U.S. Environmental Protection Agency
National Vehicle and Fuel Emissions Laboratory
Ann Arbor, Michigan

September 27, 2001

MEMORANDUM

TO: Karl Edlund, Director
Multimedia Planning and Permitting Division
Region VI

FROM: Robert Larson, Acting Director
Transportation and Regional Programs Division
Office of Transportation and Air Quality (OTAQ)

RE: Texas Low Emission Diesel (LED) Fuel Benefits

As you know, we were concerned about the NOx emission reduction benefits claimed by Texas for its LED fuel program as part of the SIPs submitted by Texas for demonstrating attainment with the 1-hour ozone NAAQS in both Houston and Dallas. Because of this concern, we initiated an effort last November to evaluate the emission benefits of varying diesel fuel parameters. In July, we issued a Staff Discussion Document[1] with the preliminary results of this analysis. Today we are sending you the NOx emission factors we believe should be used in estimating the NOx emission reductions attributable to the LED rule.

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

After reviewing the comments made at the workshop, we have estimated the NOx emission factors for the LED fuel program, based on this analysis. In making this estimate, we are separating our use of the draft NOx model presented in the Staff Discussion Document for evaluating the benefits of the LED fuel program from a more general use of the model to evaluate the emissions benefits of any particular diesel fuel parameter or program.

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[1] "Strategies and Issues in Correlating Diesel Fuel Properties with Emissions," Staff Discussion Document, EPA report number EPA420-P-01-001, July 2001.

Our conclusions resulting from this draft NOx model concerning the NOx emission reduction benefits of the Texas LED fuel program are described in the following table:

Table 1
Estimated Percent NOx Emission Reductions Under The Texas LED Program

	Percent NOx reduction for engines using Low Emission Diesel
Highway or >50 hp nonroad engines without EGR	6.2
Highway or >50 hp nonroad engines with EGR	4.8
<50 hp nonroad engines	undetermined

Exhaust gas recirculation (EGR) is expected to play a significant role in new engines designed to meet the 2004 heavy-duty emission standards (many of which are expected to be produced as early as 2002). EGR may also play a prominent role for nonroad engines designed to meet the Tier 3 standards beginning with model year 2005.

We believe that the benefit estimates given in Table 1 represent the best possible estimates at this time. Since the public comment period on our Staff Discussion Document will not close until October 30, 2001, we may yet receive comments which affect the estimates we are providing you today. However, we believe that the NOx benefits estimates in Table 1 are appropriate for use in the LED rulemaking. We will notify you if we intend to make any changes to these estimates after the comment period has closed. Additionally, we note that our estimate does not account for changes in driving patterns or re-fueling patterns about which some stakeholders expressed concerns regarding the use of LED fuel in Texas.

We describe in more detail in the attached technical summary some of the issues that were raised by stakeholders at the public workshop and which have the most direct bearing on our NOx benefit estimates for the Texas LED program. We reiterate that the draft NOx model should not be used on a more general basis to evaluate any other diesel fuel control program. Development of a more general model to be used in estimating the benefits of any diesel fuel changes would require more work than has been accomplished to date. If any other state should request a SIP revision for a diesel fuel control program, we would need to evaluate such a program on a case-by-case basis.

Attachment

ATTACHMENT– TECHNICAL SUMMARY

Issues in applying the draft EPA NOx model to the Texas LED program

In an effort to most accurately estimate the benefits of the Texas LED program, staff in EPA's Office of Transportation and Air Quality assembled a comprehensive database of all available emissions data and used it to develop a draft model correlating diesel fuel properties with NOx emissions. Our analytical approach and preliminary conclusions are described in the Staff Discussion Document referenced in the cover memorandum. Because there were a number of unresolved issues related to the development and application of the draft model, we established an open public process to gather input, including a public workshop held on August 28, 2001, with a written comment period which closes on October 30, 2001. We realize that the end of our comment period actually follows the October 15, 2001 deadline by which EPA's final action on the SIP for Houston must be taken. This occurs because, before there is any possible use of this model in contexts outside of the Houston SIP, we wanted to ensure that our stakeholders had sufficient time to review and comment on our analytical approach. Even so, we believe that the comments we have received thus far have enabled us to estimate the benefits of the Texas LED program even if the draft model is not appropriate for other contexts.

