂ emissions from diesel engines and a reduction in the sulfate formation in diesel exhaust.

Technology for producing 15 ppmw sulfur diesel fuel

The removal of sulfur from liquid and gaseous fuels has been long regarded as the most effective way to remove sulfur compounds from the exhaust of systems that burn such fuels. Technology for such sulfur removal processes also has a long history. It was initially developed to reduce sulfur content of refinery process streams to protect catalysts used in the refining process whose activity was reduced by sulfur. The basic process involves the addition of hydrogen to the fuel stream over a catalyst. The hydrogen reacts with the sulfur to form hydrogen sulfide, H₂S, which is then removed and treated to produce elemental sulfur. This basic process is known as hydrotreating, and variations of this process are in use or proposed for advanced use.

The application of sulfur removal to diesel fuel on a widespread basis is a more recent application of this technology. The current level of 500 ppmw was required in the South Coast Air Basin and Ventura County starting in 1985 and was required by California and federal regulations in 1993. Before these dates, the sulfur content of diesel fuel was limited by the specifications of the American Society for Testing and Materials (ASTM) to a level of 5000 ppmw, but was generally less than this level for highway diesel fuel. The production of diesel fuel with the low levels of sulfur required by the regulations proposed here (and similar EPA regulations) extends this technology beyond the current capacity of most refineries. The ARB staff report notes that some new technologies may be used to meet the 15 ppmw level, but this level can be met with existing technology.*

Additional background on the technology for producing 15 ppmw sulfur diesel fuel can be found in EPA regulatory documents. In the regulatory impact analysis for the EPA rule, the Agency noted the variability among refineries in the U.S. and the need to provide flexibility for individual refineries.⁷ Several comments to EPA's 15 ppmw sulfur

* The staff report notes that about 20% of the diesel fuel currently produced in California meets the 15 ppmw sulfur level.

requirement proposal noted that the lead time provided might not be sufficient for the development of alternative, lower-cost technologies to the expansion of conventional hydrotreating.⁸ Recent reviews by EPA⁹ and a subcommittee of the Clean Air Act Advisory Committee¹⁰ generally concluded that, for the national rule, the refining industry is making appropriate progress to produce 15 ppmw sulfur diesel fuel for highway engines in 2006. The review subcommittee report noted that some of its members raised issues about the ability of the refining industry to meet the national demand. EPA is planning one or more workshops to discuss various issues related to the fuel and engine standards for highway diesel.*

The situation for California refineries will be different from the national picture. California refineries have the 10%v aromatics limitation, which is not applicable nationally, and the current sulfur levels for California diesel fuel are less than the national average. The ARB staff report contains, in Appendix L, copies of two surveys that were sent to all California refineries that produce diesel fuel. No particular problems or concerns about achieving the 15 ppmw sulfur level are cited in the staff report. Although there are always questions about meeting future standards, some technologies for meeting the 15 ppmw sulfur level are well established and uncertainties in the application of these technologies are much less than the uncertainties about the vehicle emission control technologies required in the same time frame.

The production capacity and demand level for diesel fuel produced in California, taken from pages 86 and 87 of the ARB staff report, are shown in Table 1.

Table 1 – California Diesel Fuel Production and Capacity in 2007 (thousands of barrels per day)		
Fuel Type	Projected Production	Production Capacity
California Diesel	231	275
Federal Diesel	132	120
Total	363	395

This table shows that the expected total capacity is only 9% greater than the expected total production (which presumably is the demand). For California diesel, the capacity is 19% greater than the expected production. The production is described on page 86 as the production of on-road diesel. However, on page 110 the derivation of the 2007 production figure, 231 thousand bpd, is stated to be on-road and off-road diesel. As noted on page 110, the 2007 production data assume an increase of about 4% per year. If this rate of increase continues, the production would have to exceed the 2007 capacity by 2012.

* A workshop is currently scheduled for August 6-7, 2003 in Chicago. Information is available on the web site: <http://www.epa.gov/otaq/diesel.htm#engine-workshops>.

The report seems to indicate that there will be no problem with producing the required quantities of California diesel fuel; however two concerns come to mind: (1) this balance will only last a few years without additional refining capacity, and (2) the contradiction between the use of “on-road” on pages 86-87 and the description of “on-road and off-road” on page 110 should be clarified and expanded to include the production of diesel fuel for use in stationary and portable engines.

Cost of producing 15 ppmw sulfur diesel fuel

The technology required to produce diesel fuel meeting the low sulfur requirement, and the cost of meeting this requirement, will vary among individual refiners in the state. The costs of the proposed regulations are discussed in Chapter XVIII. The overall cost is estimated at 2 to 5 cents per gallon during the first year of production in which “temporary limitations on supply and production ... could result in potential first year costs of up to 1 cent per gallon.” In subsequent years, the cost estimate is between 2 and 4 cents per gallon. The largest component of this cost is the production cost, discussed below. The remaining components are distribution system costs, fuel economy penalty, and lubricity additives whose combined costs are estimated to range from 0.2 to 1.1 cents per gallon.

The average statewide cost of 2.2 to 2.7 cents per gallon to produce the 15 ppmw sulfur fuel is discussed on pages 110 and 111. This cost is based on the capital costs reported in the refiner surveys, which showed a total statewide capital cost between \$170 million and \$250 million. To arrive at a cost per gallon, the ARB staff has assumed that this capital cost will be amortized over a ten-year period at a rate of 7% per year. This produces a capital recovery factor of 0.1424. Differences in the rate and period assumptions made to compute this factor often lead to the most significant discrepancies in different cost estimates. For example, a decision to amortize the cost over a five-year period at a rate of 10% would produce a capital recovery factor of 0.2638; this would increase the annualized capital cost by 85%.

The statewide operating and maintenance costs from the proposed revisions are estimated to range from \$50 million to \$60 million per year. (This estimate is not consistent with a previous statement in the report that the annual O&M costs range from 10% to 20% of the initial capital expenditure; this percentage range would give annual O&M cost estimates of \$17 million to \$50 million.) The total annual cost, the sum of the annual O&M cost and the annualized capital cost, is divided by the 2007 production estimate of 3.5 billion gallons to give the cost range of 2.2 to 2.5 cents per gallon. Cost estimates for individual refineries range from zero to 11 cents per gallon.

Other cost estimates for production of 15 ppmw sulfur fuel are shown in Table XVIII-4 on page 115 of the staff report. Cost estimates prepared by the South Coast Air Quality Management District (as adjusted by ARB staff for consistency with their calculations) range from 1.3 to 3.5 cents per gallon. All other studies examined, which were based on the national rule that starts from a higher sulfur baseline, ranged from 4.2 to 6.8 cents per gallon. The February 2002 study by MathPro, which shows a cost of 5 to 8 cents per gallon, was based on refineries in one Petroleum Administration District for

Defense, PADD 4, which is expected to have the highest compliance costs for the national rule.

Cost estimations typically vary over a wide range and the differences between the cost estimates in the staff report and those in the other references cited are within the range of variability usually encountered for such estimates. The lower estimates for control costs in California, as compared to national data, are expected because California refineries are already producing lower sulfur diesel fuel. In summary, the cost estimates are reasonable ones, given the uncertainty in such estimates and the differences between California refineries and national refineries for which most of the other cost estimate data are prepared.

Lubricity requirement

The discussion of this topic in the staff report presents a good picture of the following elements for this proposed regulation:

- the requirements for lubricating properties of diesel fuel
- the need for a simple test that provides a measure of fuel lubricity
- the current bench-scale lubricity tests known as SLBOCLE (scuffing load ball-on-cylinder lubricity evaluator) and HFRR (high frequency reciprocating rig)
- the problems of finding an exact correlation among these two bench-scale tests and the more extensive (and expensive) wear tests
- the current voluntary standard in California for SLBOCLE level of 3,000 grams or higher
- the need for additional studies in this area and the plans of the Coordinating Research Council (CRC) for such studies
- the current ASTM ballot for an HFRR maximum wear standard of 520 μm .

The proposed requirement for a lubricity standard in the ARB regulations is different from the current approach in California that relies on refiners maintaining appropriate lubricity levels. It also differs from the approach proposed by EPA in its regulation for 15-ppmw sulfur highway diesel fuel. EPA recognized the need for diesel fuel lubricity during their rulemaking for low-sulfur, highway diesel fuel; however EPA decided not to set a standard. Instead, the Agency relied on refiners voluntarily producing fuels with appropriate lubricating properties to meet the needs of their customers.

The issue of setting a lubricity standard is more a policy issue than a technical issue. The staff proposal specifies the HFRR test with a maximum wear standard of 520 μm . This is the same as the one currently under consideration by the ASTM. Furthermore, the staff proposes two additional elements of the standard. The first is a reevaluation of data from subsequent studies to modify the standard for the 15 ppmw diesel fuel if required. The second element is to withdraw the standard if the ASTM adopts a lubricity standard. Such a standard for diesel fuel would be enforced in California by the

Department of Weights and Measures. This seems like a reasonable approach to including the lubricity standard in the emission regulations. The decision to include such a standard or to rely on a voluntary approach does not change the technical rationale; lower sulfur diesel fuels will have lower lubricity that will accelerate wear in diesel engine components that rely on the lubricating property of the fuel.

Other changes

A variety of other changes are proposed in the regulations. Some of these are administrative changes; others have technical implications. These proposed changes are discussed below.

Establishment of an alternative formulation that satisfies the 10%v aromatics standard

This is an extension of the existing provision that allows refiners to produce alternative fuel formulations, which achieve the same emissions reduction as a fuel that meets the 10%v aromatics standard. At present, the only way to qualify an alternative fuel formulation is to show by engine testing that the fuel has equivalent emission reductions. Under this proposed change, any fuel that has required levels of total aromatics, polycyclic aromatics, density, cetane number, nitrogen content and sulfur content shown in Table XI-3 on page 63 would be an acceptable diesel fuel. The various levels for these properties were determined by examining data on existing diesel fuels. This proposed change is a logical extension of the provisions for alternative diesel blends. The current provision requiring testing and the proposed new provision for an alternative fuel formulation recognize that properties of diesel fuels have significant interrelationships. Different fuel formulations, with different sets of properties, may achieve the same emission results.

The properties included in the proposed equivalency levels include those typically used to evaluate the effect of diesel fuels on emissions; in particular, the density (API gravity), total and polycyclic aromatic content and cetane number are commonly used to evaluate the impact of different fuel formulations on emissions. Since the proposed equivalency levels correspond to average properties for California diesel fuels, a fuel meeting all these levels should have equivalent emissions benefits. However, there is no demonstration that this will be the case. It is also interesting to note that only one of the five fuels shown in Table XI-1 would meet the equivalency limits. (This is a fuel that meets the requirements specified by executive order G-714-001; all others have a polycyclic aromatic content that is larger than the one specified in the proposed new equivalent limits.)

Modification of the criterion for accepting an alternative fuel formulation

The tests for alternative fuel formulations compare emissions from a reference fuel that meets the 10%v aromatics limitation and a proposed alternative fuel, known as the candidate fuel. The criterion for accepting the candidate fuel is that the mean emissions

for the candidate and reference fuel, \bar{x}_C and \bar{x}_R , respectively, satisfy the following inequality.

$$\bar{x}_C \leq \bar{x}_R + \delta - t_{0.15, 2n-2} S_P \sqrt{\frac{2}{n}} = \bar{x}_R (1 + \varepsilon) - t_{0.15, 2n-2} S_P \sqrt{\frac{2}{n}}$$

Here n is the number of tests for each fuel, S_P is the pooled standard deviation for the tests on the two fuels, and $t_{0.15, 2n-2}$ is the 15% percentage point of the t distribution for $2n - 2$ degrees of freedom. At least 40 tests – 20 on each fuel – are required. The $(1 + \varepsilon)$ term is designed to provide a margin of safety to the company proposing the candidate fuel. In the present regulation $\varepsilon = 2\%$ for NO_x, 4% for particulate matter (PM) and 12% for the soluble organic fraction (SOF) of particulate matter. The proposed regulations would cut these ε values in half (1% for NO_x, 2% for PM and 6% for SOF). This would reduce the cushion for qualifying the alternative fuel.

The proposed revisions to the allowed values of ε are based on an analysis of data reported for 335 tests conducted in the same laboratory on the fuels of 16 large refiners. The analysis evaluated the minimum values of ε that would be required to qualify the average fuel; these were 0.45% for NO_x, 1.2% for PM and 5.2% for SOF. The proposed maximum value of ε is 0.55 percentage points greater than this minimum for NO_x and 0.80 percentage points greater than the minimum for PM and SOF. (Expressed as a ratio, the proposed ε values are 2.2, 1.7, and 1.2 times the minimum values for NO_x, PM and SOF, respectively.) There is no analysis of how the proposed ε values were determined from the calculations. It would be interesting to show how many of the fuels that qualified with the previous ε values would not qualify with the new ones.

Reducing the allowed value of ε should reduce the possibility that alternative formulations with higher emissions would be approved. The approach of setting an allowed value of ε that is different for each species and related to the measurement error for each species is an appropriate approach. However, the quantitative effects of the proposed changes on emissions or on the likelihood of accepting a candidate fuel are not clear.

Airborne toxics control measure

The report recommends that the Board adopt an airborne toxics control measure (ATCM) that would require California diesel fuel to be burned in nonvehicular engines. Such a measure would require local air pollution control districts to place this requirement in their local rules. The combustion process in stationary and portable engines may differ from that in onroad and offroad engines, but the combustion process is similar enough to provide benefits from this fuel. Local districts often require the use of such fuel in stationary engines at present, at least in the specification of best available control technology for new engines. According to the staff report, most stationary diesel engines now use California diesel fuel because of the single fuel

distribution network. The effect of this proposed ATCM is to ensure that this continues in the future when local districts pass regulations requiring the use of retrofit equipment on stationary diesel engines.

Other changes not reviewed in detail

This section lists additional changes that are proposed and provides brief comments on those changes.

- The level of sulfur allowed in fuel, which is used to certify new engines to their emission standards, is adjusted to be consistent with the 15 ppmw sulfur requirement. This follows a longstanding practice of using certification fuels that match fuels used in the marketplace.
- Similarly, the level of sulfur in candidate and reference fuels, for alternative fuel formulations, is adjusted to be consistent with the new 15 ppmw sulfur limit.
- The sulfate credit, which was applied to alternative fuel formulations with sulfur levels less than 500 ppmw required by the current regulations is eliminated. With the new 15 ppmw sulfur level, this credit will be negligible and need not be considered.
- Additional property data on alternative fuel formulations is required to be reported. Since the emissions values of diesel fuels can depend on a range of interrelated properties, this change seems reasonable.
- Expand the reporting requirements for candidate fuels to include all the properties that must be reported for reference fuels, and require candidate fuels to have properties within certain ranges. This change is aimed at ensuring that all relevant properties of equivalent fuels are maintained in a range that produces low emissions. This change seems reasonable; however, there is no discussion of any problems that it may cause in actual production of the alternative fuel formulations.
- Eliminate the use of number one diesel fuel as a candidate fuel to allow production of number two diesel fuel. The staff's reasoning that number one diesel has better emissions performance is correct. However, this change may be redundant to the proposed changes in the property specifications for the candidate and reference fuels.
- The proposed change in the test method for sulfur to allow accurate measurements of lower sulfur levels is appropriate.
- The revision of definitions, miscellaneous wording changes, and the exemption for military operations do not appear to be technical issues and were not reviewed.

Environmental effects

Chapter XVII reviews the potential environmental effects of the proposal. The basic intent of the proposed revisions is to enable the use of advanced emission control systems on diesel engines, which would provide additional reductions in NO_x and PM emissions from those engines. In addition, some reductions in sulfur oxides would result from these revisions. Thus, the main effect of implementing the proposal is an environmental benefit. The environmental chapter examines possible side effects that would cause an environmental disbenefit.

The effect on water quality is analyzed by considering changes in the solubility that are likely to occur because of the production of lower sulfur diesel fuel. The report notes that such changes are expected to reduce the solubility of diesel fuel components in water and consequently there should be no deleterious impact on water quality. No water-quality effects have been noted since the change from high-sulfur fuels to the current statewide average level of 133 ppmw.

The report concludes that the proposed revisions “could have a small net effect on global warming.” Although the report considers emissions of methane (CH₄) and nitrous oxide (N₂O), most of the analysis is directed to changes in carbon dioxide (CO₂) emissions, since CO₂ accounts for over 99% of the greenhouse gas emissions from diesel-fueled transportation sources. The analysis concludes that the revisions to the regulation will result in a 0.012% increase in CO₂ emissions.

The analysis of CO₂ emissions was done by examining the increase in CO₂ emissions due to the production of the lower sulfur fuel. Because the hydrotreating to reduce sulfur alters the hydrogen/carbon ratio of the diesel fuel, there is a decrease in the CO₂ emissions, per unit of energy, from the combustion of the resulting fuel. The balance between these two processes is the net increase given above.

The calculations were not reviewed in detail. One item of concern is the natural gas composition used in the analysis: CH₄, C₂H₆, and CO₂ with molar concentrations of 77.5%, 16.0% and 6.5%, respectively. This natural gas composition is not typical of natural gases in California. In addition, the heat of combustion of 18,300 Btu/lb_m used for this natural gas composition does not appear to be correct.

The construction of new facilities to produce the 15 ppmw diesel fuel may cause environmental impacts. The report notes that such construction may be exempted from the need to obtain offsets, resulting in a permanent increases in emissions from stationary sources. Because of a lack of specific information in responses to the surveys sent to refiners, there is no quantitative discussion of these emission increases. On a regional basis, these increases, if any, should be less than the emission reductions from diesel engines that can be accomplished because of the use of the 15 ppmw diesel fuel. However, the potential increases in refinery emissions may be concentrated in local areas, raising concerns about ARB's environmental justice policies.

Summary

This review has considered the technical feasibility of the proposed changes to the regulations. Other items covered in the staff report, including the need for emission reductions, the health benefits of emission reductions, and impacts of the regulations on the California economy have not been reviewed here.

EFFECT OF CURRENT REGULATIONS

Appendix D of the staff report reviewed here contains a March 2003 draft report titled “Staff Review of the Emission Benefits of California’s Diesel Fuel Program.”^{*} The report concludes that the “predicted emission reductions associated with California diesel fuel averaged about 26 percent and six percent, respectively for PM and NOx.” The report also concluded that reductions in sulfur compounds were “estimated to be at least 95 percent.” This part of the review examines the basis for these conclusions.

Background

The predicted emission reductions are based on an analysis of several studies that have been made on the effects of diesel fuel properties on emissions. Table 6 of Appendix D lists the 35 studies considered in the staff estimate of benefits, showing that these studies used 300 different fuels with 73 different engines or engine configurations.

Over 50 of these engines had model years between 1991 and 1996. Most of these studies were also considered in the diesel fuel analysis conducted by EPA.^{4,5}

The formation of sulfur dioxide and sulfates by the combustion of the fuel sulfur is straightforward. Reductions in diesel sulfur will produce proportionate reductions in sulfur oxides in the exhaust. The influence of individual diesel fuel properties on other emissions is less clear. These effects come from the ways in which fuel properties influence different parts of the diesel combustion process: the fuel injection, the initial premixed burning, and the final diffusion burning phase. In theory, individual diesel fuel properties are expected to have the following effects on the combustion process.¹¹

- Higher ***cetane numbers*** reduce the ignition delay and the amount of time spent in the premixed burning phase. This reduces temperatures, which should reduce NOx emissions. Excessively high cetane numbers can increase PM.
- Fuel ***density*** and fuel ***viscosity*** influence the injection and mixing process. Reduced density is usually correlated with lower emissions.
- ***Aromatic content*** is expected to increase particulate matter whose atomic structure consists of aromatic rings. In addition, aromatic components, with their lower hydrogen to carbon ratio, produce higher temperatures for the same air/fuel equivalence ratios. Aromatic content is measured in terms of total aromatics or subdivided into ***monocyclic and polycyclic aromatics***.
- ***Distillation temperatures*** of the fuel can affect the evaporation and combustion of the fuel spray. (The temperatures at which 10%, 50% and 90% of the fuel evaporate are designated T10, T50, and T90.)
- Fuel ***sulfur*** can react to form particulate sulfate matter.

* In this section of the review all page numbers and table numbers without a specific document reference refer to the March 2003 “Staff Review of the Emission Benefits of California’s Diesel Fuel Program” contained in Appendix D of the June 6 staff report which is the subject of this overall review.