Of the comments we have received thus far from stakeholders on our draft emissions model, many pertain to the broader use of the model rather than to the specific case of estimating NOx benefits of the Texas LED program. In reviewing the comments, we believe it is possible to meet the short-term need of estimating benefits for the Texas LED program while continuing to evaluate all stakeholder comments regarding the general use of the model in a longer-term process. Below we review a number of the comments and provide preliminary responses in the limited context of evaluating the Texas LED program. A more comprehensive review and response to comments on our draft model will follow the close of the comment period on October 30, 2001.

Issue 1: *The natural cetane term in the draft model had a coefficient of zero, while the additized cetane term (via cetane improver additives) was non-zero. Many previous studies show natural cetane to be strongly correlated with NOx emissions. Also, previous studies have not found different effects for natural versus additized cetane.*

Response: We intend to more fully investigate the reasons that the natural cetane term was highly non-significant in the maximum likelihood curve-fitting that comprises the last step of our NOx model development approach, and to identify other modeling approaches that might produce legitimate alternative results that compare more favorably with engineering expectations. However, the colinearities between fuel properties in the database provide evidence that the emission effects that one might expect to be associated with natural cetane have been "aliased" by aromatics, specific gravity, and other fuel terms. This issue is discussed more fully in a subsequent issue below.

One approach for determining if the absence of a natural cetane term in the draft NOx model truly dilutes its credibility as a predictor of emission effects is to replace the natural and additized cetane terms with a single total cetane term. When this is done and the entire draft NOx model is reconstructed from scratch, the total cetane term remains statistically significant. In addition, the predicted NOx impact of the Texas LED program remains the same. As a result, we do not believe that the absence of a natural cetane term materially affects our estimates of the NOx benefits of the Texas LED program.

Issue 2: *The studies in the EPA database were not subjected to the same level of peer review as those used to develop the Complex Model.*

Response: Of the 35 studies in our database, 28 were SAE papers that were subjected to peer review before publication. Three other large studies were developed through the Coordinating Research Council which includes representatives from the fuel production and vehicle manufacture industries. The Heavy-Duty Engines Workgroup study was carried out through the Federal Advisory Committee Act, which governs the means through which the Agency pursues consensus on scientific investigations including test program design, implementation, and data interpretation. In addition, prior to model development we conducted our own review of the available studies to ensure that those included in our database met expectations for a properly conducted test program. Our own review included an examination of the quality of emission measurement equipment, test program structure, adherence to accepted engine conditioning procedures, etc.

Issue 3: *The database contains far fewer observations than that used to develop the Complex Model for gasoline. In addition, many of the observations were not produced from well-controlled test programs.*

Response: The database on which our draft NOx model was based contains approximately 1800 observations, compared to nearly 5400 for the gasoline Complex Model for NOx. However, the Complex Model for toxics only contained approximately 1800 observations. We do not believe that the size of the diesel database per se is problematic for construction of a fuel effects model. However, there are limitations to the diesel database that fall into two primary areas: technology representativeness and colinearities. With regard to evaluating the Texas LED program, we provide preliminary responses to these two issues below.

Issue 4: *1997 and newer model years are not well represented in the database. In particular, EGR-equipped engines are represented by only a single engine, and there are no engines that would include NOx adsorbers and PM traps expected for engines meeting the 2007 heavy-duty standards.*

Response: There is good reason to believe that the emission effects exhibited by the draft NOx model provide a sufficient description of the in-use fleet for evaluating the Texas LED program. First, of the 128 possible technology group-by-fuel property interactions, only six were statistically significant. This result suggests that fuel property effects on NOx emissions are largely consistent across different types of engine technologies.