In the combustion of diesel fuel, all these properties interact to provide the final emissions level in a given engine. The interrelationship among properties of diesel fuel can be shown by consideration of the correlation among the different fuel properties. Table 2 below was developed by EPA to show this correlation for the fuels in its database.⁶ In these standardized correlation coefficients, a value of ± 1 indicates a perfect correlation and a value of zero shows no correlation. The data in Table 2 show that the aromatic content of the fuels in the database is strongly correlated with the specific gravity and with natural cetane. Because of these correlations, it is not possible to unambiguously assign a particular emissions effect to a particular fuel property.

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

The correlation among fuel properties can lead to different conclusions regarding the fuel property that has the most significant effect on emissions. The staff report of emission benefits in Appendix D has an appendix that gives a brief summary of each study considered. Here are three extracts from those summaries deliberately chosen to show the divergence in the conclusions of individual studies: For the EPEFE study, the summary states, in part, that “[f]uel density was the most influential property to reduce NOx.” The summary for SAE 932685 starts with the statement that “[i]ncreasing cetane number reduced NOx emissions whereas total aromatics content had no influence on NOx emissions.” The summary for SAE 932800 says that “[t]he results of this study clearly show that aromatic content is the dominant fuel property that can be used to reduce emissions.”

The collection of studies on the effects of diesel fuel properties on emissions raises an important question. How representative are these studies of actual in-use engines and fuels? Often special diesel fuel blends are used in these studies to minimize the correlation effects noted in Table 2. In addition, there are only limited data on (prototype) engines designed to operate with low NOx levels required by the 2004 standards. The further reductions required by the 2007 standards will be met by aftertreatment devices and their combustion behavior should be similar to those of 2004 engines. Thus, the effects of fuel properties on emissions should be similar for engines meeting either the 2004 or 2007 standards.

Reductions in sulfur compounds

The report does not explicitly show the calculation of the sulfur-oxide emission benefits. The estimated reduction of at least 95% is apparently based on data in Table 3, which shows that the sulfur content of diesel fuel (statewide average, except for the South Coast Air Basin and Ventura County) was 2800 ppmw before the current regulations and averaged 133 ppmw between 1995 and 2000 (after the regulations were implemented). This reduction from 2800 to 130 ppmw corresponds to a 95.4% reduction in fuel sulfur, which should translate to a similar reduction in sulfur compounds in the exhaust. This is apparently the basis for the conclusion that sulfur compound reductions are estimated to be at least 95%.

The calculation described above includes both the 1988 rulemaking, which required sulfur reductions statewide, and an earlier reduction, which required diesel sulfur reductions in the South Coast Air Basin and Ventura County. If the benefits of only the 1988 rulemaking are desired, it is necessary to find the fraction of fuel sales in the South Coast Air Basin and Ventura County, where the fuel sulfur limit was 500 ppmw, effective January 1, 1985. If the fraction of fuel sold in these areas is denoted as f and the measured average sulfur concentration in the diesel fuel sold in that area prior to the implementation of the 1998 regulation is designated as S_0 , the reductions attributable to the 1988 rule would be computed as follows.

$$\frac{(1-f)2800 + fS_0 - 133}{(1-f)2800 + fS_0}$$

This percent reduction will still be high. A guess that $f = 40\%$ and $S_0 = 500$ ppmw gives a percent reduction of 93%.

A third approach to evaluating the sulfur benefits of the rule is to compare the value of 330 ppmw for the average fuel sulfur (outside of California and Alaska) shown in Table 3, with the 130 ppmw value for California. This gives a reduction of 61% in sulfur when California diesel fuel is compared to current federal diesel fuel. All three approaches listed above are valid measures of the effect of the rule, provided that the basis for the comparison is made clear.

Analysis of reductions in NOx and PM

For NOx and PM, the overall approach is clear. The ARB staff reviewed previous studies that measured the effect of diesel fuel properties on emissions. Table 6 lists these studies, which used 300 different fuels and 73 different engines or engine configurations.* ARB staff developed statistical relationships to represent these data. They then applied these relationships to two sets of fuel properties: (1) the properties of diesel fuel in California before the implementation of the current regulations, and (2)

* These numbers are different from the numbers for test programs, engines, and fuels cited in the first paragraph on page 8 of Appendix D.

average fuel properties after regulation. The estimated benefits of the regulation are the differences in emissions predicted by the statistical relationships for these two cases.

Although the overall approach is clear, the details of the calculations used to determine the PM and NO_x benefits are limited. There are two separate calculations of the NO_x benefits, which are presented in Table 7 and Table 9. Table 7 also presents estimates of the PM reductions, which are not contained in Table 9. Table 7 is described as “a ‘mixed-modeling’ statistical analysis of the test programs” reviewed by the staff. Table 9 is described as an analysis of the “U. S. EPA Diesel Fuel Effects database” with regression coefficients estimated using an “approach similar to the one used in the [Heavy Duty Engine Working Group] HDEWG study.”

One of the differences between these two tables is the choice of variables used in the regression equation. For Table 7, almost all the regression equations use cetane number, sulfur, aromatics, distillation temperatures, and specific gravity as the regression variables.* The regression variables in Table 9 are cetane number, total aromatics, and specific gravity. There were also differences in the studies used in the two tables.†

Presumably, the results of the “‘mixed-modeling’ statistical analysis” used for Table 7 was one in which the fuel effects were treated as fixed effects and the effects of different engines were treated as random effects. This approach is commonly used in the analysis of fuel effects to account for differences in engines (which can often have a larger effect than differences in fuels). In addition, treating the engine as a random effect allows one to estimate the variance caused by different engines in the engine population from which the engines used in the study are taken.

The results in Table 9 are presented in terms of standardized regression coefficients. According to the description of the results in this table, ARB staff used “the log of the data” and a modeling “approach similar to the one used in the HDEWG study.” The HDEWG statistical analysis did not use log transformations. That study did various analyses to check for outliers, determine the significance of individual variables, and to see how well the results of the regression satisfied the assumptions for regression analysis.¹² There is no indication that similar data checks were done in the Table 9 analysis.

Because very little information is given about the details of the regression analyses that give the results in Tables 7 and 9, one can ask several questions about the way these were done. For example, were log transformations used for the emissions or fuel property variables? Were the fuel properties used directly in the equations or were they centered or normalized before the analysis? Were all three distillation temperatures used in the analyses? No values are given for the distillation temperatures in the before

* For one study (SAE 961974) the only variable was sulfur; for another study (SAE 1999-01-1117) distillation temperatures were not used in the regression.

†The following studies in Table 7 were not included in Table 9: SAE 1999-01-1117, SAE 1999-01-3606, SAE 790490, SAE 852078, and SAE 881173.

and after fuel properties; what values were used in the analysis? What was the significance level of the fuel-property regression coefficients in the various studies? What was done in the fuel property data that were not available for one study or for one or more fuels in a study? How were the data for repeat experiments on individual fuels and engines grouped for the final regression results on individual studies? How were the overall reductions determined from the data on individual studies? Were the data from the different studies weighted to account for the distribution of engines in the on-road fleet?

Because of all these questions, the ARB staff should post the data that they used, with a longer description of the exact methods, on the ARB web site so that they are publicly available for individuals to review and confirm the analyses.

A simplified analysis of two studies, ACEA and SAE 1999-01-1478, was done as part of this review, using the simple linear regression functions of Excel. The data were taken from the EPA database.¹³ Each study used only one engine and the regressions used only cetane number, specific gravity and aromatics content as the variables in the regression equation. These were the same values used by ARB staff in Table 9. The percent reductions in PM and NOx using these simplified analyses were determined by using the pre-1993 and 1995-2000 data in Table 3 of Appendix D as the before and after property data. Details of these calculations are contained in the appendix to this review and the results are shown in Table 3.

Table 3 – Comparison of Percent Reductions Computed Here with Values in Tables 7 and 9 of Staff Report Appendix D						
Study	Engine Model Year	NOx Reductions			PM Reductions	
		Computed	Table 7	Table 9	Computed	Table 7
ACEA	1991	3.1%	3.3%	5.0%	11.1%	43.4%
SAE 1999-01-1478	1993	5.5%	5.1%	5.4%	3.5%	3.9%
Note: The engines used in both studies were turbocharged, direct-injection Detroit Diesel engines with a displacement of 11.1 liters and a rated output of 330 HP.						

The agreement between the calculations here and those in Appendix D are reasonable for the estimated NOx reductions and the estimated PM reductions from the SAE 1999-01-1478 study. However, the estimated PM reductions from the ACEA study are not close to those shown in Table 7. The reason for this is not clear. ARB staff may have used data from the original study, which are different from those in the EPA database. Also, Table 7 states that distillation temperatures and sulfur were used in addition to cetane, aromatics and specific gravity as regression variables. This was not done here because the sulfur level and distillation temperature data were not available for all the data in the ACEA study.

Fuel effects in engines equipped with exhaust gas recirculation (EGR)

One of the issues not discussed in detail in Appendix D is the possible difference in the emission reductions of clean diesel fuel on engines that are equipped with EGR. In its consideration of the Texas low emission diesel (LED) fuel program, EPA allowed a 6.2% reduction in NO_x from engines without EGR and 4.8% for engines with EGR.¹⁴ These values are apparently based on the regression equations EPA developed and applied to its data for baseline national diesel fuel and California diesel fuel.⁵ (The coefficients in the EPA regression equation are shown in Table 8 of Appendix D.)

All the data used to develop the regression equations with EGR were obtained in two studies on a single engine, a Caterpillar 3176.^{*} The original engine was designed with emission controls to meet 1994 standards and was “considered state of the art for the 1994-1997 year models.”¹⁵ It was modified to include EGR to determine the fuel effects on a prototype engine for the 2004 emission standards. Both studies obtained data over the steady-state, eight-mode AVL cycle which has been shown to correlate with the transient test procedure for gaseous emissions, but not for particulate emissions.

In the HDEWG II study, fuel properties were controlled so that the effect of individual fuel properties could be determined. The following observations were made about the cetane response of the engine used in the study:¹⁵

- The overall conclusion was that the engine had a “very low sensitivity to cetane number . . . [that] differs from the results of similar experiments in engines that are not equipped with EGR.”
- Table 5 of the paper showed that the regression coefficient for NO_x with cetane had a small positive value whose p-value (level of significance) was 0.024.
- Figure 2 of the paper showed that an increase in cetane number from 42 to 52 would *increase* NO_x by 1.3%.

The paper reported data with and without EGR, but did not explicitly compare the effects of cetane on NO_x, with and without EGR. Table 4, below, is taken from Table 8 of the HDEWG statistical results paper.¹² The NO_x results in this table are the averages of the entries for two fuels with the same cetane number in the original paper. The fuels that have an N in their designation are natural cetane fuels that do not have any additized cetane. *E.g.*, fuels 16 and 16N are both reported as having a “target” cetane level of 52. The paper also analyzed the emission results from fuels with the same cetane number where one fuel had cetane improving additives and the other did not. This analysis showed that the effect of a natural cetane number could not be statistically distinguished from the effects of fuels where the same cetane number was produced by an additive to improve cetane. Thus, it is reasonable to compare fuels in this study with the same cetane numbers, regardless of how they are obtained.

* The study/engine combinations for this engine are noted in Table 9 of Appendix D as the HDEWG II study with the HDEWG EGR engine and the SAE 2000-01-2880 study with the 04 SWRI/CAT 10.3 engine.

Table 4 – HDEWG Data for Cetane NOx Effect With and Without EGR ⁸							
Fuels	Cetane	NOx data with EGR			NOx without EGR		
		g/bhp-hr	Percent change		g/bhp-hr	Percent change	
7N+14N	42	2.368	Per step	Initial to final	3.740	Per step	Initial to final
8+8N	47	2.415	2.0%		3.803	1.7%	
16+16N	52	2.346	-2.9%	-0.9%	3.684	-3.1%	-1.5%

The results of Table 4 show that the effect of cetane on NOx is similar with or without EGR, for the engine used in the study. In both cases, there is an increase of about 2% as the cetane number is increased from 42 to 47 and a decrease of about 3% as the cetane number is increased from 47 to 52. The overall effect of increasing the cetane number from 42 to 52 is a NOx decrease of 0.9% with EGR and a NOx decrease of 1.5% without EGR.

Table 4 shows that the effects of cetane on NOx for this engine are similar with and without EGR. Although the engine has a low sensitivity to cetane, it is likely that this effect is not due to EGR. Instead, it is due to some other differences between this engine and engines tested previously. The most likely explanation is that fuel injection controls on newer diesel engines have changed the combustion process to significantly reduce the amount of premixed combustion. The discussion of Figures 9 to 12 of the HDEWG test result paper states that “there is very little premixed burning....”¹⁵ Since the premixed burning phase of diesel combustion is the one that is affected by changes in cetane number, an engine that is designed to nearly eliminate this premixed-burning phase should have a low sensitivity to cetane. This hypothesis was also suggested in the other study that used this EGR engine.¹⁶

EPA’s cetane report⁶ analyzed the sensitivity of NOx reduction to change in cetane over model years from 1991 to 1998. The Agency wanted to determine whether this sensitivity decreased over time, indicating that newer engines might have less sensitivity to cetane because of their design. EPA found that there was a decrease in this sensitivity, but it was not statistically significant.

The ARB staff analysis of this engine in Appendix D, Table 9, shows that California diesel fuel should achieve NOx reductions of 5.6% from the data in the HDEWG II study and 7% for the data in the SAE 2000-01-2890 study. These data are similar to the results from other studies and no overall percent reduction was computed in Table 9. The EPA analysis, based on data for this engine and a comparison of national baseline fuel to California diesel determined that the NOx reduction was 4.8%.

One study not considered in the staff report or EPA database used an advanced light-duty engine developed as part of the government-industry partnership for a new generation of vehicles (PNGV) program.¹¹ This engine had both electronic injection and EGR. This study looked only at a few operating points, rather than a duty cycle, to improve understanding of emission reductions by fuel properties. The fuels used included California diesel and three other fuels that were designed to be cleaner than California diesel. The study concluded that additional reductions in NOx and PM were possible, in advanced engines for light-duty vehicles, by using cleaner diesel fuels.

Because of the lack of data on prototype engines designed to meet future emission standards, there are no firm conclusions about such engines. However, the data on a single heavy-duty engine indicate that future heavy-duty engines, with advanced fuel injection systems that reduce premixed burning or EGR, may provide less NO_x emission reduction from clean diesel fuel than engines in the current fleet.

Conclusions regarding NO_x and PM benefits

Despite all the difficulties with the technical analysis of the effect of fuel properties on exhaust emissions, all studies on this subject show that changes in diesel fuel properties can reduce emissions. Although different studies identify different variables as important and the quantitative results from such studies have a large variability, there is a general conclusion that reductions in aromatics and density and increases in cetane number can reduce emissions of NO_x and particulate matter.

The differences in NO_x reduction for the same studies that are shown in both Table 7 and Table 9 of Appendix D illustrate the problems associated with a quantitative determination of benefits. However, studies of diesel fuel impact on emissions, taken as a whole, show that appropriate fuel blends can reduce emissions, even if the exact relationship between fuel properties and emission reduction is not quantitatively known.

Limited data on one heavy-duty engine, developed as a prototype to meet the 2004 standards, indicate that future engines may have less NO_x reduction benefit than older engines.

CONCLUSIONS

The proposed regulation changes center on the reduction of sulfur in diesel fuel. The main reason for this regulation is to allow the use of advanced emission control technologies such as NO_x adsorbers and catalytic particulate traps on diesel engines. This regulation is consistent with current EPA regulations for 15 ppmw sulfur fuel in highway vehicles and proposed EPA regulations for such fuel in offroad engines. The major conclusions about the proposed revisions are summarized below.

- The proposed 15 ppmw sulfur diesel fuel is technologically feasible and is necessary to allow the use of advanced emission control technologies on diesel engines.
- The cost of the modifications will be a few cents per gallon of diesel fuel.
- The requirement for a lubricity standard is consistent with the need to provide good lubricating properties in low-sulfur diesel fuels. The choice to have such a standard in the regulations, as opposed to a voluntary program, is a policy question, not a technical question.
- The establishment of a specific set of fuel properties to define alternative fuel formulations without engine testing should provide similar emission reductions without the need for costly engine tests.
- The revised acceptance criterion for alternative fuel formulations should provide greater assurance that these formulations have lower emissions than the candidate fuels that comply with the 10%v aromatics standard.

This review also examined the draft staff report on the evaluation of the benefits from the current regulations contained in Appendix D of the staff report. This review drew the following major conclusions.

- The reduction in exhaust sulfur oxides is directly proportional to the concentration of sulfur in the diesel fuel. The percent reduction depends on the baseline used for the calculations.
- Reductions of other compounds, in particular NO_x and PM, are difficult to evaluate because of conflicting results of studies to measure the effects of fuel properties on these emissions. The differences in these results are often due to the strong correlation among diesel fuel properties, which makes it difficult to unambiguously assign emission reduction values to individual fuel properties.
- Despite the previous conclusion, published studies of the effect of diesel fuel properties on NO_x and PM emissions generally show that reductions in density and aromatics and increases in cetane number will reduce emissions of NO_x and PM. Other diesel fuel properties have been used in some studies to correlate emission reductions.
- Limited test results indicate that the effect of fuel properties on NO_x reductions may be less in future engines.

REFERENCES

- ¹ California Air Resources Board, "Proposed Amendments to the California Diesel Fuel Regulations Staff Report: Initial Statement of Reasons," June 6, 2003.
- ² *Federal Register* **66**, 5002–5193, January 18, 2001.
- ³ *Federal Register* **68**, 28328–28603, May 23, 2003.
- ⁴ Robert L. Mason and Janet P. Buckingham, "A Diesel Fuel Impact Model Data Analysis Plan Review, Draft Final Report, Work Assignment 2-7," EPA Contract 68-C-98-169, Southwest Research Institute, July 2001.
- ⁵ U. S. Environmental Protection Agency, "Strategies and Issues in Correlating Diesel Fuel Properties with Emissions," Staff Discussion Document EPA420-P-01-001, July 2001.
- ⁶ U. S. Environmental Protection Agency, "The Effect of Cetane Number Increase Due to Additives on NOx Emissions from Heavy-Duty Highway Engines," Final Technical Report EPA420-R-03-002, Office of Transportation and Air Quality, February, 2003.
- ⁷ U. S. Environmental Protection Agency, "Regulatory Impact Analysis: Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements," USEPA Office of Air and Radiation, Report EPA420-R-00-026, December 2000.
- ⁸ U. S. Environmental Protection Agency, "Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements: Response to Comments," USEPA Office of Transportation and Air Quality, Report EPA420-R-00-027, December 2000.
- ⁹ U. S. Environmental Protection Agency, "Highway Diesel Progress Review," USEPA Office of Transportation and Air Quality, Report EPA420-R-02-016, June 2002.
- ¹⁰ Clean Diesel Independent Review Subcommittee, "Final Report Meeting Technology Challenges for the 2007 Heavy-Duty Highway Diesel Rule," presented to the Clean Air Act Advisory Committee, Washington, D. C., October 30, 2002.
- ¹¹ Timothy P. Gardner, Scott S. Low, and Thomas E. Kenny, "Evaluation of Some Alternative Diesel Fuels for Low Emissions and Improved Fuel Economy," SAE Paper 2001-010149, presented at SAE World Congress, Detroit, Michigan, March 5-8, 2001.
- ¹² Robert L. Mason *et al.*, "EPA HDEWG Program – Statistical Analysis," SAE Paper 2000-01-1859, presented at International Spring Fuel and Lubricants Meeting, Paris, France, June 19-22, 2000.
- ¹³ This database is in the Excel file hdd-db7.xls, available at the EPA diesel-analysis web site, <http://www.epa.gov/otaq/models/analysis.htm>. This is version seven of the database, dated June 12, 2001, which contains all the repeat data and cycle data that EPA rejected in previous analyses.
- ¹⁴ Memorandum from Robert Larson, Acting Director, Transportation and Regional Programs to Karl Edlund, EPA Region VI, "Texas Low Emission Diesel (LED) Fuel Benefits," September 27, 2001.
- ¹⁵ Andrew C. Matheaus, *et al.*, "EPA HDEWG Program – Engine Tests Results," SAE Paper 2000-01-1858, presented at International Spring Fuel and Lubricants Meeting, Paris, France, June 19-22, 2000.

¹⁶ Ken Mitchell, "Effects of Fuel Properties and Source on Emissions from Five Different Heavy Duty Diesel Engines," Society of Automotive Engineers paper 2000-01-2890, presented at International Fall Fuels and Lubricants Meeting and Exposition, Baltimore, Maryland, October 16-19, 2000.

APPENDIX

The two spreadsheets shown in this appendix use a simple regression analysis of the data for two studies in the EPA database, using the linest function of Excel. Regression coefficients are computed for NO_x and PM emission rates (in g/bhp-hr) using cetane number, aromatics content and specific gravity as the regression variables. Once the regression coefficients are determined, the reduction in NO_x and PM emissions is computed by applying these coefficients to two different sets of diesel fuel properties. These fuel properties are the same ones used in the ARB staff analysis.