Engines designed to meet the 2004 emission standards (many of which will be sold starting in 2002) may be exceptional, however. These engines are expected to use primarily exhaust gas recirculation (EGR) to meet these standards. An EGR-equipped engine was tested thoroughly under the auspices of the Heavy-Duty Engines Workgroup (HDEWG). The test fuels for this test program were extremely well controlled, and all of the data from this test program was included in the diesel database. Our draft approach to model development resulted in statistically significant cetane terms for technology group L, which represents EGR engines. The NOx impacts of the Texas LED program as predicted by the technology group L model exactly matches the predictions from the regression equation developed as part of the HDEWG test program. Since the technology group L cetane effects have been incorporated into the draft model presented in our Staff Discussion Document (see page 51), we believe that the draft NOx model appropriately represents the effects of EGR-equipped engines on the in-use fleet.

As for engines built to meet the 2007 model year emission standards, we agree that they may exhibit different responses to changes in fuel properties than pre-2007 engines. However, they will not be a significant part of the fleet in 2007, the year that Texas must demonstrate attainment in their SIP. As prototype 2007 engines become available, we can pursue additional testing and incorporate the data into the diesel database in preparation for a revision to the model.

Issue 5: *Colinearities between fuel properties in the database can produce different models which explain the data equally well but may differ significantly in their ability to predict in-use NOx impacts.*

Response: There are significant colinearities between fuel properties in the diesel database, the result of test programs in which the production and selection of the test fuels was not well controlled. The result is that a subset of the fuel properties may be sufficient to describe the impact of all fuel properties on emissions. If the colinearities are strong enough, different subsets of fuel terms can explain the data in the database equally well. However, these different subsets of fuel terms may produce very different predictions of emission effects for in-use fuels.

The stepwise regressions inherent in our draft NOx model development approach chose fuel terms for inclusion in the model which may have been surrogates for other fuel terms not included in the model. For instance, the draft NOx model does not contain a natural cetane term. Since both aromatics and specific gravity are highly correlated with natural cetane, it is possible that the aromatics and specific gravity term coefficients represent not just the effect of aromatics and specific gravity on NOx emissions, but also the missing natural cetane effect. This result can be referred to as "aliasing." Thus the absence of a natural cetane term may not noticeably affect the ability of the model to explain the data in the database, i.e. the r^2 value may not be materially affected.

However, the application of the draft NOx model to in-use fuels may be of greater concern. Changes to natural cetane would be expected to result in changes in NOx emissions based on previous studies and analyses, but the draft NOx model would suggest no impact of natural cetane on NOx at all. The exception to this problem would be if a change in natural cetane for which NOx emissions impact predictions are sought was accompanied by changes in other fuel properties that occur naturally in the production of diesel fuel. In this case, it would be not just natural cetane which changes, but multiple fuel properties, and the draft NOx model may then provide credible predictions of impacts on NOx emissions.

There is no obvious way to include the impact of in-use colinearities when changes in only a single fuel property are the focus. The one case in which this may occur naturally is when evaluating not individual fuel batches or hypothetical fuels, but averages of many real fuel batches. In this case, the refinery production processes that produce colinearities between diesel fuel properties would be represented in the average fuel properties being evaluated. The aliasing of fuel property effects would therefore be less of a concern, and the draft NOx model may be appropriate. This is the case for the Texas LED program, in which our best estimates for both the baseline fuel and Low-Emission Diesel fuel are derived from averages of in-use survey data. For this reason we continue to believe that the draft NOx model is appropriate for evaluating the benefits of the Texas LED program.

Issue 6: *The baseline fuel that EPA used may not be representative of average Texas fuel or of future fuels.*

Response: In order to determine the benefits of the Texas LED program, we needed both a baseline fuel to represent current average diesel fuel properties in the areas where the fuel program will apply, and a fuel that represents the expected production under the LED program. The difference in predicted NOx emissions according to our draft model for these two fuels provides an estimate of the benefits of the LED program. Our Staff Discussion Document discuses both the baseline fuel and the fact that we have used AAM survey data for Los Angeles to represent the Texas LED program.

The baseline fuel would ideally be based on recent fuel property data specific to the areas to which the LED program will apply. There was no such survey data available for Houston. There was, however, recent survey data from the Alliance of Automobile Manufacturers (AAM) for San Antonio. We compared the average fuel properties for San Antonio to those for the nation as a whole (excepting California) using the same survey data and discovered that San Antonio and nationwide average fuel properties were very similar. Given that we could not provide certainty that the San Antonio average fuel was a better representation of Houston fuel than the nationwide average fuel given the small differences between the two, it seemed prudent to use the nationwide average fuel properties to represent the baseline fuel. In other areas of the country, the nationwide fuel properties may not be an appropriate baseline.

By mid-2006, highway diesel fuel will be subject to new sulfur standards. Although the draft NOx model does not contain a sulfur term, we expect that the very low sulfur levels will result in a corresponding small change in density that *would* affect the predicted NOx emissions. This density impact has not been incorporated into MOBILE model predictions that form the basis for NOx inventory projections in the Houston SIP. Accounting for this density impact in our draft NOx model would result in NOx estimates that are inconsistent with the inventories that Texas estimates in its SIP, resulting in artificially lower estimated NOx benefits for the Texas LED program. Therefore, we have determined that it is more appropriate to use current nationwide average diesel fuel properties to represent the baseline fuel for all years.

Issue 7: *The fuel that EPA used to represent the Texas LED program may not be correct.*

Response: The Texas LED program is modeled upon the California diesel fuel program. It might be appropriate to model this program using only the program's 10 vol% cap for aromatics. However, in California most refiners take advantage of the option to produce alternative formulations that are deemed equivalent to the specification fuel. These alternative formulations have higher aromatics levels, but also higher cetane levels. Since this approach offers refiners greater flexibility with the opportunity to minimize costs, we expect the same to occur under the Texas LED program as well. In fact, the Texas LED rule specifically allows any fuel certified under California's alternative formulations process to be used as an equivalent fuel for LED. Therefore, we believe that the most credible description of likely average fuel properties under the Texas LED program is the current average fuel in California. Once again we used AAM survey data to estimate the average fuel properties for California fuel.

Still, there are a number of concerns with the use of average California fuel to represent the Texas LED program. First, the AAM survey data represents only samples taken in Los Angeles. Although these samples represent a number of different refineries, they obviously do not represent all of California. However, contacts in the California Air Resources Board indicate that the AAM survey data meet their expectations and observations for average fuel being sold currently in California. Proprietary information on the certified alternative formulations for individual California refineries would not provide a more accurate description of in-use fuel properties because those alternative formulations are defined by caps on specific fuel properties, not the narrow ranges that would permit averages to be calculated. Additional survey data from other sources may be available in the near future, and we will re-evaluate our estimates of average California fuel properties once this data is in hand.

A second concern with the use of California data is the fact that California refineries are not designed and operated the same as those that supply fuel to Houston. However, insofar as this is the case, there is no straightforward way to adjust average California fuel properties to account for this difference. Thus in the absence of better data, we believe that the AAM survey data for California provides the best representation of the fuel we would expect under the Texas LED program.

Issue 8: *The EPA model was not based on nonroad engines, and so should not be used to represent nonroad engines.*

Response: There was too little data to develop an independent model for nonroad engines. However, as described in the Staff Discussion Document, there is an engineering expectation that large nonroad diesel engines will respond to changes in fuel properties in a manner similar to that for heavy-duty highway diesel engines, based on their similarities in engine design and technology. The smallest nonroad engines, on the other hand, tend to be much more dissimilar to their heavy-duty counterparts, and so would not be expected to be well represented by our draft NOx model. As a result, we believe it is reasonable to apply the effects from the draft NOx model to large nonroad engines, but to treat nonroad engines rated at less than 50 hp as though they were not represented by the draft NOx model. This approach is consistent with the fact that light-duty diesel engines are also not expected to be represented by the draft NOx model.