Regression Analysis of ACEA Data

Fuel	NOx	PM	Cetane	Aromatics	Sp grav	Repeats
EPD11	4.2283	0.1543	57.1	16.94	0.827	3
EPD6	4.259	0.1797	50.2	27.34	0.8555	3
EPD9	4.2568	0.1847	59.1	28.61	0.8554	3
RFCAL	4.1349	0.1673	49.9	12.913	0.8445	9
SC1	4.0647	0.1349	57.9	2.62	0.8144	3

Data taken from EPA data base; each repeat has identical data; this procedure was followed by EPA when original reference gave the number of repeat tests, but only average results instead of results for each test.

NOx regression

	Sp grav	Aromatics	Cetane	Intercept
Coefficients	-3.42779	0.01246884	-0.003628	7.045863
Coefficient Std. Errors	0.423619	0.00063059	0.0008789	0.3853
R2 / Std err	0.983932	0.00975491	#N/A	#N/A
F/ df	347.0025	17	#N/A	#N/A
sums of squares	0.09906	0.00161769	#N/A	#N/A
t value	-8.09169	19.7733748	-4.127825	18.28671
p(coeff = 0)	3.12E-07	3.6051E-13	0.0007031	1.29E-12

Calculate percent reduction from California Diesel

Property	Coefficient	Pre-reg	Post-reg
Intercept	7.0458633	1	1
Sp grav	-3.43E+00	0.856	0.837
Cetane	-3.63E-03	45	52
Aromatics	1.25E-02	36	22
Emissions (g/bhp-hr)		4.40	4.26
Percent NOx reduction			-3.1%

Particulate Regression

	Sp grav	Aromatics	Cetane	Intercept
Coefficients	1.005851	0.00024651	0.0003247	-0.70205
Coefficient Std. Errors	0.057788	8.6022E-05	0.0001199	0.052561
R2 / Std err	0.993883	0.00133072	#N/A	#N/A
F/ df	920.7458	17	#N/A	#N/A
sums of squares	0.004891	3.0104E-05	#N/A	#N/A
t value	17.40579	2.86570535	2.7084849	-13.3569
p(coeff = 0)	2.86E-12	0.01071272	0.0149085	1.92E-10

Calculate percent reduction from California Diesel

Property	Coefficient	Pre-reg	Post-reg
Intercept	-0.70204983	1	1
Sp grav	1.01E+00	0.856	0.837
Cetane	3.25E-04	45	52
Aromatics	2.47E-04	36	22
Emissions (g/bhp-hr)		0.18	0.16
Percent PM reduction			-11.1%

Regression analysis used linest function of Excel.

Before and after properties taken from Appendix D, Table 3, of June 6, 2003 ARB staff report on proposed new revisions to California Diesel Fuel regulations.

All "repeat" data (21 points total) used in the regression analysis.

Regression Results for 1999-01-1478 Study

Fuel	NOx	PM	Cetane	Aromatics	Sp Grav	Repeats
FUEL1	5.139	0.1421	39.7	43.4	0.86	16
FUEL1A	5.08	0.1369	42.1	43.4	0.86	4
FUEL1B	5.047	0.1349	43.2	43.4	0.86	4
FUEL1C	4.973	0.134	45.8	43.4	0.86	5
FUEL1D	4.92	0.1309	47.9	43.4	0.86	5
FUEL1E	4.918	0.1316	51.1	43.4	0.86	4
FUEL1F	5.096	0.1378	41.6	43.4	0.86	6
FUEL1G	5.047	0.138	42.5	43.4	0.86	6
FUEL1H	5.018	0.1341	45.7	43.4	0.86	6
FUEL1I	4.946	0.135	47.9	43.4	0.86	4
FUEL1J	4.883	0.1301	51.1	43.4	0.86	4
FUEL2	4.813	0.1351	46.3	29.2	0.849	17
FUEL2A	4.757	0.135	48.9	29.2	0.849	5
FUEL2B	4.733	0.1314	51.6	29.2	0.849	4
FUEL2C	4.738	0.1274	54.6	29.2	0.849	4
FUEL2D	4.713	0.126	59.1	29.2	0.849	4
FUEL2E	4.722	0.1255	60.5	29.2	0.849	4
FUEL2F	4.762	0.134	48.3	29.2	0.849	6
FUEL2G	4.783	0.1309	51.1	29.2	0.849	6
FUEL2H	4.752	0.128	54.9	29.2	0.849	4
FUEL2I	4.718	0.1297	58.4	29.2	0.849	4
FUEL2J	4.671	0.1263	61.2	29.2	0.849	4

Data taken from EPA data base; each repeat has identical data; this procedure was followed by EPA when original reference gave the number of repeat tests, but only average results instead of results for each test.

NOx Regression

	Sp grav	Aromatics	Cetane	Intercept
Coefficients	1.495378	0.011256	-0.012345	3.803826295
Coefficient Std. Errors	0	0	0.000727	0
R2 / Std err	0.941593	0.037601	#N/A	#N/A
F/ df	655.5996	122	#N/A	#N/A
sums of squares	2.780799	0.172492	#N/A	#N/A

Calculate percent NOx reduction from California Diesel

Property	Coefficient	Pre-reg	Post-reg
Intercept	3.803826	1	1
Sp grav	1.50E+00	0.856	0.837
Cetane	-1.23E-02	45	52
Aromatics	1.13E-02	36.00	22
Emissions (g/bhp-hr)		4.93	4.66
Percent NOx reduction			-5.5%

PM Regression

Property	Coefficient	Pre-reg	Post-reg
Intercept	0.134359	1	1
Sp grav	4.69E-02	0.856	0.837
Cetane	-7.66E-04	45	52
Aromatics	-1.02E-04	36.00	22
Emissions (g/bhp-hr)		0.136	0.131
Percent PM reduction			-3.5%

Calculate percent PM reduction from California Diesel

Property	Coefficient	Pre-reg	Post-reg
Intercept	0.134359	1	1
Sp grav	4.69E-02	0.856	0.837
Cetane	-7.66E-04	45	52
Aromatics	-1.02E-04	36.00	22
Emissions (g/bhp-hr)		0.136	0.131
Percent PM reduction			-3.5%

Regression analysis used linest function of Excel.

Before and after properties taken from Appendix D, Table 3, of June 6, 2003 ARB staff report on proposed new revisions to California Diesel Fuel regulations.

All repeat data (126 data points total) used in regression calculations.

Proposed Diesel Sulfur Regulations and Emission Benefits of Current Regulations

Scientific Peer Review

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Introduction

This is a review for the California Air Resources Board proposed changes and additions to regulations for the California reformulated diesel fuel. This review is prepared under Interagency Agreement #98-004 between the University of California and the California Environmental Protection Agency.

This review covers the document titled "*Proposed Amendments to the California Diesel Fuel Regulations, Staff Report: Initial Statement of Reasons*" dated June 6, 2003. In addition, I reviewed some of the additional references provided by the Air Resources Board, as well as the comment and reviews of the Western States Petroleum Association, Prof. Robert Sawyer of UC Berkeley, and Prof. Lawrence Caretto of California State University, Northridge.

Proposed Revisions

The Staff of the Air Resources Board is proposing amendments to the California diesel fuel regulations. These major changes proposed would:

1. Reduce the sulfur content limit from 500 ppmw to 15 ppmw for diesel fuel sold in California for use in on-road and off-road motor vehicles starting in mid-2006.
2. Adopt an Air Toxics Control Measure to require the use of vehicular diesel fuel in all nonvehicular diesel engines.
3. Revise the sulfur specifications for diesel certification fuel used to determine whether diesel engines comply with heavy-duty diesel emission standards.
4. Revise the requirements for certification of alternative diesel formulations to require 15 ppmw sulfur limits for candidate and reference fuels.
5. Establish additional requirements for certification of alternative diesel formulations to ensure that the fuels produced under the alternative formulation has comparable emissions performance to the candidate fuel.
6. Adopt new specifications for equivalency to the aromatic hydrocarbon limit for diesel fuel to provide another compliance option.
7. Adopt standards for diesel fuel lubricity.
8. Make other changes, including improvements to the sulfur test method and a revision of the definition of diesel fuel, to ensure that regulation works effectively.

Review of *Proposed Amendments to the California Diesel Fuel Regulations, Staff Report: Initial Statement of Reasons*, dated June 6, 2003.

Specific Comments relating to proposed amendments:

1. Reduce the sulfur content limit from 500 ppmw to 15 ppmw for diesel fuel sold in California for use in on-road and off-road motor vehicles starting in mid-2006.

The U.S. Environmental Protection Agency will impose a 15 ppmw sulfur limit on diesel fuel in 2006. The main reason for this standard is to protect the emissions controls that are most likely to be used for diesel engines to meet the 2007-2010 heavy duty emission standards and the 2007 light duty emission standards. These systems will be catalyzed diesel particle filter, NO_x after-treatment, and other advanced after-treatments.

The need for low sulfur fuel for these systems is reviewed in the staff report and is reasonable. The effect of higher sulfur levels on these systems is shown to be detrimental. In addition, there is a direct effect on particle emissions due to reduced sulfate and other sulfur derived emissions, such as sulfur dioxide. There is considerable evidence both from the U.S. EPA and California that lower sulfur levels are needed, and that setting the level at 15 ppm, the same as the federal standard, is appropriate.

The alternative of even lower sulfur standards was addressed. For the exhaust technologies, lower sulfur levels are not cost-effective, but newer treatment methods may require even lower sulfur levels. A zero sulfur level diesel fuel may be desirable in the future, and the ARB should continue to consider this as a future alternative.

2. Adopt an Air Toxics Control Measure to require the use of vehicular diesel fuel in all nonvehicular diesel engines.

The rationale for adopting this standard for both on-road and off-road vehicles is sound. Without new regulations, the EPA 15 ppmw standard will apply, but only to on-road diesel fuel use. The SCAQMD 15 ppmw standard applies to on-road, off-road, and stationary engines, but it is limited in that the standard is not state-wide, which is necessary if for retrofitting older engines as well as new engines requiring advanced exhaust treatment. Off-road diesel PM emissions are larger than on-road emissions, so including these engines is important.

The amendment would require the same diesel fuel to be burned in nonvehicular engines. This should produce benefits in reduced emissions from stationary engines. As noted in the report, most diesel engines in California already use the same fuel since the state has

a single fuel distribution system. This change would ensure that the benefits obtained from the lower sulfur fuels are maintained.

As noted in the report, U.S. EPA regulations are needed to reduce emissions from locomotives, aircraft, heavy-duty vehicles used in interstate commerce, and other sources that are preempted from state control. The ARB should continue to work with the EPA and others to develop control measures for these engines.

3. Revise the sulfur specifications for diesel certification fuel used to determine whether diesel engines comply with heavy-duty diesel emission standards.

It makes sense to have a certification fuel with similar properties to the fuels that will be used in heavy-duty diesel engines. The lower sulfur levels in the certification fuels will also allow the use of both NO_x and PM aftertreatment devices.

4. Revise the requirements for certification of alternative diesel formulations to require 15 ppmw sulfur limits for candidate and reference fuels.

5. Establish additional requirements for certification of alternative diesel formulations to ensure that the fuels produced under the alternative formulation has comparable emissions performance to the candidate fuel.

Consistency with the sulfur standard in Section 2281.

Having the same 15 ppmw sulfur limit for both the reference and candidate fuels is appropriate.

Emission equivalency of candidate fuels to in-use fuels

This would ensure that future candidate fuels tested in the laboratory are fully characterized. The action is appropriate.

Emission equivalency of candidate fuels to reference fuels.

This would tighten the tolerances allowed for each pollutant. The new values are based on 16 fuels tested in the same laboratory, and are reasonable.

Elimination of the sulfate credit

The elimination of the sulfate credit is reasonable, as the 15ppmw limit makes difference between the sulfur levels in the reference and candidate fuels insignificant.

6. Adopt new specifications for equivalency to the aromatic hydrocarbon limit for diesel fuel to provide another compliance option.

The adoption of alternative compliance options that provides equivalent environmental benefits to the 10% aromatics hydrocarbon limit is a good proposal. Allowing different formulations that meet and retain equivalent environmental benefits is reasonable, as the emissions from fuels are key factors here, not the composition of the fuel.

Regarding the new fuel specifications for equivalency to the aromatic hydrocarbon limit, these comments are directed at Appendix D (*Staff Review of the Emission Benefits of California's Diesel Fuel Program*, with a date of March, 2003), Appendix E (*Staff Analysis of Future Emission Benefits of California's Diesel Fuel Program*), and Appendix.F (*Effects of Changes in Diesel Fuel Properties on Emissions*).

As noted by the other reviewers, there are considerable problems in determining the effects of individual fuel parameters when these parameters are interrelated. I agree with the conclusions of Profs. Sawyer and Caretto that the interdependence of fuel parameters such as aromatics, specific gravity, and Cetane number make it difficult to quantify the effect of varying a single property.

This being said, there is considerable evidence from the 31 studies reviewed that emissions of NO_x and PM are reduced when sulfur and aromatics are limited. As noted in the report, the HDEWG model may have limited applicability, since the data is from one engine operating in one configuration, and no PM measurements were made. These studies used a variety of fuels and engines. However, the vast majority of the engines are 1996 model year or earlier. The addition of new engines and engines retrofitted with advanced exhaust treatment systems is another factor that has a large uncertainty that is not clearly covered.

7. Adopt standards for diesel fuel lubricity

Lower sulfur levels will reduce the lubricity of diesel fuel as a result of severe hydrotreating refiners are expected to use to meet the new standards.

There are currently no government or industry standards in the U.S. controlling diesel fuel lubricity. In California, there is a voluntary minimum lubricity level of a Scuffing Load Ball-on-Cylinder- Lubricity Evaluator (SLBCOCLE) scuffing load of 3,000 grams or higher. The U.S. EPA allows industry and the market to address the lubricity issue in the most economical manner. The ASTM has not been able to agree on a lubricity standard nor a testing method. However, other agencies in Canada and Europe have adopted lubricity standards.

While it appears that lubricity additives will be used by refiners, the nature of the additive is not specified. If the ARB wants to specify a lubricity standard, they might want to also ban certain types of additives, such as acidic additives that can form harmful salts.

Change in the fuel specifications can produce concerns that engine or engine parts failures are due to the different fuels, with accompanying costs due to legal actions. The adoption of a standard may reduce these concerns, but it is not clear that this is an emissions issue. In the report, there is a discussion of the pump wear data, and results are presented in Appendix G. There is a statement on page 73 that “ fuels with insufficient lubricity contribute to excessive wear that results in reduced equipment life and performance. Excessive wear in these systems is also expected to increase emissions due to compromised pump performance.” While that is a reasonable conclusion to reach, there are no references or test data given to support that statement.

In light of the lack of U.S. standards, it might be better to allow the industry to continue with the current practice, and wait until a consensus is reached by ASTM, as suggested as an alternative in the staff report. This would also bring the California regulations more into alignment with the U.S. standards.

8. Make other changes, including improvements to the sulfur test method and a revision of the definition of diesel fuel, to ensure that regulation works effectively.

Test method for sulfur

The staff proposes to change the method for determining the sulfur content of diesel fuel. Current regulations require that sulfur in diesel fuel be determined by ASTM D2622-94 (x-ray spectrometry). As the current method doesn't not have the sensitivity or precision needed to measure sulfur at levels of 15 ppmw, another method is required. The method proposed (ultraviolet fluorescence, D5453-93) is reasonable, and it has been used in similar fuels with lower sulfur levels.

Definition of diesel fuel

The definition of a diesel fuel as any predominantly hydrocarbon liquid fuel without specifying or clarifying what “predominantly” means can be a problem for diesel fuels that might contain significant amounts of a non-hydrocarbon, such as oxygenated species. However, if oxygenated fuels are considered, then additional problems with other issues such as water quality (some oxygenated compounds are soluble in water) and the cost of producing these fuels would change.

Other comments:

In Section V, Health Benefits Of Diesel Emissions Reductions (page 27), the complexity of the chemical composition is mentioned, but there is little discussion of the effects of particle size on health, especially the role of ultrafine particles. While 94% of the mass of diesel particles are contained in particles smaller than 2.5 microns, diesel particles produced by modern engines are better characterized by sizes in the hundreds of nanometers and smaller. Reducing the sulfur content should reduce the formation of particles formed from the condensation of sulfuric acid, but their role in the health effects is unclear.

Potential Cancer Risk

The discussion on page 25 assumes that a reduction in diesel PM will lead to a proportional reduction in cancer risk. Some caution should be taken here since the changes proposed here will certainly not only change the mass of diesel PM, but will probably change the chemical composition of the resulting particles, and it is not clear that all of the possible carcinogenic compounds in the exhaust will be reduced by the same fraction.

Overall costs of the proposed amendments

The ARB staff estimates that the costs of reducing the sulfur content of diesel fuel and adding required lubricity additives as between 2 and 4 cents per gallon of diesel. It is noted, but not emphasized, that most of the costs to refiners would occur as a result of adopted U.S. EPA and SCAQMD regulations. The real cost of the amendments is thus the cost of extending the regulations to the 25% of the total diesel fuel consumed by off-road diesel vehicles outside the SCAQMD. Staff estimates that as much as 90% of the cost can be attributed to the other regulations. The real cost of the proposed changes thus appears to be 0.2 to 0.4 cents per gallon of diesel fuel.

Water Quality

The assessment in Appendix K concludes that there would be no impacts on ground water associated with proposed low-sulfur diesel fuel. This is correct for the hydrocarbon portion of the fuel. However, the proposed redefining of “diesel fuel” to be any mixture of primarily liquid hydrocarbons raises the issue of the impact of non-hydrocarbon compounds, such as oxygenated compounds, that could be more water soluble. The effects of oxygenates in gasoline has been studied by the ARB previously, and could be cited here. The report also states that alternative diesel fuels generally contain more than tract amounts of oxygenated fuel constituents or are emulsified with water.

Diesel Engine Lubrication Oils

As the emissions from burning diesel fuel decrease, the fraction of the emissions that arise from lubricating oils can increase. There are two ongoing research efforts that are examining the impact of lubricating oils and oil additives on emissions and emission control devices. Preliminary results from Advanced Petroleum-Based Fuels Program Diesel Emission Control- Sulfur Effects (APBF – DECSE) suggest that some oil formulations produce higher levels of sulfur emissions. These results are an indication that staff needs to follow and support this and related work, especially in the effects of oils and oil additives on advanced aftertreatment technologies.

**Review of
California Environmental Protection Agency
California Air Resources Board**

**PROPOSED AMENDMENTS TO THE CALIFORNIA
DIESEL FUEL REGULATIONS**

***STAFF REPORT: INITIAL STATEMENT OF REASONS
March 28, 2002***

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OVERVIEW

This is one of four independent peer reviews provided on the staff of the Air Resources Board proposed changes and additions to regulations for California reformulated diesel including a new standard for lubricity. These reviews are prepared under Interagency Agreement #98-004 between the University of California and the California Environmental Protection Agency, the California Air Resources Board (ARB). This review also treats the ARB staff assessment of the emissions reductions associated with the current California Reformulated Diesel regulations, which were adopted in 1988 and became effective in 1993. Some, but not all, of the provided additional references and references cited in the report also have been reviewed.

MAJOR REVIEW CONCLUSIONS

The staff report provides a justification for the need for new diesel fuel regulations and a convincing assessment of the effect of the new regulations on the reduction of emissions that is consistent with the currently available technical data. The three most important issues that would benefit from additional attention are:

- 1) *The role oxygenate additives in diesel fuel formulation; the impact of the regulations on oxygenate additives; the distinction among diesel, alternative diesel fuels, and their blends; and the impact of all of these on emissions needs further clarification and exposition.*

- 2) *The adequacy of the equivalency specification to provide comparable or better emissions reductions across the range of diesel engine applications is questioned because its derivation is not clearly explained and that data set upon which it is based is judged inadequate.*

3) *The accuracy of relating the lung cancer health benefits from reformulation to particulate mass reduction when reformulation is likely to have greater or lesser effect on reducing the specific carcinogenic compounds is questioned.*

4) *The lubricity standard may not be needed. It might be better policy to leave responsibility for adequate lubricity with the refiners, where it is now.*

Discussion of these issues appears in more detail in the following text.

Additional recommendations dealing with other issues also follow in the more detailed review of each section of the report.