In order to verify that this approach is reasonable, we compared the NOx emission effects of fuel changes from recent data collected on nonroad engines to predicted NOx effects from our draft model. See “Nonroad Diesel Engines Under 50 hp,” Memorandum from Cleophas Jackson, U.S. Environmental Protection Agency, to Docket for the Houston SIP/ Low Emission Diesel Rule, dated September 27, 2001. The results do not indicate any sort of bias when comparing predicted to observed values. As a result, there is no reason to believe, based on currently available information, that it would be inaccurate to apply the results from the draft NOx model to large nonroad engines. The smallest nonroad engines exhibited the largest differences between predicted and observed values, though the few data points and their high variability were insufficient to determine if a bias exists between predicted and observed values. Thus the data does not provide sufficient information to reject our expectation that our draft NOx model cannot be used to represent small nonroad engines.

Beyond engine technology, differences in operating characteristics between highway and nonroad engines could have an impact on how nonroad engines respond to changes in diesel fuel properties. However, the same nonroad data also showed that, for large nonroad engines, fuel effects on emissions were very similar for the FTP and for candidate nonroad cycles. Therefore, we do not believe that differences in operating characteristics between highway and nonroad engines will affect our estimates of the benefits of the Texas LED program.

Conclusions

The issues described above, in addition to many others raised by our stakeholders, will be addressed in detail as we address comments regarding the general use of the draft model in a longer-term process. However, for the purposes of this memorandum, we believe that our draft NOx model allows us to respond to the immediate need to estimate NOx benefits for the Texas LED program. The benefits estimates provided by our model have been corroborated by estimates from other sources, as described more fully below, giving us confidence that the benefits estimates in Table 1 are the best possible at this time.

We have applied the draft NOx model to the Texas LED program in an effort to quantify the expected benefits. We believe that this is an appropriate use of the draft model despite the fact that outstanding questions remain about its possible broader applicability. We restate that the draft NOx model may not be appropriate for use in other contexts, and we intend to evaluate claims of NOx benefits from other fuels programs on a case-by-case basis.

The draft NOx model is composed of two portions, one representing pre-2002 engines, and another representing 2002 and later engines, many of which we expect to include EGR. Since the relative contribution that these two groups of engines make to the NOx inventory changes over time, so also would the estimates of the NOx benefits of the Texas LED program. In Table 1 we provided the estimated benefits separately for engines equipped with EGR and engines not equipped with EGR so that you can weight them together appropriately in the context of the LED rulemaking. In our Staff Discussion Document, we made our own estimates of weighting factors based on nationwide NOx inventories for heavy-duty highway diesel engines. This effect can be seen in Table 2.

Table 2
Impacts of highway EGR engines on predicted NOx impacts of Texas LED program based on nationwide average fleet characteristics

	pre-2002 engines	2002+ engines	Percent reduction in NOx for in-use highway fleet
Percent reduction in NOx due to Texas LED program	6.2	4.8	
Predicted contribution to the highway NOx inventory			
2002	0.95	0.05	6.1
2003	0.87	0.13	6.0
2004	0.78	0.22	5.9
2005	0.70	0.30	5.7
2006	0.62	0.38	5.6
2007	0.55	0.45	5.5

The EGR vs. non-EGR weighting factors for nonroad engines would be somewhat different, though the trend would be similar: beginning in 2005 when EGR is expected to play a role in nonroad engines designed to meet the Tier 3 standards, the NOx benefits would begin falling from 6.2 percent. However, it is our engineering expectation, which has not been countered by the available data, that the smallest nonroad engines would not respond to changes in fuel properties in like fashion to heavy-duty highway engines. Therefore, we have determined that nonroad engines under 50 hp cannot be assigned a NOx benefit for the Texas LED program on the basis of data considered by EPA.