REVIEW

The details of my review follow the structure of the staff document: *Proposed Amendments to the California Diesel Fuel Regulations, Staff Report: Initial Statement of Reasons*, dated June 6, 2003

I. INTRODUCTION AND SUMMARY

This section provides an appropriate and concise overview of the need for and nature of the proposed regulation.

The current diesel fuel regulation applies to on-road fuel consumption, limits sulfur to 500 ppmw, and limits aromatics to 10% with an exception to 20% for small refiners and an equivalency alternative based on demonstration for large refiners. Most refiners use the equivalency alternative and produce diesel fuels with more than 10% aromatics.

The proposed diesel fuel regulation applies to both on-road and off-road fuel consumption (but excludes diesel fuels used exclusively in locomotive or marine engines), drops

the sulfur limit to 15 ppmw and retains the nominal limit on aromatics of 10% but specifies equivalency limits that allow refiners alternatives to meeting the aromatic limit. Additionally, the new regulations propose a new lubricity standard, new requirements for certifying alternative formulations, a new (emissions) certification fuel, a new sulfur test method, and an exemption for qualifying military vehicles.

The primary reason to reduce sulfur is to enable the exhaust emissions control technology (catalyzed traps for particulate control and NO_x adsorbers for NO_x control) that are likely to be applied for diesels to meet the 2007-2010 heavy duty emissions standards and 2007 light duty emission standards. Since the U.S. Environmental Protection Agency will impose a 15 ppmw sulfur limit on diesel fuel during 2006, the other fuel specifications, applications, and procedures are additional to the EPA requirements and are the items of primary importance. The ARB staff correctly believes that requirements additional to those of the EPA are essential to providing the additional emissions reductions needed to meet California air quality goals. Extending the fuel requirement to off-road applications will provide emissions reductions from existing engines and enable the application of on-road emissions control to the off-road engines. The other changes are largely procedural and primarily designed to ease implementation, improve the effectiveness of implementation, and to provide additional flexibility. They primarily retain the emissions reductions of the current fuel rather than provide additional emissions reductions.

II. RECOMMENDATIONS

This section succinctly lists the eight primary recommended board actions. The first two, reducing sulfur to 15 ppmw and extending application of reformulated diesel to most diesel applications, but not locomotive and marine engines, are the primary actions. The remaining six are primarily procedural—but some difficulties may be associated with these details.

III. BACKGROUND

The factual description of diesel fuels and engines and their use and application in California is complete. The emission inventory estimates are reasonable but contain the uncertainties inherent to the EMFAC model from which they are produced. The dependency of emissions upon fuel properties is complex with many of the properties interdependent, which makes associating emissions dependence upon single fuel parameters difficult. This will be discussed more in Section IX.

IV. NEED FOR EMISSIONS REDUCTION

The need for further diesel emissions reductions is tied by the staff report to both criteria (ozone, carbon monoxide, and particulate matter) and toxics. Diesels are small contributors to the VOCs and CO inventory. Fuel reformulation has a small effect on the emissions of VOCs and CO and an even smaller effect on the inventory. Therefore the focus should be on NO_x, PM, and toxics.

Since the NO₂ air quality standard is met statewide, it is the role NO_x in the production of ozone and nitrate particulates that is of interest. The discussion of diesel NO_x and ozone ignores the increased understanding that much of the state is and is becoming hydrocarbon limited. In some areas additional NO_x reduction will make attainment of ozone standards more difficult, that is, will require even greater VOC reduction. Additionally, Figure IV-1 would benefit from some clarification. I believe that this figure is for the 1-hour ozone standard and should be so stated. Mention of the 8-hr ozone standard and its implication to California should be made. Also, the designations are by air basins whereas presenting the maps by counties, while correct in a regulatory context, gives the wrong implication for the air quality of various regions of the state.

The pending PM_{2.5} designations and the increased relative contribution and importance of diesel particulate emissions should be mentioned.

The uncertainty in predicting risk of death from lung cancer from diesel particulate exposure is high. While reporting such risks, Table IV-1, may be useful in supporting regulations, it is improper to do so without quantifying or at least mentioning the uncertainty.

V. HEALTH BENEFITS OF DIESEL EMISSIONS REDUCTIONS

The discussion of diesel particulate health effects (page 28) lacks any explicit mention of ultrafines and the increasing understanding of the mechanism of their adverse health effects, and increasing concerns. The known relation between fuel properties and particulate emissions is primarily for particulate as PM₁₀ or TPM, Data are largely lacking, but needed, that relate fuel properties to PM_{0.1}. Reducing sulfur content will reduce ultrafine, some of which result from the condensation of sulfuric acid.

VI. EXISTING DIESEL FUEL REGULATIONS

The summary and discussion of diesel fuel regulations is clear and useful.

VII. PM RISK REDUCTION ACTIVITIES

This section provides a factual accounting of diesel PM reduction activities in the state.

VIII. PROPOSED AMENDMENTS TO SULFUR STANDARD FOR CALIFORNIA DIESEL

The statement (page 42) that current sulfur levels prevent effective operating of NO_x control technology is not strictly true if the possibility of selective catalytic reduction (SCR) is included. I agree that NO_x adsorption control technology is preferable and likely. However, this technology is not fully demonstrated and the competing SCR technology is seeing widespread application in Europe. There should be some mention of SCR and assessment of its sulfur tolerance.

IX. PROPOSED AMENDMENTS TO THE DIESEL ENGINE CERTIFICATION FUEL REGULATION

Changing the fuel used to certify new engines beginning in 2007 to reflect the 2006 reformulated diesel fuel (RFD-2006) is appropriate. The properties specified in Table IX-1 (page 49) are reasonable and appropriate.

X. PROPOSED AMENDMENTS TO REGULATORY PROVISIONS ON CERTIFIED ALTERNATIVE DIESEL FUEL FORMULATION

The concept of an alternative diesel fuel formulation that has properties constrained by those of a “candidate fuel” shown to yield emissions less than or equal to those of the “reference fuel”) is established to provide refiner flexibility while retaining emissions reductions. One issue that is not made clear in the staff report is just how emissions equivalency is to be demonstrated beginning in 2007 when on-road engines with new aftertreatment systems start to appear and the use of RFD-2006 in off-road engines begins. Ideally emissions equivalency would be obtained and demonstrated across the range of applications. Practically, emissions equivalency demonstration is important for three categories of engines, 1) pre-2007 on-road heavy-duty engines, 2) 2007 and later on-road heavy-duty engines, and 3) off-road engines. Essentially all of the data relating emissions to fuel properties are for pre-2002 on-road heavy-duty engines. Presumably the details of working out just how emissions equivalency is to be demonstrated is left to the staff and approval of the ARB Executive Officer. This issue needs to be addressed.

Tightening test tolerances and the elimination of the sulfate credit are appropriate actions.

XI. PROPOSED NEW FUEL SPECIFICATIONS FOR EQUIVALENCY TO THE AROMATIC HYDROCARBON LIMIT

In addition to providing for the sale of alternative fuel formulations by demonstration through test of equivalent emissions reductions, a general equivalency to the aromatic hydrocarbon limit is proposed that places limits on five fuel properties (aromatic content, PAH content, API gravity, Cetane Number, and Nitrogen Content) as specified in Table XI-3. The absolute 15 ppmw sulfur limit, of course, also applies to the alternative fuel. This equivalent limit specification is a key element of the proposed RFD-2006 regulation. Confidence that any fuel within these equivalent limits provides equivalent emissions reductions to the reference fuel derives from data summarized in the report *Staff Review of the Emissions Benefits of California's Diesel Fuel Program*, March 2003 (Draft) presented in Appendix D. While the data base is greatly expanded beyond that available at the time the original California RFD regulations were adopted (and reassuringly confirms the originally estimated emissions reductions) it is dominated by 1998 and earlier on-road diesels with a few tests of 2004 prototype on-road diesels. There is little off-road engine emissions data and, of course, no data from 2007 on-road diesel technology.

How the equivalent limits for the five properties were derived from the emissions data base is not clear. The first four properties are interdependent and most of the tests were not designed to extract the effect the change of a single property. The effect of Cetane Number can be examined over a limited range through the use of Cetane Number improver additive. The effect of fifth property, nitrogen content, which in practice is primarily associated with the Cetane Number improver additive, can also be varied independently of other fuel properties. It is impossible to assure that all fuels within the specified equivalent limits would match or exceed the emissions reductions of the reference fuel. Additionally, there is no basis for confidence that the emissions reductions also apply to off-road diesel engines or to 2007 and later on-road diesel technology. Note that the 2007 and later issue is not of practical significance since the emissions should be so low that fuel effects for this segment will have a minor effect on the inventory.

There is some evidence for concern that the data used by the ARB to establish fuel property—emissions relations are not applicable to off-road engine and duty cycles. The EPA report *Strategies and Issues in Correlating Diesel Fuel Properties with Emissions—Staff Discussion Document*, EPA420-P-01-00, July 2001, which is based largely on non-road diesel

engines, shows a lower impact of CFD on particulate mater reduction that reported by the ARB which is based largely on on-road diesel engine tests.

XII. PROPOSED REGULATION ESTABLISHING A DIESEL FUEL LUBRICITY STANDARD

The basic issue of a lubricity standard is whether or not it is needed. The alternative is to trust that the refiners as part of their product quality control and customer satisfaction concerns would assure an adequate level of lubricity in their product. Since the heavy hydrodesulphurization necessary for sulfur reduction is likely to reduce lubricity there is a potential for a problem if corrective action were not taken by refiners. A secondary issue is whether the proposed test, the High Frequency Reciprocating Rig test (ASTM standard D6079-02) and wear scar diameter limit of 520 microns is appropriately protective, or even the right test. Since level of protection provided by the proposed lubricity standard approximates the industry's current voluntary standard, the practical impact may be negligible. By adopting such a standard will the ARB be assuming responsibility for a quality control issue that is properly the responsibility of the refining industry?

XIII. OTHER PROPOSED AMMENDMENTS TO THE DIESEL FUEL REGULATIONS

The need to switch to a more sensitive test for fuel sulfur is certain. The proposed ultraviolet fluorescence method, ASTM D5453-93 is appropriate.

The proposed definition of diesel fuel is not clearly stated. This is a much bigger issue than might at first be perceived or than is indicated by the very limited discussion. One might argue that any fuel used in a compression ignition engine is a diesel fuel. The ARB does not intend that this regulations should apply to alternative diesel fuels (note that the word "alternative" is used in two different contexts: first as in an alternative formulation of conventional diesel and second as in an alternative to conventional diesel. Unfortunately the

distinction between diesel fuels and alternative diesel fuels is vague, especially when it comes to blends of alternative and petroleum based diesel fuels. The description “any liquid fuel that is predominantly a mixture of hydrocarbons” leaves uncertainties about the inclusion of biodiesel, esters of biodiesel, and their blends with petroleum diesel and/or liquid diesel fuels derived from natural gas, coal, or biofeedstocks. The addition of a variety of oxygenates to diesel is an effective way to reduce particulate emissions and this possibility should not be eliminated or discouraged by the definition of diesel fuel or the specifications.

XIV. FEASIBILITY OF REFINING LOW SULFUR DIESEL FUEL

The discussion of refining options confirms that adequate technology exists to provide low sulfur reformulated diesel fuel. This technology either already exists at California refineries or can be acquired.

XV. POTENTIAL IMPACTS OF THE PROPOSED SPECIFICATION ON THE PRODUCTION OF DIESEL FUEL BY CALIFORNIA REFINERIES

The ARB review identifies no barriers to providing the required diesel fuel. Since similar low sulfur on-road diesel fuels will be required nationally at the same time, differences between California and Federal reformulated diesel fuels will be small. The ARB may want to consider allowing the temporary use of diesel fuel meeting Federal specifications should an unforeseen shortage arise.

XVI. OTHER ISSUES

Exemptions for small refiners have always been a problematic but expedient policy. While exemption from the aromatic content limits is not a big deal, exemption from the sulfur limit is because of its affect on aftertreatment technology, including both increased emissions

and possible damage to emissions control equipment. The ARB may want to consider as a possible relief measure, if necessary, the diversion of diesel fuel with greater than 15 ppmw sulfur to off-road applications where new exhaust aftertreatment technology has not been applied.

The role of lubricant and concern for sulfur and additives on emissions is outlined in the report. This issue is being studied and understanding improved. The ARB should commit to participating in these studies and working for the national adoption of lubricant standards, if necessary, to treat emission system and emission effects.

A description of biodiesel fuels is provided. It might be noted that Fischer-Tropsch diesel can be derived from coal, biowastes, cellulose, and other feedstocks—not only natural gas. Again, it is not clearly stated that alternative diesel fuels are to be excluded from this regulation and, if so, what level of blending divides alternative diesel fuels from the regulated diesel fuels. This issue needs to be clarified least the use of biodiesel, biodiesel-diesel blends, oxygenate additives, and other “unconventional” diesel fuels that have emissions reduction and renewable advantages be excluded by this regulation.

It is reassuring that similar low sulfur diesel reformulation is occurring internationally. The report does not discuss the future possibility of a zero sulfur diesel fuel as called for in the World-Wide Fuel Charter. If and how the ARB will address this issue in the future should be included.

XVII. ENVIRONMENTAL EFFECTS OF THE PROPOSED AMENDMENTS TO THE DIESEL FUEL REGULATIONS

The ARB provides a multimedia analysis of the effects of the proposed diesel fuel regulations in satisfaction of the California Environmental Quality Act (CEQA) and ARB policy.

They judge all air quality effects to be positive. One pollutant for which this may not be true is NO₂. Both the catalyzed trap technology and NO_x adsorption technology have the potential to convert NO to NO₂. While NO_x is reduced in the process it is possible that NO₂ emissions could increase. Sulfur inhibits this conversion, probably in both technologies, hence the lower the sulfur the higher the NO₂. While the effect may be negligible, the possibility needs to be discussed. Also the possible adverse effect of NO_x reduction on ozone in some areas of California, raised earlier, needs to be considered.

The new technology also is likely to increase the conversion of sulfur to SO₃ and sulfate. With the large proposed reduction of fuel sulfur the net result should be a lowering of SO₃ and sulfate. This needs to be discussed and confirmed.

The issue of greenhouse gas emissions is a bit more complex than indicated in the ARB analysis. It is possible that N₂O emissions will be increased by one or both of the exhaust treatment devices and that the conversion of NO to N₂O may be affected by fuel composition. Little or no data exist on this subject but the possibility should be noted. Also, black carbon is thought to contribute to global climate change. Since RFD-2006 reduces particulate matter and diesel particulate matter is largely black carbon, the effect will reduce climate change effects. This should be noted in this section (it is acknowledged later).

Effects on water quality are judged to be insignificant. One possibility is any use of an additive to assist in meeting emissions equivalency that in turn might have an adverse effect on water quality. There is no indication that this is planned.

XVIII. COSTS TO PRODUCE LOW SULFUR DIESEL FUEL

Cost analyses of fuel modifications are always difficult to make because they can vary widely from refinery to refinery and the needed information is proprietary. The ARB staff has not attempted a refinery by refinery cost estimate. This is reasonable. The cost estimates are consistent with other analyses of desulfurization. One statement that needs qualification or removal appears on page 122 is “Staff’s evaluation of this proposal [to reduce sulfur levels

below the current proposed regulation] concluded that the reductions in fuel sulfur below 15 ppmw would result in significant cost increase with little or no increase in benefits.” This statement would seem to close the door on future consideration of the proposals of the World Wide Fuel Charter’s call for a sulfur-free fuel. If the statement is to remain then it must be justified with a documentation of the referenced analysis. There are issues of engine and aftertreatment durability that are affected by fuel sulfur level. The understanding of these effects is currently is judged insufficient for a reliable cost benefit analysis. A more conservative approach, considering the uncertainties, would be to eliminate the statement.

XIX. ECONOMIC IMPACTS OF THE PROPOSED AMENDMENTS TO THE DIESEL FUEL REGULATIONS

The economic impact analysis is based on based on a modification of the Dynamic Revenue Analysis Model. It predicts no significant impact on the California economy. Negative impacts accrue primarily to the refining, agricultural, and trucking sectors. Differential effects with adjoining states should be reduced from current levels because of the coincident adoption of the Federal low sulfur diesel fuel requirements.

XX. NEED FOR NONVEHICULAR DIESEL-ENGINE FUEL REGULATION

The ARB staff ties the need for non-vehicular diesel-engine fuel regulations to a proposed Airborne Toxicant Control Measure (ACTM). This sector consists of stationary, portable, and transportation refrigeration unit (TRU) diesel engines. Considering the uncertainty and controversy related to diesel emission toxicity, justification through their contribution to the criteria pollutants, NO_x and PM would seem useful in addition. The PM emission inventory of Table XX-1 lumps the three elements above with locomotive and marine contributions. It would seem reasonable to break non-vehicular sources into the five separate categories: stationary, portable, TFU, locomotive, and marine diesel.

This in turn raises the question of why locomotives and marine diesels are not included in the RDF-2006 regulation. If there are policy or legal reasons for their exemption, they should be explained as part of the report. If such reasons do not exist, then not including locomotives and marine diesels is a major shortcoming.

APPENDICES

The appendices are both informative and, in some cases, supportive of the proposed regulations.

APPENDIX A: Provides the wording of the changes to the FRD-2006 regulation.

APPENDIX B: Provides the wording changes to exhaust emissions standards and test procedures.

APPENDIX C: Provides background information on diesel fuel aromatic content and polycyclic aromatic hydrocarbon (PAH) emissions. Since many of PAHs (and their nitrate derivatives) are known human carcinogens, much of the attention on diesel PM carcinogenicity has focused on these compounds.

APPENDIX D: This appendix presents a key document, *Staff Review of the Emissions Benefits of California's Diesel Fuel Program*, which was discussed earlier. The primary conclusion of this reviewer is that the data base is insufficient to characterize the effect of fuel changes on emissions from new technology (not an important component in the inventory), on-road engines, non-road vehicles, and non-vehicular diesel engines. This is a major shortcoming in the assessment of the effects of RDF-2006 on emissions. I also question whether the interdependence of MAHCs, PAHCs, specific gravity, and Cetane Number allow determination of the emissions effect of changes in individual properties.

APPENDIX E: Baseline and future year inventories from the EMFAC emissions model contain the uncertainties inherent in the model. Particularly troublesome are predictions for years in which the numbers of diesel vehicles with aftertreatment devices become significant. There is no way to project durability of emission systems, deterioration in emissions control, or the effect of fuel composition on emissions from in-use engines. It is highly likely that the EMFAC projections are optimistic.

APPENDIX F: The results of an EPA regression analysis of the relation between emissions and fuel properties are presented. The signs of the coefficients (slopes) are consistent with understanding of physical processes. The presentation is limited to effects on NO_x emissions. Effects on PM emissions should also be presented.

APPENDIX G: Provides pump wear data related to lubricity.

APPENDIX H: Provides a comprehensive review of technology available for reducing sulfur levels in diesel fuel.

APPENDIX I: Describes diesel engine lubricating oils and discusses current understanding of the relation between lubricant composition and emissions.

APPENDIX J: Provides background information on effects of the proposed regulations on greenhouse gas emissions, including a full fuel cycle analysis.

APPENDIX K: Discusses potential effects on water quality, judged to be negligible.

APPENDIX L: Records the questionnaires provided California refiners.

APPENDIX M: Contains spreadsheets that record the details of the economic impact on California agriculture.

APPENDIX N: Assesses the impact of fuel taxes on purchases of out-of-state diesel fuel and explains the excise tax balancing between states based on where the fuel is consumed.

APPENDIX O: References

Proposed Diesel Sulfur Regulations and Emission Benefits of Current Regulations

Scientific Peer Review

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Introduction

This is a review for the California Air Resources Board proposed changes and additions to regulations for the California reformulated diesel fuel. This review is prepared under Interagency Agreement #98-004 between the University of California and the California Environmental Protection Agency.

This review covers the document titled "*Proposed Amendments to the California Diesel Fuel Regulations, Staff Report: Initial Statement of Reasons*" dated June 6, 2003. In addition, I reviewed some of the additional references provided by the Air Resources Board, as well as the comment and reviews of the Western States Petroleum Association, Prof. Robert Sawyer of UC Berkeley, and Prof. Lawrence Caretto of California State University, Northridge.

Proposed Revisions

The Staff of the Air Resources Board is proposing amendments to the California diesel fuel regulations. These major changes proposed would:

1. Reduce the sulfur content limit from 500 ppmw to 15 ppmw for diesel fuel sold in California for use in on-road and off-road motor vehicles starting in mid-2006.
2. Adopt an Air Toxics Control Measure to require the use of vehicular diesel fuel in all nonvehicular diesel engines.
3. Revise the sulfur specifications for diesel certification fuel used to determine whether diesel engines comply with heavy-duty diesel emission standards.
4. Revise the requirements for certification of alternative diesel formulations to require 15 ppmw sulfur limits for candidate and reference fuels.
5. Establish additional requirements for certification of alternative diesel formulations to ensure that the fuels produced under the alternative formulation has comparable emissions performance to the candidate fuel.
6. Adopt new specifications for equivalency to the aromatic hydrocarbon limit for diesel fuel to provide another compliance option.
7. Adopt standards for diesel fuel lubricity.
8. Make other changes, including improvements to the sulfur test method and a revision of the definition of diesel fuel, to ensure that regulation works effectively.

Review of *Proposed Amendments to the California Diesel Fuel Regulations*, Staff Report: *Initial Statement of Reasons*, dated June 6, 2003.

Specific Comments relating to proposed amendments:

1. Reduce the sulfur content limit from 500 ppmw to 15 ppmw for diesel fuel sold in California for use in on-road and off-road motor vehicles starting in mid-2006.

The U.S. Environmental Protection Agency will impose a 15 ppmw sulfur limit on diesel fuel in 2006. The main reason for this standard is to protect the emissions controls that are most likely to be used for diesel engines to meet the 2007-2010 heavy duty emission standards and the 2007 light duty emission standards. These systems will be catalyzed diesel particle filter, NO_x after-treatment, and other advanced after-treatments.

The need for low sulfur fuel for these systems is reviewed in the staff report and is reasonable. The effect of higher sulfur levels on these systems is shown to be detrimental. In addition, there is a direct effect on particle emissions due to reduced sulfate and other sulfur derived emissions, such as sulfur dioxide. There is considerable evidence both from the U.S. EPA and California that lower sulfur levels are needed, and that setting the level at 15 ppm, the same as the federal standard, is appropriate.

The alternative of even lower sulfur stands was addressed. For the exhaust technologies, lower sulfur levels are not cost-effective, but newer treatment methods may require even lower sulfur levels. A zero sulfur level diesel fuel may be desirable in the future, and the ARB should continue to consider this as a future alternative.

2. Adopt an Air Toxics Control Measure to require the use of vehicular diesel fuel in all nonvehicular diesel engines.

The rationale for adopting this standard for both on-road and off-road vehicles is sound. Without new regulations, the EPA 15 ppmw standard will apply, but only to on-road diesel fuel use. The SCAQMD 15 ppmw standard applies to on-road, off-road, and stationary engines, but it is limited in that the standard is not state-wide, which is necessary if for retrofitting older engines as well as new engines requiring advanced exhaust treatment. Off-road diesel PM emissions are larger than on-road emissions, so including these engines is important.

The amendment would require the same diesel fuel to be burned in nonvehicular engines. This should produce benefits in reduced emissions from stationary engines. As noted in the report, most diesel engines in California already use the same fuel since the state has

a single fuel distribution system. This change would ensure that the benefits obtained from the lower sulfur fuels are maintained.

As noted in the report, U.S. EPA regulations are needed to reduce emissions from locomotives, aircraft, heavy-duty vehicles used in interstate commerce, and other sources that are preempted from state control. The ARB should continue to work with the EPA and others to develop control measures for these engines.

3. Revise the sulfur specifications for diesel certification fuel used to determine whether diesel engines comply with heavy-duty diesel emission standards.

It makes sense to have a certification fuel with similar properties to the fuels that will be used in heavy-duty diesel engines. The lower sulfur levels in the certification fuels will also allow the use of both NO_x and PM aftertreatment devices.

4. Revise the requirements for certification of alternative diesel formulations to require 15 ppmw sulfur limits for candidate and reference fuels.

5. Establish additional requirements for certification of alternative diesel formulations to ensure that the fuels produced under the alternative formulation has comparable emissions performance to the candidate fuel.

Consistency with the sulfur standard in Section 2281.

Having the same 15 ppmw sulfur limit for both the reference and candidate fuels is appropriate.

Emission equivalency of candidate fuels to in-use fuels

This would ensure that future candidate fuels tested in the laboratory are fully characterized. The action is appropriate.

Emission equivalency of candidate fuels to reference fuels.

This would tighten the tolerances allowed for each pollutant. The new values are based on 16 fuels tested in the same laboratory, and are reasonable.

Elimination of the sulfate credit

The elimination of the sulfate credit is reasonable, as the 15ppmw limit makes difference between the sulfur levels in the reference and candidate fuels insignificant.

6. Adopt new specifications for equivalency to the aromatic hydrocarbon limit for diesel fuel to provide another compliance option.

The adoption of alternative compliance options that provides equivalent environmental benefits to the 10% aromatics hydrocarbon limit is a good proposal. Allowing different formulations that meet and retain equivalent environmental benefits is reasonable, as the emissions from fuels are key factors here, not the composition of the fuel.

Regarding the new fuel specifications for equivalency to the aromatic hydrocarbon limit, these comments are directed at Appendix D (*Staff Review of the Emission Benefits of California's Diesel Fuel Program*, with a date of March, 2003), Appendix E (*Staff Analysis of Future Emission Benefits of California's Diesel Fuel Program*), and Appendix.F (*Effects of Changes in Diesel Fuel Properties on Emissions*).

As noted by the other reviewers, there are considerable problems in determining the effects of individual fuel parameters when these parameters are interrelated. I agree with the conclusions of Profs. Sawyer and Caretto that the interdependence of fuel parameters such as aromatics, specific gravity, and Cetane number make it difficult to quantify the effect of varying a single property.

This being said, there is considerable evidence from the 31 studies reviewed that emissions of NO_x and PM are reduced when sulfur and aromatics are limited. As noted in the report, the HDEWG model may have limited applicability, since the data is from one engine operating in one configuration, and no PM measurements were made. These studies used a variety of fuels and engines. However, the vast majority of the engines are 1996 model year or earlier. The addition of new engines and engines retrofitted with advanced exhaust treatment systems is another factor that has a large uncertainty that is not clearly covered.

7. Adopt standards for diesel fuel lubricity

Lower sulfur levels will reduce the lubricity of diesel fuel as a result of severe hydrotreating refiners are expected to use to meet the new standards.

There are currently no government or industry standards in the U.S. controlling diesel fuel lubricity. In California, there is a voluntary minimum lubricity level of a Scuffing Load Ball-on-Cylinder- Lubricity Evaluator (SLBCOCLE) scuffing load of 3,000 grams or higher. The U.S. EPA allows industry and the market to address the lubricity issue in the most economical manner. The ASTM has not been able to agree on a lubricity standard nor a testing method. However, other agencies in Canada and Europe have adopted lubricity standards.

While it appears that lubricity additives will be used by refiners, the nature of the additive is not specified. If the ARB wants to specify a lubricity standard, they might want to also ban certain types of additives, such as acidic additives that can form harmful salts.

Change in the fuel specifications can produce concerns that engine or engine parts failures are due to the different fuels, with accompanying costs due to legal actions. The adoption of a standard may reduce these concerns, but it is not clear that this is an emissions issue. In the report, there is a discussion of the pump wear data, and results are presented in Appendix G. There is a statement on page 73 that “ fuels with insufficient lubricity contribute to excessive wear that results in reduced equipment life and performance. Excessive wear in these systems is also expected to increase emissions due to compromised pump performance.” While that is a reasonable conclusion to reach, there are no references or test data given to support that statement.

In light of the lack of U.S. standards, it might be better to allow the industry to continue with the current practice, and wait until a consensus is reached by ASTM, as suggested as an alternative in the staff report. This would also bring the California regulations more into alignment with the U.S. standards.

8. Make other changes, including improvements to the sulfur test method and a revision of the definition of diesel fuel, to ensure that regulation works effectively.

Test method for sulfur

The staff proposes to change the method for determining the sulfur content of diesel fuel. Current regulations require that sulfur in diesel fuel be determined by ASTM D2622-94 (x-ray spectrometry). As the current method doesn't not have the sensitivity or precision needed to measure sulfur at levels of 15 ppmw, another method is required. The method proposed (ultraviolet fluorescence, D5453-93) is reasonable, and it has been used in similar fuels with lower sulfur levels.

Definition of diesel fuel

The definition of a diesel fuel as any predominantly hydrocarbon liquid fuel without specifying or clarifying what “predominantly” means can be a problem for diesel fuels that might contain significant amounts of a non-hydrocarbon, such as oxygenated species. However, if oxygenated fuels are considered, then additional problems with other issues such as water quality (some oxygenated compounds are soluble in water) and the cost of producing these fuels would change.

Other comments:

In Section V, Health Benefits Of Diesel Emissions Reductions (page 27), the complexity of the chemical composition is mentioned, but there is little discussion of the effects of particle size on health, especially the role of ultrafine particles. While 94% of the mass of diesel particles are contained in particles smaller than 2.5 microns, diesel particles produced by modern engines are better characterized by sizes in the hundreds of nanometers and smaller. Reducing the sulfur content should reduce the formation of particles formed from the condensation of sulfuric acid, but their role in the health effects is unclear.

Potential Cancer Risk

The discussion on page 25 assumes that a reduction in diesel PM will lead to a proportional reduction in cancer risk. Some caution should be taken here since the changes proposed here will certainly not only change the mass of diesel PM, but will probably change the chemical composition of the resulting particles, and it is not clear that all of the possible carcinogenic compounds in the exhaust will be reduced by the same fraction.

Overall costs of the proposed amendments

The ARB staff estimates that the costs of reducing the sulfur content of diesel fuel and adding required lubricity additives as between 2 and 4 cents per gallon of diesel. It is noted, but not emphasized, that most of the costs to refiners would occur as a result of adopted U.S. EPA and SCAQMD regulations. The real cost of the amendments is thus the cost of extending the regulations to the 25% of the total diesel fuel consumed by off-road diesel vehicles outside the SCAQMD. Staff estimates that as much as 90% of the cost can be attributed to the other regulations. The real cost of the proposed changes thus appears to be 0.2 to 0.4 cents per gallon of diesel fuel.

Water Quality

The assessment in Appendix K concludes that there would be no impacts on ground water associated with proposed low-sulfur diesel fuel. This is correct for the hydrocarbon portion of the fuel. However, the proposed redefining of “diesel fuel” to be any mixture of primarily liquid hydrocarbons raises the issue of the impact of non-hydrocarbon compounds, such as oxygenated compounds, that could be more water soluble. The effects of oxygenates in gasoline has been studied by the ARB previously, and could be cited here. The report also states that alternative diesel fuels generally contain more than tract amounts of oxygenated fuel constituents or are emulsified with water.

Diesel Engine Lubrication Oils

As the emissions from burning diesel fuel decrease, the fraction of the emissions that arise from lubricating oils can increase. There are two ongoing research efforts that are examining the impact of lubricating oils and oil additives on emissions and emission control devices. Preliminary results from Advanced Petroleum-Based Fuels Program Diesel Emission Control- Sulfur Effects (APBF – DECSE) suggest that some oil formulations produce higher levels of sulfur emissions. These results are an indication that staff needs to follow and support this and related work, especially in the effects of oils and oil additives on advanced aftertreatment technologies.

**Review of
California Environmental Protection Agency
California Air Resources Board**

**PROPOSED AMENDMENTS TO THE CALIFORNIA
DIESEL FUEL REGULATIONS**

***STAFF REPORT: INITIAL STATEMENT OF REASONS
March 28, 2002***

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OVERVIEW

This is one of four independent peer reviews provided on the staff of the Air Resources Board proposed changes and additions to regulations for California reformulated diesel including a new standard for lubricity. These reviews are prepared under Interagency Agreement #98-004 between the University of California and the California Environmental Protection Agency, the California Air Resources Board (ARB). This review also treats the ARB staff assessment of the emissions reductions associated with the current California Reformulated Diesel regulations, which were adopted in 1988 and became effective in 1993. Some, but not all, of the provided additional references and references cited in the report also have been reviewed.

MAJOR REVIEW CONCLUSIONS

The staff report provides a justification for the need for new diesel fuel regulations and a convincing assessment of the effect of the new regulations on the reduction of emissions that is consistent with the currently available technical data. The three most important issues that would benefit from additional attention are:

- 1) The role oxygenate additives in diesel fuel formulation; the impact of the regulations on oxygenate additives; the distinction among diesel, alternative diesel fuels, and their blends; and the impact of all of these on emissions needs further clarification and exposition.*

- 2) The adequacy of the equivalency specification to provide comparable or better emissions reductions across the range of diesel engine applications is questioned because its derivation is not clearly explained and that data set upon which it is based is judged inadequate.*

3) *The accuracy of relating the lung cancer health benefits from reformulation to particulate mass reduction when reformulation is likely to have greater or lesser effect on reducing the specific carcinogenic compounds is questioned.*

4) *The lubricity standard may not be needed. It might be better policy to leave responsibility for adequate lubricity with the refiners, where it is now.*

Discussion of these issues appears in more detail in the following text.

Additional recommendations dealing with other issues also follow in the more detailed review of each section of the report.

REVIEW

The details of my review follow the structure of the staff document: *Proposed Amendments to the California Diesel Fuel Regulations, Staff Report: Initial Statement of Reasons*, dated June 6, 2003

I. INTRODUCTION AND SUMMARY

This section provides an appropriate and concise overview of the need for and nature of the proposed regulation.

The current diesel fuel regulation applies to on-road fuel consumption, limits sulfur to 500 ppmw, and limits aromatics to 10% with an exception to 20% for small refiners and an equivalency alternative based on demonstration for large refiners. Most refiners use the equivalency alternative and produce diesel fuels with more than 10% aromatics.

The proposed diesel fuel regulation applies to both on-road and off-road fuel consumption (but excludes diesel fuels used exclusively in locomotive or marine engines), drops

the sulfur limit to 15 ppmw and retains the nominal limit on aromatics of 10% but specifies equivalency limits that allow refiners alternatives to meeting the aromatic limit. Additionally, the new regulations propose a new lubricity standard, new requirements for certifying alternative formulations, a new (emissions) certification fuel, a new sulfur test method, and an exemption for qualifying military vehicles.

The primary reason to reduce sulfur is to enable the exhaust emissions control technology (catalyzed traps for particulate control and NO_x adsorbers for NO_x control) that are likely to be applied for diesels to meet the 2007-2010 heavy duty emissions standards and 2007 light duty emission standards. Since the U.S. Environmental Protection Agency will impose a 15 ppmw sulfur limit on diesel fuel during 2006, the other fuel specifications, applications, and procedures are additional to the EPA requirements and are the items of primary importance. The ARB staff correctly believes that requirements additional to those of the EPA are essential to providing the additional emissions reductions needed to meet California air quality goals. Extending the fuel requirement to off-road applications will provide emissions reductions from existing engines and enable the application of on-road emissions control to the off-road engines. The other changes are largely procedural and primarily designed to ease implementation, improve the effectiveness of implementation, and to provide additional flexibility. They primarily retain the emissions reductions of the current fuel rather than provide additional emissions reductions.

II. RECOMMENDATIONS

This section succinctly lists the eight primary recommended board actions. The first two, reducing sulfur to 15 ppmw and extending application of reformulated diesel to most diesel applications, but not locomotive and marine engines, are the primary actions. The remaining six are primarily procedural—but some difficulties may be associated with these details.

III. BACKGROUND

The factual description of diesel fuels and engines and their use and application in California is complete. The emission inventory estimates are reasonable but contain the uncertainties inherent to the EMFAC model from which they are produced. The dependency of emissions upon fuel properties is complex with many of the properties interdependent, which makes associating emissions dependence upon single fuel parameters difficult. This will be discussed more in Section IX.

IV. NEED FOR EMISSIONS REDUCTION

The need for further diesel emissions reductions is tied by the staff report to both criteria (ozone, carbon monoxide, and particulate matter) and toxics. Diesels are small contributors to the VOCs and CO inventory. Fuel reformulation has a small effect on the emissions of VOCs and CO and an even smaller effect on the inventory. Therefore the focus should be on NO_x, PM, and toxics.

Since the NO₂ air quality standard is met statewide, it is the role NO_x in the production of ozone and nitrate particulates that is of interest. The discussion of diesel NO_x and ozone ignores the increased understanding that much of the state is and is becoming hydrocarbon limited. In some areas additional NO_x reduction will make attainment of ozone standards more difficult, that is, will require even greater VOC reduction. Additionally, Figure IV-1 would benefit from some clarification. I believe that this figure is for the 1-hour ozone standard and should be so stated. Mention of the 8-hr ozone standard and its implication to California should be made. Also, the designations are by air basins whereas presenting the maps by counties, while correct in a regulatory context, gives the wrong implication for the air quality of various regions of the state.

The pending PM_{2.5} designations and the increased relative contribution and importance of diesel particulate emissions should be mentioned.

The uncertainty in predicting risk of death from lung cancer from diesel particulate exposure is high. While reporting such risks, Table IV-1, may be useful in supporting regulations, it is improper to do so without quantifying or at least mentioning the uncertainty.

V. HEALTH BENEFITS OF DIESEL EMISSIONS REDUCTIONS

The discussion of diesel particulate health effects (page 28) lacks any explicit mention of ultrafines and the increasing understanding of the mechanism of their adverse health effects, and increasing concerns. The known relation between fuel properties and particulate emissions is primarily for particulate as PM₁₀ or TPM, Data are largely lacking, but needed, that relate fuel properties to PM_{0.1}. Reducing sulfur content will reduce ultrafine, some of which result from the condensation of sulfuric acid.

VI. EXISTING DIESEL FUEL REGULATIONS

The summary and discussion of diesel fuel regulations is clear and useful.

VII. PM RISK REDUCTION ACTIVITIES

This section provides a factual accounting of diesel PM reduction activities in the state.

VIII. PROPOSED AMENDMENTS TO SULFUR STANDARD FOR CALIFORNIA DIESEL

The statement (page 42) that current sulfur levels prevent effective operating of NO_x control technology is not strictly true if the possibility of selective catalytic reduction (SCR) is included. I agree that NO_x adsorption control technology is preferable and likely. However, this technology is not fully demonstrated and the competing SCR technology is seeing widespread application in Europe. There should be some mention of SCR and assessment of its sulfur tolerance.

IX. PROPOSED AMENDMENTS TO THE DIESEL ENGINE CERTIFICATION FUEL REGULATION

Changing the fuel used to certify new engines beginning in 2007 to reflect the 2006 reformulated diesel fuel (RFD-2006) is appropriate. The properties specified in Table IX-1 (page 49) are reasonable and appropriate.

X. PROPOSED AMENDMENTS TO REGULATORY PROVISIONS ON CERTIFIED ALTERNATIVE DIESEL FUEL FORMULATION

The concept of an alternative diesel fuel formulation that has properties constrained by those of a “candidate fuel” shown to yield emissions less than or equal to those of the “reference fuel”) is established to provide refiner flexibility while retaining emissions reductions. One issue that is not made clear in the staff report is just how emissions equivalency is to be demonstrated beginning in 2007 when on-road engines with new aftertreatment systems start to appear and the use of RFD-2006 in off-road engines begins. Ideally emissions equivalency would be obtained and demonstrated across the range of applications. Practically, emissions equivalency demonstration is important for three categories of engines, 1) pre-2007 on-road heavy-duty engines, 2) 2007 and later on-road heavy-duty engines, and 3) off-road engines. Essentially all of the data relating emissions to fuel properties are for pre-2002 on-road heavy-duty engines. Presumably the details of working out just how emissions equivalency is to be demonstrated is left to the staff and approval of the ARB Executive Officer. This issue needs to be addressed.

Tightening test tolerances and the elimination of the sulfate credit are appropriate actions.

XI. PROPOSED NEW FUEL SPECIFICATIONS FOR EQUIVALENCY TO THE AROMATIC HYDROCARBON LIMIT

In addition to providing for the sale of alternative fuel formulations by demonstration through test of equivalent emissions reductions, a general equivalency to the aromatic hydrocarbon limit is proposed that places limits on five fuel properties (aromatic content, PAH content, API gravity, Cetane Number, and Nitrogen Content) as specified in Table XI-3. The absolute 15 ppmw sulfur limit, of course, also applies to the alternative fuel. This equivalent limit specification is a key element of the proposed RFD-2006 regulation. Confidence that any fuel within these equivalent limits provides equivalent emissions reductions to the reference fuel derives from data summarized in the report *Staff Review of the Emissions Benefits of California's Diesel Fuel Program*, March 2003 (Draft) presented in Appendix D. While the data base is greatly expanded beyond that available at the time the original California RFD regulations were adopted (and reassuringly confirms the originally estimated emissions reductions) it is dominated by 1998 and earlier on-road diesels with a few tests of 2004 prototype on-road diesels. There is little off-road engine emissions data and, of course, no data from 2007 on-road diesel technology.