Despite the fact that there are unresolved concerns about the possible broader application of the draft NOx model presented in our Staff Discussion Document, a number of other models corroborate the NOx effects that it predicts for the Texas LED program. For instance, as mentioned in the discussion of issues above, one significant concern with the draft NOx model was the absence of a natural cetane term. To investigate the impact that its absence had on the NOx emission benefit predictions of the draft model, we replaced the separate natural and additized cetane terms with a single total cetane term, and reconstructed the model. The resulting model with total cetane continues to predict a NOx benefit of 6.2 percent for the Texas LED program for engines not having EGR, the same as our draft NOx model.

Some stakeholders expressed concern that the NOx reduction benefit of the LED program is extremely small and could be closer to zero than our draft model results indicate. To address this concern, we have looked at the small number of existing alternative models which were based on data from multiple studies of diesel fuel emission impacts. These other models also predict similar effects for the Texas LED program in comparison to our draft NOx model. Some examples are listed below:

- Ethyl Petroleum Additives, Inc. produced a model which they presented at our August 28, 2001 workshop[2]. This model was based on a different curve-fitting approach and used only that subset of the database containing cetane improver additives and their base fuel counterparts. Still, this model predicts a NOx benefit of 6.1 percent for engines not equipped with EGR for the Texas LED program.

- In the context of the recent rulemaking setting new standards for heavy-duty highway engines [66 FR 5002, January 18, 2001], we assembled a "composite model" for use in evaluating the need to set new standards for diesel fuel properties other than sulfur[3] to enable engines to meet the new certification standards. This composite model used a much simpler approach: existing models from the literature were weighted together to form a single model intended to represent the fleet. This composite model included both EGR-equipped engines and non-EGR engines, and predicts a NOx reduction of 6.2 percent for the Texas LED program.

- The Heavy-Duty Engines Workgroup produced a model that is specific to engines equipped with EGR[4]. This model predicts a NOx benefit of 4.8 percent for EGR engines for the Texas LED program, the same as our draft NOx model.

- Several years ago, the State of Arizona contracted with MathPro, Inc. to produce a model[5]. Although their database was much smaller than our own and does not contain any data on EGR-equipped engines, their model still predicts a NOx emissions benefit of 4.8 percent for non-EGR engines for the Texas LED program. This estimate is based on a much smaller database, yet it differs from our own estimate by only 1.4 percent.

- Crawford Energy Systems recently produced a model using Principle Components Analysis (PCA)[6]. Although this approach is fundamentally different than that used to

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[2] "Modeling NOx Emissions using the EPA Diesel Emissions Database," Ethyl Petroleum Additives, Inc., presentation at EPA workshop on August 28, 2001

[3] "Exhaust emissions as a function of fuel properties for diesel-powered heavy-duty engines," EPA memorandum to EPA Air Docket A-99-06, document number II-B-01. Sept. 13, 1999.

[4] "Gaseous emissions from a Caterpillar 3176 (with EGR) using a matrix of diesel fuels (Phase 2)," Southwest Research Institute report under EPA contract 68-C-98-169, September 1999.

[5] "Evaluation of gasoline and diesel fuel options for Maricopa County," MathPro Inc., under contract 97-0013AA, February 16, 1998.

[6] Crawford, Robert W., "Documentation of emission benefit predictions based on DOE/ORNL eigenfuel models," Crawford Energy Systems, September 14, 2001.

develop our own draft NOx model, it still predicts a NOx benefit of 5.0 percent for the Texas LED program for engines not equipped with EGR. We have not concluded our review of the utility of a PCA approach, but the fact that its predicted effects are so similar to those from our draft NOx model suggests that even dramatically different modeling approaches are unlikely to produce results that differ significantly from those produced by our own draft model.