How the equivalent limits for the five properties were derived from the emissions data base is not clear. The first four properties are interdependent and most of the tests were not designed to extract the effect the change of a single property. The effect of Cetane Number can be examined over a limited range through the use of Cetane Number improver additive. The effect of fifth property, nitrogen content, which in practice is primarily associated with the Cetane Number improver additive, can also be varied independently of other fuel properties. It is impossible to assure that all fuels within the specified equivalent limits would match or exceed the emissions reductions of the reference fuel. Additionally, there is no basis for confidence that the emissions reductions also apply to off-road diesel engines or to 2007 and later on-road diesel technology. Note that the 2007 and later issue is not of practical significance since the emissions should be so low that fuel effects for this segment will have a minor effect on the inventory.

There is some evidence for concern that the data used by the ARB to establish fuel property—emissions relations are not applicable to off-road engine and duty cycles. The EPA report *Strategies and Issues in Correlating Diesel Fuel Properties with Emissions—Staff Discussion Document*, EPA420-P-01-00, July 2001, which is based largely on non-road diesel

engines, shows a lower impact of CFD on particulate mater reduction that reported by the ARB which is based largely on on-road diesel engine tests.

XII. PROPOSED REGULATION ESTABLISHING A DIESEL FUEL LUBRICITY STANDARD

The basic issue of a lubricity standard is whether or not it is needed. The alternative is to trust that the refiners as part of their product quality control and customer satisfaction concerns would assure an adequate level of lubricity in their product. Since the heavy hydrodesulphurization necessary for sulfur reduction is likely to reduce lubricity there is a potential for a problem if corrective action were not taken by refiners. A secondary issue is whether the proposed test, the High Frequency Reciprocating Rig test (ASTM standard D6079-02) and wear scar diameter limit of 520 microns is appropriately protective, or even the right test. Since level of protection provided by the proposed lubricity standard approximates the industry's current voluntary standard, the practical impact may be negligible. By adopting such a standard will the ARB be assuming responsibility for a quality control issue that is properly the responsibility of the refining industry?

XIII. OTHER PROPOSED AMMENDMENTS TO THE DIESEL FUEL REGULATIONS

The need to switch to a more sensitive test for fuel sulfur is certain. The proposed ultraviolet fluorescence method, ASTM D5453-93 is appropriate.

The proposed definition of diesel fuel is not clearly stated. This is a much bigger issue than might at first be perceived or than is indicated by the very limited discussion. One might argue that any fuel used in a compression ignition engine is a diesel fuel. The ARB does not intend that this regulations should apply to alternative diesel fuels (note that the word "alternative" is used in two different contexts: first as in an alternative formulation of conventional diesel and second as in an alternative to conventional diesel. Unfortunately the

distinction between diesel fuels and alternative diesel fuels is vague, especially when it comes to blends of alternative and petroleum based diesel fuels. The description “any liquid fuel that is predominantly a mixture of hydrocarbons” leaves uncertainties about the inclusion of biodiesel, esters of biodiesel, and their blends with petroleum diesel and/or liquid diesel fuels derived from natural gas, coal, or biofeedstocks. The addition of a variety of oxygenates to diesel is an effective way to reduce particulate emissions and this possibility should not be eliminated or discouraged by the definition of diesel fuel or the specifications.

XIV. FEASIBILITY OF REFINING LOW SULFUR DIESEL FUEL

The discussion of refining options confirms that adequate technology exists to provide low sulfur reformulated diesel fuel. This technology either already exists at California refineries or can be acquired.

XV. POTENTIAL IMPACTS OF THE PROPOSED SPECIFICATION ON THE PRODUCTION OF DIESEL FUEL BY CALIFORNIA REFINERIES

The ARB review identifies no barriers to providing the required diesel fuel. Since similar low sulfur on-road diesel fuels will be required nationally at the same time, differences between California and Federal reformulated diesel fuels will be small. The ARB may want to consider allowing the temporary use of diesel fuel meeting Federal specifications should an unforeseen shortage arise.

XVI. OTHER ISSUES

Exemptions for small refiners have always been a problematic but expedient policy. While exemption from the aromatic content limits is not a big deal, exemption from the sulfur limit is because of its affect on aftertreatment technology, including both increased emissions

and possible damage to emissions control equipment. The ARB may want to consider as a possible relief measure, if necessary, the diversion of diesel fuel with greater than 15 ppmw sulfur to off-road applications where new exhaust aftertreatment technology has not been applied.

The role of lubricant and concern for sulfur and additives on emissions is outlined in the report. This issue is being studied and understanding improved. The ARB should commit to participating in these studies and working for the national adoption of lubricant standards, if necessary, to treat emission system and emission effects.

A description of biodiesel fuels is provided. It might be noted that Fischer-Tropsch diesel can be derived from coal, biowastes, cellulose, and other feedstocks—not only natural gas. Again, it is not clearly stated that alternative diesel fuels are to be excluded from this regulation and, if so, what level of blending divides alternative diesel fuels from the regulated diesel fuels. This issue needs to be clarified least the use of biodiesel, biodiesel-diesel blends, oxygenate additives, and other “unconventional” diesel fuels that have emissions reduction and renewable advantages be excluded by this regulation.

It is reassuring that similar low sulfur diesel reformulation is occurring internationally. The report does not discuss the future possibility of a zero sulfur diesel fuel as called for in the World-Wide Fuel Charter. If and how the ARB will address this issue in the future should be included.

XVII. ENVIRONMENTAL EFFECTS OF THE PROPOSED AMENDMENTS TO THE DIESEL FUEL REGULATIONS

The ARB provides a multimedia analysis of the effects of the proposed diesel fuel regulations in satisfaction of the California Environmental Quality Act (CEQA) and ARB policy.

They judge all air quality effects to be positive. One pollutant for which this may not be true is NO₂. Both the catalyzed trap technology and NO_x adsorption technology have the potential to convert NO to NO₂. While NO_x is reduced in the process it is possible that NO₂ emissions could increase. Sulfur inhibits this conversion, probably in both technologies, hence the lower the sulfur the higher the NO₂. While the effect may be negligible, the possibility needs to be discussed. Also the possible adverse effect of NO_x reduction on ozone in some areas of California, raised earlier, needs to be considered.

The new technology also is likely to increase the conversion of sulfur to SO₃ and sulfate. With the large proposed reduction of fuel sulfur the net result should be a lowering of SO₃ and sulfate. This needs to be discussed and confirmed.

The issue of greenhouse gas emissions is a bit more complex than indicated in the ARB analysis. It is possible that N₂O emissions will be increased by one or both of the exhaust treatment devices and that the conversion of NO to N₂O may be affected by fuel composition. Little or no data exist on this subject but the possibility should be noted. Also, black carbon is thought to contribute to global climate change. Since RFD-2006 reduces particulate matter and diesel particulate matter is largely black carbon, the effect will reduce climate change effects. This should be noted in this section (it is acknowledged later).

Effects on water quality are judged to be insignificant. One possibility is any use of an additive to assist in meeting emissions equivalency that in turn might have an adverse effect on water quality. There is no indication that this is planned.

XVIII. COSTS TO PRODUCE LOW SULFUR DIESEL FUEL

Cost analyses of fuel modifications are always difficult to make because they can vary widely from refinery to refinery and the needed information is proprietary. The ARB staff has not attempted a refinery by refinery cost estimate. This is reasonable. The cost estimates are consistent with other analyses of desulfurization. One statement that needs qualification or removal appears on page 122 is “Staff’s evaluation of this proposal [to reduce sulfur levels

below the current proposed regulation] concluded that the reductions in fuel sulfur below 15 ppmw would result in significant cost increase with little or no increase in benefits.” This statement would seem to close the door on future consideration of the proposals of the World Wide Fuel Charter’s call for a sulfur-free fuel. If the statement is to remain then it must be justified with a documentation of the referenced analysis. There are issues of engine and aftertreatment durability that are affected by fuel sulfur level. The understanding of these effects is currently is judged insufficient for a reliable cost benefit analysis. A more conservative approach, considering the uncertainties, would be to eliminate the statement.

XIX. ECONOMIC IMPACTS OF THE PROPOSED AMENDMENTS TO THE DIESEL FUEL REGULATIONS

The economic impact analysis is based on based on a modification of the Dynamic Revenue Analysis Model. It predicts no significant impact on the California economy. Negative impacts accrue primarily to the refining, agricultural, and trucking sectors. Differential effects with adjoining states should be reduced from current levels because of the coincident adoption of the Federal low sulfur diesel fuel requirements.

XX. NEED FOR NONVEHICULAR DIESEL-ENGINE FUEL REGULATION

The ARB staff ties the need for non-vehicular diesel-engine fuel regulations to a proposed Airborne Toxicant Control Measure (ACTM). This sector consists of stationary, portable, and transportation refrigeration unit (TRU) diesel engines. Considering the uncertainty and controversy related to diesel emission toxicity, justification through their contribution to the criteria pollutants, NO_x and PM would seem useful in addition. The PM emission inventory of Table XX-1 lumps the three elements above with locomotive and marine contributions. It would seem reasonable to break non-vehicular sources into the five separate categories: stationary, portable, TFU, locomotive, and marine diesel.

This in turn raises the question of why locomotives and marine diesels are not included in the RDF-2006 regulation. If there are policy or legal reasons for their exemption, they should be explained as part of the report. If such reasons do not exist, then not including locomotives and marine diesels is a major shortcoming.

APPENDICES

The appendices are both informative and, in some cases, supportive of the proposed regulations.

APPENDIX A: Provides the wording of the changes to the FRD-2006 regulation.

APPENDIX B: Provides the wording changes to exhaust emissions standards and test procedures.

APPENDIX C: Provides background information on diesel fuel aromatic content and polycyclic aromatic hydrocarbon (PAH) emissions. Since many of PAHs (and their nitrate derivatives) are known human carcinogens, much of the attention on diesel PM carcinogenicity has focused on these compounds.

APPENDIX D: This appendix presents a key document, *Staff Review of the Emissions Benefits of California's Diesel Fuel Program*, which was discussed earlier. The primary conclusion of this reviewer is that the data base is insufficient to characterize the effect of fuel changes on emissions from new technology (not an important component in the inventory), on-road engines, non-road vehicles, and non-vehicular diesel engines. This is a major shortcoming in the assessment of the effects of RDF-2006 on emissions. I also question whether the interdependence of MAHCs, PAHCs, specific gravity, and Cetane Number allow determination of the emissions effect of changes in individual properties.

APPENDIX E: Baseline and future year inventories from the EMFAC emissions model contain the uncertainties inherent in the model. Particularly troublesome are predictions for years in which the numbers of diesel vehicles with aftertreatment devices become significant. There is no way to project durability of emission systems, deterioration in emissions control, or the effect of fuel composition on emissions from in-use engines. It is highly likely that the EMFAC projections are optimistic.

APPENDIX F: The results of an EPA regression analysis of the relation between emissions and fuel properties are presented. The signs of the coefficients (slopes) are consistent with understanding of physical processes. The presentation is limited to effects on NO_x emissions. Effects on PM emissions should also be presented.

APPENDIX G: Provides pump wear data related to lubricity.

APPENDIX H: Provides a comprehensive review of technology available for reducing sulfur levels in diesel fuel.

APPENDIX I: Describes diesel engine lubricating oils and discusses current understanding of the relation between lubricant composition and emissions.

APPENDIX J: Provides background information on effects of the proposed regulations on greenhouse gas emissions, including a full fuel cycle analysis.

APPENDIX K: Discusses potential effects on water quality, judged to be negligible.

APPENDIX L: Records the questionnaires provided California refiners.

APPENDIX M: Contains spreadsheets that record the details of the economic impact on California agriculture.

APPENDIX N: Assesses the impact of fuel taxes on purchases of out-of-state diesel fuel and explains the excise tax balancing between states based on where the fuel is consumed.

APPENDIX O: References

PEER REVIEW

REVISIONS TO THE CALIFORNIA DIESEL FUEL REGULATIONS, INCLUDING A STANDARD FOR LUBRICITY, AND EMISSION BENEFITS FOR THE EXISTING REGULATIONS

Prepared for California Air Resources Board
Under Interagency Task Agreement 98-004, Task Order 42-2

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Executive Summary

The California Air Resources Board (ARB) has always taken the lead for many new regulations due to California's problems with meeting several of the National Ambient Air Quality Standards (NAAQS). These regulations include the regulations in 1988 and 1990 of the sulfur and aromatic hydrocarbon contents of motor vehicle diesel fuel. In 2000, the EPA passed new regulations for control of emissions from heavy-duty diesel engines and the sulfur content of highway diesel fuel. Given this background the ARB has proposed new amendments to the sulfur content of highway diesel fuel, a new lubricity standard and an ATCM for nonvehicular diesel applications.

This document is a scientific review of the ARB regulations dealing with the control of sulfur and aromatic content and lubricity of Motor Vehicle Diesel Fuel. The overall document can be viewed in several sections. The first section harmonizes the sulfur content of the ARB regulations with the recent EPA regulation and everything is quite straightforward from this reviewer's perspective. However, this review suggests that lowering the sulfur content, as an ATCM, needed further justification so the advice is to follow current research and report to the Board in 2005.

Another section introduces a need for a regulated lubricity standard and that there is a divided opinion with the proposed standard. The justification shows that such a standard is needed and recommends a value equal to the current value of ARB diesel, as there does not seem to be any field problems. This reviewer agreed strongly with the need for regulation and the proposed limit, even though the limit is less than desired by the automotive industry.

The final section deals with the aromatic limit and alternative diesel fuel formulations for meeting the aromatic limit. This review of the literature shows that fuel composition changes can lower emissions in diesel engines and that the regulations adopted in 1988 and 1990 that limited the aromatic content were in agreement with the best scientific data available at that time. Subsequent research has produced a haze of information; however, an overwhelming finding and common threat is that diesel fuel properties can reduce emissions from engines and the effect is about a 6% benefit as established by the EPA and ARB modeling exercises. The proposed changes to the alternative diesel formulations reflect recent knowledge about how the commercial and candidate fuels have compared and are well founded. The most important part of the proposed regulations is the introduction of the generic formula based on the ARB diesel compositions in the field and this review strongly endorses that concept, but did have some questions about the process used to define the numbers in the proposed amendments.

Taken in total, the benefits of the proposed amendments are significant and will lead to improved air quality in California.

1.0 Background

The Air Resources Board (ARB) established the first regulations for diesel fuel in November 1988 as part of their strategic plan to limit the emissions of nitric oxides (NO_x) and particulate matter (PM) from diesel engines. These regulations limited the sulfur content to 500 ppmw and the aromatic content to 10 volume percent for large refiners and 20 volume percent for small refiners for diesel fuel produced after October 1, 1993. At the same time, the EPA limited the sulfur content of diesel fuel to 500 ppmw and set a cetane index/aromatic content limit.

Part of the ARB regulation in 1988 included provisions to certify an alternative diesel formulation that had the same emission benefits as a diesel fuel with 10 volume percent aromatics. The regulation for certifying an alternative fuel was revised in October 1990. The main thrust of the 1990 amendments was to apply a more appropriate statistical protocol that ensured the emissions of the certified fuels were truly equivalent and that the certified fuel had the same benefits. The Board adopted the amendments.

Recent research has led to a better understanding of the health risk associated with particulate matter and the role of sulfur content towards enabling the technology that is evolving to control PM. In 1998, the ARB identified diesel exhaust as a toxic air contaminant. Since then the ARB has established the Diesel Risk Reduction Plan in order to reduce the overall PM inventory and associated cancer risk by 85% in 2020. EPA has released an assessment that stated that “there are human hazards associated with the exposure to diesel exhaust” and promulgated new regulations to control the diesel exhaust emissions and the sulfur content of diesel fuel to a limit of 15 ppmw. The basis for the lower sulfur limit is that it allows the widespread implementation of new PM control technology as it enables the diesel particulate filters to remove over 90% of the PM and work for long periods of time.

The purpose of this report is to provide a scientific peer review of the ARB’s diesel fuel regulations including: the Regulations Limiting the Sulfur Content and the Aromatic Content of Motor Vehicle Diesel Fuel from 1988 and 199, and the Proposed Amendments for the California Diesel Fuel Regulations from June 2003. The main thrust of the review was to assess whether the evidence presented in the Staff Report substantiates the claimed environmental benefits for the proposed amendments.

2.0 Review of the Proposed 2003 Amendments to the California Diesel Fuel Regulations

The amendments were divided into several sections or chapters within the staff report and each section is reviewed as a stand-alone unit.

2.1 Proposed Amendments to Sulfur Standard for California Diesel Fuel

This chapter deals with staff's proposed amendments to Title 13, CCR, Section 2281, "Sulfur Content of Diesel Fuel." Staff proposes that the specification for the maximum sulfur content of motor fuel diesel fuel for both on-road and off-road vehicles be reduced from 500 ppmw to 15 ppmw.

Their recommendation harmonizes the sulfur content of the ARB and the US EPA regulations so the recommendation is quite appropriate. Furthermore sufficient justification is offered in both the ARB staff report (2003) and the US EPA report (2000) to justify the very low sulfur content. Basically the key fuel parameter to enable new emissions control technology to be installed on diesel engines for control of PM and NOx is very low sulfur content. As the report mentions, all sections of the ARB regulations with the low sulfur fuel (<500 ppmw) must be changed to reflect the very low sulfur (<15ppm) content.

2.2 Proposed Amendments to the Diesel Engine Certification Fuel Regulation

This chapter deals with the amendments to several sections of CCR Title 13 and incorporated test procedures. The thrust of the amendments is to make the diesel certification fuel consistent with the proposed amendment to the sulfur specification for commercial diesel fuel. Staff proposes that the sulfur content of the certification fuel for exhaust testing be in a range of 7 to 15 ppmw, the same as that set by the EPA.

Staff justified the need for the certification fuel to reflect the properties of the commercial fuel, thus the sulfur content was adjusted. Using that approach raises the question why the nitrogen content is set between 100 to 500 ppmw, given that data in Table XI-2 show that the nitrogen content of commercial fuels can be less than 100 ppmw.

2.3 Proposed Amendments to Regulatory Provisions on Certified Alternative Diesel Fuel Formulations

This chapter deals with the proposed amendments to Title 13, CCR, subsection 2282(g), "Certified Diesel Fuel Formulations Resulting in Equivalent Emission Reductions." The amendments are proposed to ensure consistency in the sulfur limits and to further ensure that the alternative formulation diesel sold in California results in emissions that are

equivalent to the emissions achieved with diesel that complies with the 10 volume percent aromatic hydrocarbon standard. It also eliminates the sulfate credit.

Staff has developed good rationale that the existing alternative diesel formulations must meet the proposed sulfur standard and that future testing should not allow a sulfate credit for the PM filters as the difference in sulfur content between the candidate and reference fuels will result in a negligible weight in the future.

The other amendments are concerned with assuring emission equivalency of candidate fuels to reference fuels and emissions equivalency for in-use fuel to candidate fuels. The proposed changes to the emission equivalency of candidate fuels to reference fuels deal primarily with adjusting the test tolerance while assuring that a fuel tested against itself will be to satisfy the equivalency requirements. Staff's analysis that the test tolerance is lower than that suggested at the implementation of the regulations is not a surprise and the magnitude of a factor of two seems about right. From my experience the repeatability within a single lab of experienced analysts is often about 50% of the ASTM limits. Staff's approach and the proposed changes seem appropriate.

The amendment dealing with the emissions equivalency for in-use and candidate fuels is needed. The report suggests that candidate fuels are not produced commercially; thereby, creating doubt about the emission equivalency of the candidate and commercially produced fuels. The solution proposed by staff is for the candidate fuel to:

- 1) Report the same property slate as that for the reference fuel,
- 2) Meet ASTM 975 for No. 2 diesel and
- 3) Maintain the properties of the candidate fuel within half of the allowable ranges for the reference fuel.

All of the changes were clear and technically defensible in order to assure that there is emission equivalency and benefits between the candidate and the in-use fuels. What was less clear was a discussion of the process used for fuels with properties that fuel fell outside the allowed range. In such cases, the fuel properties would be modified before issuing the executive order by some undefined process. More detail on the processes used to modify the executive order would be helpful.

Not covered in the amendments for this section is a discussion of the current testing protocol, including the selection of engine. The current regulation allows the Executive Officer to select another engine if the DDC Series 60 with electronically controls is no longer representative of the post-1990 heavy-duty engines. Clearly most of the current in-use emissions come from engines that look like the DDC Series 60. However, it seems that a discussion would have been helpful as to why staff believed this was still the best test engine given that newer engine technology has been introduced in the past decade. Such discussion would provide some insight as to how ARB will deal with the low-NOx engines for 2004 and the fully controlled engines that are introduced to meet the EPA rule.

2.4 Proposed New Fuel Specification For Equivalency To The Aromatic Hydrocarbon Limit

This chapter deals with the creation of diesel fuel specifications with equivalent benefits to the 10% aromatic rule and which allow the refiner additional flexibility for manufacture of CARB diesel.

The thrust of the new amendment is well founded in that the benefits of existing regulations are maintained while manufacturers have more options to produce the ARB fuel. However, the process used to arrive at the proposed property limits raises some questions.

Table X1-1 shows individual properties for five certified formulations and average properties of eleven certified formulations. The Table shows very wide differences in properties between the individual and average fuels and these differences can lead to significant differences in manufacturing cost. For example, the cetane number averages 4 numbers higher for the individual formulae, suggesting a fuel that is up to 4 cents per gallon more expensive to produce than a fuel from the eleven-fuel population. It is no wonder that the average from the survey of in-use fuels shown in Table X1-2 has a cetane number of 52.6 and closer to the eleven-fuel average of 52.5 rather than the five-fuel average of 56.7. Similar rationale can be used for aromatics and sulfur contents, as most in-use diesel fuel does not resemble the first five individual fuels. Thus one should discount the weight of the five fuels in subsequent averaging, as it is apparent that over the past decade, the manufacturers have optimized the production of a lower-cost, low-pollution ARB diesel.

Given that the thrust of this amendment is the development of specifications for fuel properties with equivalent emissions, then the focus should be on the properties and averages of the in-use fuels shown in Table X1-2. An immediate question, and one needing further development, is whether the emissions vary linearly with fuel properties. If so, then linear averaging of properties can be used to maintain equivalent emissions. If emissions vary non-linearly with fuel properties then the weighting must accommodate those properties accordingly. However, at least the publication by Lee (1998) suggests that emissions vary linearly over the range of properties for normal commercial fuels. Staff must show that emissions are maintained over the range of commercial fuel properties as well as the average of that property.

Another issue with the averages developed in Table X1-3 is the use of straight or unweighted averages. A better approach would be the use of property averages weighted by the fraction of that fuel that is consumed in the California. Possibly the variation in fuel properties is small and within the measurement error, then such averages might not be needed. For example if the aromatic content was 19.9 ± 0.5 , one might not need such weighted averages. However, it is difficult to tell based on the information presented in the report and staff might want to report range and averages in order to gauge the need for market-weighted averages.

Moving from Table X1-2 to Table X1-3 also raised questions. My opinion is that only the properties of the in-use fuels from Table X1-2 should be averaged. Therefore the average aromatic content of 20.3 vol.% or 20.7 wt% should be the average shown in Table X1-3 – unless there is staff rationale for a different number. In that case then staff must present the reasons for a different number. For example, an aromatic level of 20.7 vol.% is recommended over the average of 20.3 vol.% because of a margin of safety or ...??

The one property average that raised some concern was the nitrogen level in that the average was 110 ppmw and the proposed limit was ≤ 500 ppmw. Earlier in Table III-1, the average nitrogen level is shown as 150 ppmw. The staff report needs further development to justify the 500 ppmw and the manufacturing data suggest that a lower limit might be an acceptable commercial fuel. It seemed that the current commercial level of sulfur was used to establish the sulfur specification and similar rationale could have been used to establish the nitrogen level or staff could have selected a higher nitrogen number to accommodate an additive that raised cetane by 2 numbers, for example. In any event, the numbers in Table X1-3 should be representative of the in-use averages or if they differ, then sufficient rationale must be developed. Repeating an earlier comment, it would be helpful to know the typical (average), range and variation of the in-use properties.

The staff developed well the rationale for including a specification for the density of fuel. Numerous reports starting with the Lange (1991) have shown that emissions do vary with fuel density, thus density should be included in the proposed equivalent limits. This information was not known at the time of the implementation of the original ARB rule.

2.5 Proposed Regulation for Establishing a Diesel Fuel Lubricity Standard

This chapter deals with a new regulation, namely the establishment of a minimum lubricity standard for commercial diesel fuel.

Staff aptly points out that adequate levels of fuel lubricity are necessary to protect the contact points in fuel pumps and fuel injectors in order to maintain reliable performance. The report discusses that the new fuels are likely be lower in lubricity and needing more additive. However, I believe the report could have included more information about the critical nature of preventing wear to the fuel injectors and fuel pump in order to maintain the factory emission levels. For example, ARB provides estimates in EMFAC 2000 that PM emissions for a heavy-duty vehicle will increase from about 50% from a minor injector problem to >700% for severe injector problem. The same table shows PM emissions will increase about 25% for a high fuel rate for a heavy-duty vehicle. While these figures are based on limited data and the malfunction may not have been caused by wear, the numbers convey the magnitude of the issue when the fuel system equipment is compromised and not maintained at the factory specifications. Given this background, it would seem that maintenance of the fuel components and emission levels to those set at the factory would be of concern to the ARB at the time that a new fuel specification is being established, especially for existing equipment and as engine manufacturers introduce new fuel components to meet the future emission specifications.

The report clearly describes the issues raised at the workshops held on the proposed amendments to the diesel fuel regulations. Multiple views exist on the acceptable lubricity limit and the ASTM has not yet developed a consensus view. For example, Borsch presented data at a workshop showing that they preferred the high frequency reciprocating rig (HFRR) test method and that a suitable fuel produces a maximum wear scar diameter (WSD) of about 460 microns. Another view is included in the World Wide Fuels Charter where the maximum WSD limit is set at 400 microns. ASTM is set to ballot a maximum limit of 520 microns. Given this backdrop, staff recommends the adoption of the HFRR method to satisfy the majority of stakeholders and a maximum WSD of 520 microns. While this value is higher than the OEM recommendations, it is the level that is being balloted by ASTM and is representative of most in-use fuels in California. Staff's rationale seems justified in selecting 520 microns as the limit since CARB diesel fuel at that limit has protected existing hardware for a decade and might be adequate for the future equipment.

Staff recommends a three action steps:

- 1) The adoption of the HFRR method and limits in August 2004,
- 2) A technology assessment and report to the Board in 2005, and
- 3) A rule in 2006 if the ASTM has not issued a specification.

The report could have been clearer as to the urgency of the 2004 implementation date, given that most fuels today are sold under the voluntary SCBOCLE test that is equivalent to the HFRR method that is recommended. This reviewer supports the proposed limit of 520 microns by HFRR, the technology assessment studies and report to the Board as outlined in the report.

2.6 Need for Nonvehicular Diesel-Engine Fuel Regulation

This chapter deals with the adoption of an Airborne Toxicant Control Method (ATCM) requiring the use of low-sulfur CARB diesel fuel in all nonvehicular diesel engines subject to ATCM's implemented as part of the CARB's Risk Reduction Plan for PM. Equipment subject to the ATCMs include stationary, portable and transportation refrigeration units but not locomotives and marine vessels. Also each air district could propose its own ATCM to reduce diesel PM. The rationale is based on the expectation that all diesel engines would be equipped with diesel particle filters (DPFs) as these devices control PM to >85% but require a diesel fuel with <15ppm sulfur to function properly.

Research on the demonstration of successful control technologies for the nonvehicular units is still in its infancy and information is just being developed about effective control strategies for the nonvehicular units. The work to date suggests DPFs will work only in certain cases. For example, ongoing research by ARB and the University of California, Riverside has unpublished results that show PM emissions from stationary/portable generators with diesel engines can be controlled using passive systems, like DPFs, to about 90% with a fuel with <15ppm sulfur.

However, besides a fuel containing <15ppm sulfur, another critical issue for the successful operation of a DPF is having an exhaust temperature that is hot enough for the device to be activated. For example, Figure 2.1 below shows the exhaust temperature of a TRU as a function of time for an operating cycle. The DPF will probably not work effectively for the time and temperature profile shown below. Research on portable units is on going to determine which ATCMs will successfully control nonvehicular units.

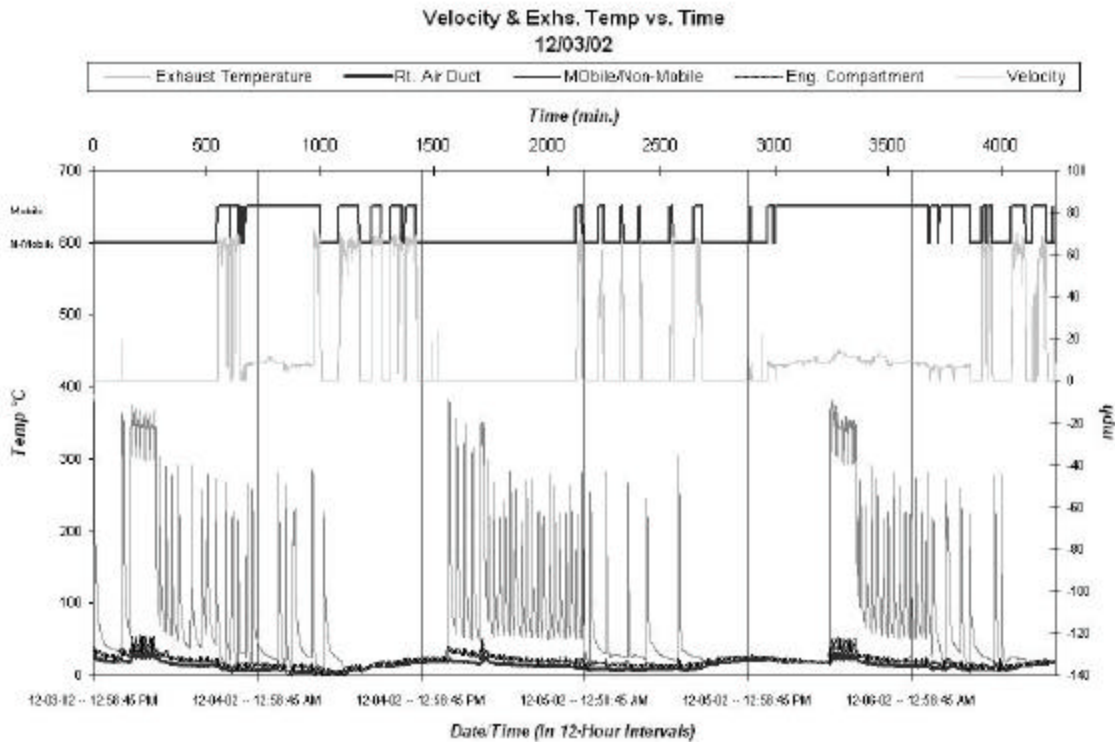


Figure 2.1. Exhaust temperature in °C as a function of minutes of operation for a TRU on a delivery truck. Upper plot is a GPS trace and represents whether the truck is moving or not.

Given that research is so active in this area and definite solutions have not been demonstrated; it seems presumptive for staff to require diesel fuel with <15ppm sulfur for all nonvehicular units. Some units, like stationary generators, have demonstrated that the control devices require <15ppm sulfur for the DPFs to control PM to >85%. However, other control technology is being tested in ARB's verification program and may not require <15ppm sulfur. Therefore, my suggestion is that this area be identified as a technology study area and that staff would make a recommendation to the Board in the 2005 timeframe, the same as for the diesel lubricity specification.

3.0 Rule for limiting Sulfur and Aromatic Content of Diesel Fuel (1988)

While the main thrust of the June 6, 2003 document deals with the reduction of the sulfur content, the introduction of a lubricity standard and some changes in the alternative diesel fuel regulations, the peer reviewers were asked to analyze the earlier rules for CARB diesel and that review is covered in this section.

A diesel fuel meeting special California requirements was initiated about the 1985 when a low-sulfur diesel fuel was introduced into the South Coast Air Basin and Ventura County. This fuel was followed by the regulation in 1988 that limited the sulfur content and the aromatic hydrocarbon content of diesel motor fuel for all of California starting in October 1993. A key element of the 1988 ARB regulation was the limitation of the sulfur content in diesel fuel to 500 ppmw and the aromatic hydrocarbon content to 10 volume percent for large refiners and to 20 volume percent for small refiners. Benefits of the new rule included reduced emissions of sulfur oxides, nitric oxides and particulate matter from diesel-fueled motor vehicles. The need for a rule was based on the requirement to reduce current and projected emissions from diesel-fueled vehicles.

The sulfur limit of 500 ppmw was easily justified based on the accompanying reduction of sulfur oxides and particulate matter in the atmosphere. Further a diesel fuel with the same sulfur content was already being used in the South Coast Air Basin and Ventura County since 1985. The issue for a sulfur requirement was quickly resolved.

However, from my recollection, the adoption of the rule limiting the aromatic hydrocarbon content to 10 volume percent was more contentious and required considerable discussion as this was the first rule to limit aromatics in diesel fuel. Furthermore as testing of heavy-duty diesel engines was expensive and complex, there were very few data available on emissions reduction due to fuel reformulation. These data were needed as the basis for the regulation so the ARB relied on new test data from a collaborative test program that was primarily planned and paid for by the automotive and petroleum industries under the banner of the Coordinating Research Council (CRC). ARB was a minor participant and provided some funding to expand the scope of the program. A number of fuels with various fuel properties were tested in a Cummins NTCC 400 and a Detroit Diesel DDAS Series 60 engine at an independent contractor (Southwest Research Institute). The Cummins engine represented current technology and the DDC represented future engine technology.

ARB's analysis of the results from the CRC program showed that reducing the aromatic content from the state-average value of 31 volume percent to the proposed 10 volume percent would lower the emissions of nitric oxides by 6% for the Cummins engine and by 13% for the DDC engine. Other studies by EPA and Caterpillar showed that reduced aromatics would lower NOx emissions and a study by Chevron found no effect on NOx emissions. Given this input, the staff weighted their analysis heavily on the CRC work and the Board adopted a rule limiting sulfur and aromatic contents in the diesel fuel and allowed for a production of a fuel with an alternative aromatic hydrocarbon content with equivalent emissions.

Looking back, I am not aware of any information that has challenged the CRC test plan or the experimental work and results from SwRI, so the ARB acted using sound technical practices when they adopted the regulation in 1988. Since 1988, much data has become available and some technical issues have developed, especially those related to the coupling of the fuel variables and the effects that engine operation can have on the apparent fuel effects. These data and reports are discussed in the next section.

4.0 Rule for limiting Sulfur and Aromatic Content of Diesel Fuel (after 1988)

Since the CRC work in 1988, considerable literature has been published about the influence of diesel fuel properties on exhaust emissions. Even with all the research since the original ARB rule in 1988; however, two points are clear from the literature. First, it is well documented that changes in diesel fuel composition can be used to reduce emissions levels, and second, the effects of the change on each fuel property cannot be easily understood because of the complex interactions between engine operating conditions and fuel properties. Studies of fuel variables are further complicated by the fact that the properties tend to be intercorrelated in the test fuels. For example, fuels with a high density often have a high content of aromatics.

Lange (1991) studied diesel fuel properties in DDC Series 60 and concluded that the fuel density rather than aromatics was the dominant factor for PM emissions as the more dense fuels led to over fueling of the engine. A follow-on study by Den Ouden (1994) considered fuel effects and PM emissions for several engines. He reports that three of the five heavy-duty engines showed a cetane effect on PM and density effects were second order in a steady-state cycle. Density effects were found for the transient cycles, however. Ullman (1991) reports that engine tuning is more important than fuel properties; however, lower emissions are favored with a fuel that has lower aromatic and sulfur contents and high cetane number. Yasuo (1991) reports that enriching the aromatic content in a fuel causes an increase in NO_x, CO and THC.

Crowley (1993) reported that sulfur, density and cetane had the most effect on PM emissions and that total aromatics had no effect. Also in 1993, Rosenthal determined that the aromatic content is the primary fuel parameter driving NO_x and PM for engines operating below 1994 emission levels. Signer (1996) reports on a very large industry study, the European Programme on Emissions, Fuels and Engine Technologies (EPEFE). Their results show that NO_x emissions increase with increased timing and polyaromatics and the degree of emissions increase depends on the engine. They concluded that fuel density was the most influential property to reduce NO_x.

Stradling (1997) reported on the influence of fuel properties and injection timing on emissions. His findings show that the NO_x emissions could be controlled by injection timing, fuel density and aromatics content. Lee's review (1998) points out that decreasing aromatics resulted in a small benefit in NO_x emissions. They also commented that one study operated in an "off-design" mode did not show an aromatic effect until it was operated in a more optimal timing regime. Lange (1998) investigated fuel properties on advanced engine technologies and concluded that the fuel effect for cetane and NO_x emissions was dependent on the test cycle and the interaction between engine design and the ignition properties of the fuel.

Yoshiyuki (2000) reports that the increasing aromatics will increase PM and NO_x. Neill (2000) reports that there was a definite trend towards higher NO_x emissions as the fuel density, and total aromatics are increased in their study. Mason (2000) reports on the

results of the EPA's heavy-duty engine working group (HDEWG) who found that NOx emissions correlated with density, cetane, and mono- and poly-aromatics.

In perspective, the understanding of the relationship between fuel composition, engine operation and emissions is more developed since 1988; however, there are a number of factors that make it difficult to unify the results. Mann (1998) attempts to explain the differences in reported findings by pointing out that fuel effects can change the engine operating conditions and emissions. EPA does develop their unified model, shown in Appendix D, and estimates a 6-percent NOx reduction for engines without EGR due to California fuel. ARB staff arrives at a similar figure for NOx reduction after an extensive analysis of many papers, including the most recent data. From my perspective, the literature data and analysis are consistent that the NOx can be reduced by a reduction in aromatic content for existing engines and the 6% reduction is about right, in that it is not 60% or even 16%.

Looking ahead to 2004 and 2007, there will be new generations of engine technology so a whole new series of testing of fuel properties and emissions will need to be undertaken. In addition to the changes in the design of the engine, there will also be significant developments in the control of NOx and PM with exhaust control technology so the engines/control systems will probably have a reduced response to the effects of fuel parameters.

4.1 Notes on Statistical Analysis Methodology

While the statistical approach seems technically correct to me, I asked a colleague, Mr. Theodore Younglove, who is a Principal Statistician at UCR to thoroughly review the methodology for the ARB staff analysis and the conclusions reached by that analysis. His analysis is attached in Appendix A.

4.2 Comments on Research Test Methods and In-use Emissions

In reviewing a number of papers, I was struck by the fact that these engines were being tested using certification cycles. However, it is well established that emissions from engines are compliant under certain operating conditions and non-compliant under other operating conditions. This non-linear result is indicative of an engine map with multiple operating modes (see Figure 4.1 below). Engines with electronic controls can operate in multiple modes as the computer attempts to optimize fuel consumption and advances the engine. Thus the fuel effects should be measured following in-use conditions rather than the certification cycles since the latter conditions may no longer represent the actual operating modes. As shown by earlier authors, engine timing does affect the fuel sensitivity so testing for electronically controlled engines should be undertaken with the engine advanced in order to gain more insight into the true effect of aromatics on nitric oxide emissions.

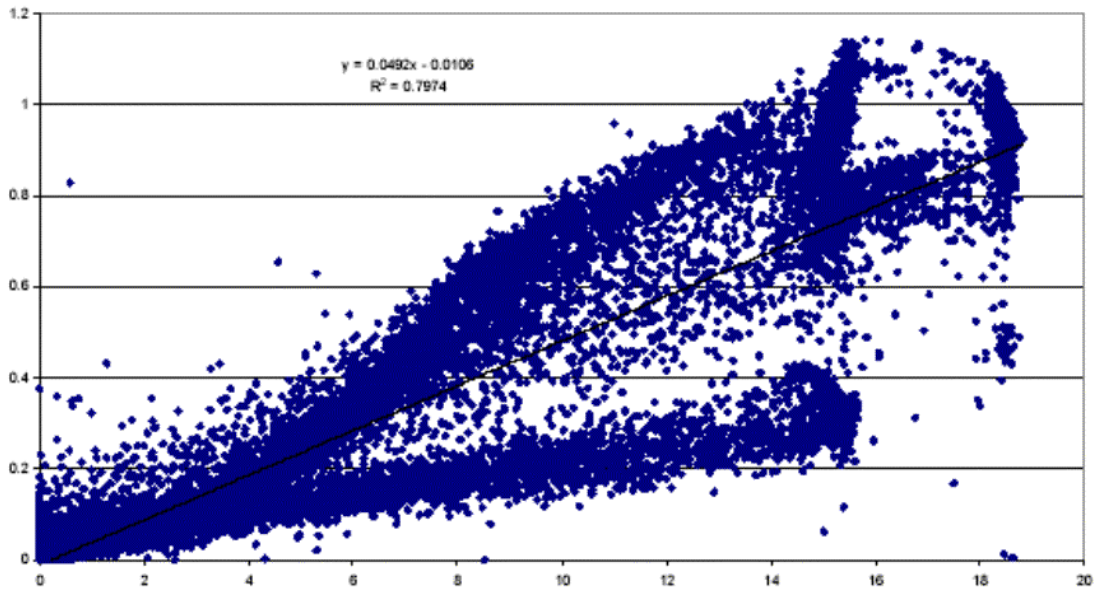


Figure 4.1. On-road, second-by-second NO_x emissions as a function of fuel consumed for an engine with multiple operating modes, including a lower track for compliance testing and a higher fuel economy mode with triple the emissions rate.

5.0 Benefit Analysis

Benefits of the proposed rule are discussed in Appendix E. The approach of using four technology tiers and EMFAC 2002 to estimate the benefits of the proposed rule seems quite in order. Cutting off the NO_x benefits for the Tier III or post-2006 engines is on the conservative side as the engine manufacturers have beyond that date to fully implement the EPA rules. Taken in total, it should be no surprise that significant benefits are carried on into the future as the diesel vehicles last over a million miles in the current EMFAC.

The NO_x and PM benefits for the 2003 rulemaking are compared with the estimates from the 1988 rulemaking in the following table. Results show a good agreement considering the time interval and the introduction of new engine technology that could not have been modeled in 1988.

Emission	1988 Proposed Rule		2003 Proposed Rule	
	2000	2005	2000	2005
NO _x , tons/day	67	78	56	38
PM, tons/day	10	10	5.5	4.6

Table 5.1 Emission benefits in 2000/2005 as estimated in the 1988 and 2003 proposed regulations.

6.0 Definitions

It seemed in reviewing the report that there were several definitions that need further thought to simplify communication. These definitions are discussed in this section.

Weight percent versus Volume Percent. Table X1-3 specifies a change from volume percent aromatics to weight percent. My preference would be to maintain the volume percent given that the original rule was a 10 vol% aromatic rule and that the proposed certification fuel still uses volume percent. Furthermore, volume percent is the current metric used in the commercial world and in most literature so it will simplify communication. For example, it is interesting that the World-Wide Fuel Charter suggests weight percent and then uses data based on volume percent to justify the need for such a specification. Also the ARB Fact Sheet on the California Low Sulfur Diesel Fuel (6/27/03) uses both volume and weight percent interchangeably and this can be confusing. The ASTM method allows an easy conversion equation from the measured weight percent to volume percent and that equation should be included in the front of the staff report as well as in the appendix.

Low-sulfur Diesel Fuel. The report uses the term low-sulfur diesel fuel. However, that is already an item of commerce indicating < 500ppmw and one that will continue for some time based on the EPA's new rule for nonroad equipment. Thus I would suggest a new name for the diesel fuel with <15 ppmw.

Diesel Fuel It would seem that continuing to use the ASTM definition would be preferred since items of commerce look to ASTM. Also issues with alternative diesel formulations, including biodiesel are arranging for their own ASTM designation.

References:

1. Asaumi, Y., Shintani, M. and Watanabe, Y., (1992) "Effects of Fuel Properties on Diesel Engine Exhaust Emission Characteristics," SAE Technical Paper No. 922214.
2. California Air Resources Board, (1988) "Proposed Adoption of Regulations Limiting the Sulfur Content and the Aromatic Hydrocarbon Content of Motor Vehicle Diesel Fuel" October
3. California Air Resources Board, (1990) "Proposed Amendments to the Regulations Limiting the Aromatic Hydrocarbon Content of Motor Vehicle Diesel Fuel" October
4. California Air Resources Board, (2003) "Proposed Amendments to the California Diesel Fuel Regulations Staff Report: Initial Statement of Reasons," June 6
5. Cowley, J.T., Stradling R.J. and Doyon, J., (1993) "The Influence of Composition and Properties of Diesel Fuel on Particulate Emissions from Heavy Duty Engines," SAE Technical Paper No. 932732.
6. Den Ouden, C.J.J., Clark, R.H., Cowley, L.T., Stradling, R.J., Lange, W.W. and Maillard, C., (1994) "Fuel Quality Effects on Particulate Matter Emissions from Light – and Heavy-Duty Diesel Engines," SAE Technical Paper No. 942022.
7. Kidoguchi, Y., Yang, C., and Miwa, K., (2000) "Effects of Fuel Properties on Combustion and Emission Characteristics of Direct-Injection Diesel Engine," SAE Technical Paper No. 2000-01-1851.
8. Lange, W.W, Cooke, J.A., Gadd, P., Zurner, H.J., Schlogl, H. and Richter, K., (1997) "Influence of Fuel Properties on Exhaust Emissions from Advanced Heavy-Duty Engines Considering the Effect of Natural and Additive Enhanced Cetane Number," SAE Technical Paper No. 972894.
9. Lange, W.W., (1991) "The Effect of Fuel Properties on Particulates Emissions in Heavy-Duty Truck Engines Under Transient Operating Conditions," SAE Technical Paper No. 912425.
10. Lee, R., Pedley, J. and Hobbs, C., (1998) "Fuel Quality Impact on Heavy Duty Diesel Emissions: - A literature Review," SAE Technical Paper No. 982649.
11. Mann, N., Kvinge, F. and Wilson, G., (1998) "Diesel Fuel Effects on Emissions-Toward a Better Understanding," SAE Technical Paper No.982486.
12. Mason, R.L., Matheaus A.C., Ryan III, T.W., Sobotowski, R.A., Wall, J.C, Hobbs, C.H., Passavant, G.W., Bond, T.J., (2000) "EPA HDEWG Program-Statistical Analysis," SAE Technical Paper No. 2000-01-1859.
13. Mitchell, K., (2000) "Effects of Fuel Properties and Source on Emissions from Five Different Heavy Duty Diesel Engines," SAE Technical Paper No. 2000-01-2890.
14. Mitchell, K., Steere, D.E., Taylor, J.A., Manicom, B., Fisher, J.E., Sienicki, E.J., Chiu, C., Williams, P., (1994) "Impact of Diesel Fuel Aromatics on Particulate PAH and Nitro-PAH Emissions," SAE Technical Paper No. 942053.
15. Neill, W.S., Chippior, W.L., Gulder, O.L., Cooley, J., Richardson, E.K., Mitchell, K. and Fairbridge, C., (2000) "Influence of Fuel Aromatics Type on the

- Particulate Matter and NO_x Emissions of Heavy-Duty Diesel Engine,” SAE Technical Paper No. 2000-01-1856.
16. Nylund, N.O., Aakko, P., Millomen, S. and Niemi, A., (1997) “Effects of Physical and Chemical Properties of Diesel Fuel on NO_x Emissions of Heavy-Duty Diesel Engines,” SAE Technical Paper No. 972997.
 17. Rosenthal, M.L., and Bendinsky, T., (1993) “The Effects of Fuel Properties and Chemistry on the Emissions and Heat Release of Low-Emissions Duty Diesel Engines,” SAE Technical Paper No. 932800.
 18. Signer, M., Heinze, P., Mercogliano, R. and Stein, H.J., (1996) “European Programme on Emissions, Fuels and Engine Technologies (EPEFE) – Heavy Duty Diesel Study,” SAE Technical Paper No.961074.
 19. Stradling, R., Gadd, P., Signer, M. and Operti, C., (1997) “The Influence of Fuel Properties and Injection Timing on the Exhaust Emissions and Fuel Consumption of an Iveco Heavy-Duty Diesel Engine,” SAE Technical Paper No. 971635.
 20. Ullman, T.L. and Human, D.M., (1991) “Fuel and Maladjustment Effects on Emissions from a Diesel Bus Engine,” SAE Technical Paper No. 910735.
 21. U.S. Environmental Protection Agency (EPA). (2000) “Control of Air Pollution from New Motor Vehicles: Heavy-duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements,” December 21.

Appendix A

Review of the Statistical Methods Selected for the staff report: Proposed Amendments to the California Diesel Fuel Regulation, June 6, 2003

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Background

Diesel fuel is composed of many compounds that to a greater or lesser extent can be modified in proportion. Regulations at the state and federal level have sought to lower the emissions from diesel vehicles through changes in the composition of diesel fuels. Recent studies have shown that in addition to the regulated diesel fuel properties, unregulated diesel fuel properties such as fuel density, T50, and T90 can also have an effect on NOx and PM emissions. Many of these compounds can directly affect emissions of diesel engines singly and in combination. For example, decreases in cetane number and aromatic content have been shown to increase NOx and PM. This complex set of compounds with the potential for large numbers of interactions between compounds present a difficult data set for statistical analysis. Adding to the complexity are the changes in diesel engine technology over the past several decades. The advent of computer controlled engines as well as the evolution of combustion chamber design, injection technology, Exhaust Gas Recirculation (EGR), and changes in induction from superchargers to turbochargers and inter-cooled turbochargers add to the complexity as well. Over the observed range of many of the compounds in typical in-use fuels the emissions response has been approximated by linear and quadratic regressions. However, the potential for higher order interactions and non-linear responses make prediction outside of observed levels potentially invalid. Further regulatory needs require valid, statistically sound analysis of the available data for support of rulemaking.

Emission Equivalency of Candidate Fuels to Reference Fuels

ARB has developed a test for candidate fuels to qualify as an alternative formulation to the California reference fuels. The average specific emissions of NOx, PM, and SOF during testing must not exceed the average emissions of the reference fuel. For this test, the interactions between fuel components that make estimation of the effects of individual fuel properties difficult do not matter. This test is a test of emissions between the candidate fuel and the reference fuel and depends only on the emissions results. The statistical test is based on the t-statistic and takes the form:

$$\text{Mean (Candidate Fuel)} < \text{Mean (Reference Fuel)} + \delta - S_p \sqrt{2/n} * t$$

Where:

δ = is a tolerance percentage that varies by fuel.

n = total number of valid tests run for each fuel.

S_p = Pooled Standard Deviation of the emissions over the n tests for each fuel.

t = the value of the one sided Students t distribution for $\alpha=0.15$ and $2n-2$ degrees of freedom.

The t-test is an appropriate test statistic for use in checking for differences from a standard reference. The t-test is a robust statistical test so that the accuracy will not be seriously affected unless large deviations from the assumption of normality are encountered. Repeated emissions tests on specific fuels are unlikely to encounter significant problems with normality and are unaffected by the interacting fuel properties as long as the fuel used in testing is consistent in mixture and storage from test to test. Proper fuel storage, transfer, and pre-conditioning should minimize test-to-test variability within fuels.

The choice of δ for the individual fuels is important in providing some safety in determining equivalency while assuring that a fuel would be able to satisfy the equivalency criteria when tested against itself. The ARB analysis on page 57 is based on a large sample of tests with reference fuels (335) and is sufficiently large for accurate estimation of the mean emissions levels and more importantly for this analysis, the estimation of S_p . The analysis is appropriate and supports lowering the tolerance levels to 1%, 2%, and 6% as noted in the text.

MODELING OF EMISSIONS EFFECTS FROM DIESEL FUEL PROPERTIES

Understanding and modeling of the relationship between fuel properties and emissions is a key component in determining the emissions reductions from low emission fuels. In the EPA's HDEWG program the fuel properties tested for emissions effects were cetane number, density, polyaromatics, and monoaromatics (Mason et al, 2000). These components were selected and the experiment was designed such that the controlled fuel properties were relatively independent. Under these conditions statistically significant equations were found for density, cetane number, monoaromatics, and polyaromatics and all fuel/emissions equations were linear. However, the equations were limited to linear regressions because of the limited number of levels of the properties in the testing. ARB staff analysis of additional data from all available studies found that cetane number had a negative slope with respect to NO_x, differing from the HDEWG results. The results of the ARB analysis are based on a broad range of data collected on a variety of engines and configurations and represent the best estimate currently available. The correlations between the fuel properties, as was pointed out by ARB staff, make direct interpretation of the coefficients risky.

The ARB estimates of the NO_x reductions due to California diesel fuel across studies ranged from 2% to 8%. The wide variety of engines and fuels used in the various test programs reviewed by ARB, as well as the previously mentioned correlations between the fuel properties likely account for the observed differences in the estimates. While it is possible that the underlying relationship between the fuel components and the emissions deviates from the linear models used, the studies were not designed to provide a thorough understanding of the underlying relationships. The analysis conducted by the EPA as well as the ARB do indicate that the linear models are adequate for modeling the effects over the range of fuel parameters observed in the studies, but as has been mentioned in both the EPA and ARB reports projection outside the data range is ill advised.

The variance about the regression line changes as a function of the distance from the mean point of the variable. For example, the confidence limits about the simple linear regression line for the mean are at a minimum at the point (mean X, mean Y) and expand with distance from the centroid (Figure 1). What this means for the fuel effects equations is that fuels that have properties near the outer range of the tested properties will have larger variance in estimated emissions about the regression line than fuels having tested properties near the mean of the tested range. Estimates of the emissions taken from the data are not affected because they are calculated from the observed data, however estimates of the emissions at the outer range of observed fuel properties based on the regression will be less precise than estimates that are near the average of the fuel properties.

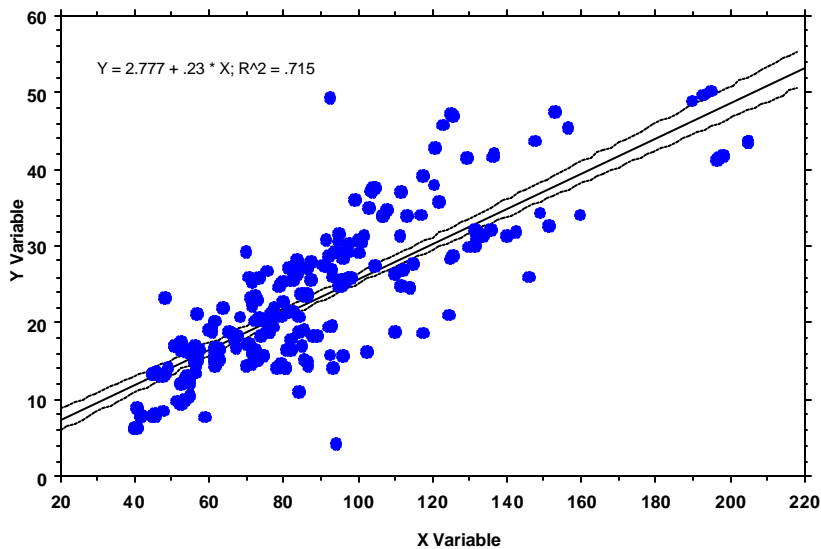


Figure 1: Example Regression with 95% Confidence Limits of the Mean.

One additional minor point is the potential for variability in the measurement of the fuel components. While the actual level of a particular fuel component in a particular batch of fuel is fixed, it is subject to measurement error. Measurement error in the X variables violates one of the assumptions for regression analysis when the experimenter selects the levels. If the assumption of no measurement error is violated the regression slope and

intercept parameters lose their unbiased and consistency properties. The reason for this is that the X variable is assumed to be fixed and not subject to random measurement error so when there is measurement error the emissions measurements will be matched against an incorrect fuel property level (see Neter and Wasserman, pg 169 for more details). These measurement errors in the fuel properties will have no effect on the regression assumptions if their expected value is 0 (the measures of the fuel properties are unbiased) and the independent variable is constant. In the case of the fuel properties, with proper storage and transfer and preconditioning the fuel properties can be assumed to be constant. Thus this is not expected to be a problem in the regressions in this case, but is brought up for completeness.

Conclusion

The ARB analysis reported in Appendix D: Staff Review of the Emission Benefits of California's Diesel Fuel Program are based on sound statistical practices and provide a good estimate of the benefits of California diesel fuel based on the current data available. The limitations of the data and methodology increase the variability of the estimated emissions reductions but are unbiased. Additional experiments that were designed to evaluate the shape of the response of emissions to the various fuel and engine properties over a broader range and in greater detail would provide better resolution; however, the colinearity of the fuel and engine variables will still have the potential to cause problems in the estimation of effects on individual fuel properties.

Reference

Neter, J. and Wasserman, W. "Applied Linear Statistical Models", Richard D, Irwin, Inc. Homewood, IL, 1974.

Appendix B

Document for briefing for the ARB Board hearing on July 24, 2003.

Good morning. Dr Lloyd and other distinguished members of the Board

My name is Dr. Wayne Miller. I am one of four people asked to review the ARB proposed amendments to the California Diesel Fuel Regulations under the interagency agreement No. 98-004 where the University agrees to provide peer scientific review of scientific work conducted by state agencies. The other reviewers included: Dr. Robert Sawyer of the University of California, Berkeley, Dr. Donald Lucas of the Lawrence Berkeley Laboratory and Dr. Laurence Caretto of California State University, Northridge.

By way of background, I have a PhD from the California Institute of Technology in Chemical Engineering and since 2001 have been Director of Emissions and Fuels Research at the CE-CERT Laboratory at the University of California, Riverside

Prior to that I spent over 25 years in the petroleum industry working on refining processes and fuels formulation. During that time, I served as a member of the research committee for the Auto/Oil program and in 2000, was a member of the Philadelphia Air Quality Board, and was a member on the DOE and National Petroleum Council's study entitled: "Assuring the Adequacy and Affordability of Cleaner Fuels."

My background includes first hand knowledge in the development and implementation of the 1988 amendments on sulfur and aromatic content as I was working in the petroleum industry at that time. Currently, my research is focused on emissions from stationary and mobile sources and especially those using diesel fuel.

As described in the staff presentation, there are a number of important issues to consider today and I'd like to compliment the staff for a thorough and thoughtful job of putting their report together. My review will touch on each area.

Reducing the Maximum Allowable Sulfur Content of Diesel Fuel

Basically very low sulfur content is the key fuel parameter that needs to be implemented in order to enable new emissions control technology to be installed on diesel engines. As stated a limit of <15 ppmw is essential.

Change the Allowable Sulfur Content of Diesel Engine Certification Fuel

Staff described well the need for consistency in the maximum permissible content for sulfur.

Adopt New Equivalent Limits for Diesel Fuel Properties

This is an important new option for complying with the 10% aromatic content. It is well founded as emission benefits are maintained while allowing more manufacturing flexibility. Staff's approach for rule development was sound; however, my review asked for clarification on a few minor aspects.

Adopt a Diesel Fuel Lubricity Standard

Staff aptly points out the critical nature of preventing wear to the fuel injectors and fuel pump in order to maintain the factory emission levels. For example, ARB provides estimates in EMFAC2000 that PM emissions for a heavy-duty vehicle will increase from about 50% from a minor injector problem to >700% for severe injector problem. Given this background, it would seem that maintenance of the fuel components and emission levels to those set at the factory should be of concern to the ARB at the time that a new fuel specification is being considered. My review agrees with the process and their technical limit.

Revise the Requirements for Certifying Alternative Diesel Formulations

This is an important section as most CARB diesel today is an alternative diesel formulation rather than a 10% aromatics fuel. Staff has used good rationale in developing the amendments; especially that in-use fuels and candidate fuels have similar properties. I agree with the proposed amendments

Adopt Diesel Fuel Standards for Non-vehicular Diesel Engine Applications

The thrust of this regulation is to assure a supply of fuel for ATCMs used in Non-vehicular Diesel Engine Applications. Since research is just now identifying solutions and the justification was not strong, my opinion was to identify this as a technology study area and that staff would make a recommendation to the Board in the 2005, the same as for the diesel lubricity specification.

Rule for limiting Sulfur and Aromatic Content of Diesel Fuel (1988)

Why we are focused for the greater portion of this meeting on sulfur content, the reviewers were also asked to evaluate the original amendments of 1988. Looking back at 1988, there were very few published studies and the regulation was based on a carefully designed and executed study of the automotive and petroleum industries. Further, I am not aware of any information that has challenged the test plan or the experimental work

and results, so the ARB acted using sound technical practices in the regulation implemented for 1988.

Since 1988 a considerable amount of literature has been published about the influence of diesel fuel properties on exhaust emissions and two points remain clear. First, it is well documented that changes in diesel fuel composition can be used to reduce emissions levels, and second, the effects of the change on each fuel property cannot be easily understood because of the complex interactions between engine operating conditions and fuel properties.

From my perspective, the literature data and analysis by EPA and ARB are consistent in that NO_x emissions can be lowered by a reduction in aromatic content for existing engines. The magnitude of the effect, about 6%, seems about right. We know that it is neither 60% nor 16%. Looking ahead, engines with new technology will have to be tested as available. I'd like to note that my final review will include an analysis by a colleague at UCR with expertise in statistics as to the appropriateness of the various statistical methods that staff choose for their analysis.

BENEFITS

In closing, the benefits in 2005 of 38 tons per day of NO_x and 4.6 tons per day of PM make these amendments a valuable contribution to improving the air quality.

Thank you