Nationwide Emission Benefits of a Low Sulfur Diesel Fuel

March 3, 1999

For: Engine Manufacturers Association

By: Tom Darlington
Dennis Kahlbaum

Air Improvement Resource, Inc.
47298 Sunnybrook Lane
Novi, Michigan
48374

Table of Contents

1.0 Summary

The Environmental Protection Agency (EPA) will release its Tier 2 Notice of Proposed Rulemaking (NPRM) early this year. In addition to lower emission standards for passenger cars and light trucks, sport utility vehicles, and vans, the NPRM is expected to include a proposal to reduce the sulfur level in gasoline by about 90%. A reduction in gasoline sulfur level is needed to reduce criteria pollutants emitted from current and future vehicles and to enable the next generation of vehicle emission control technology.

Along with lower sulfur levels in gasoline, EPA is also beginning to study lower sulfur levels in diesel fuel for both on-road and off-road engines. Sulfur in diesel fuel forms sulfur dioxide (SO_2) and sulfate (SO_4) particulate matter (PM) during combustion. These pollutants contribute to acidic deposition and raise particulate levels including ambient fine PM (i.e. < 2.5 microns) levels. EPA recently established a fine PM air quality standard that regions will have to meet. In addition to these air quality impacts, sulfur in diesel fuel contributes to increased acid levels in the engine, causing engine and emission control system wear. Finally, more stringent NOx standards for light duty diesel vehicles and trucks are being considered in the Tier 2 proposed rule, and more stringent standards for heavy-duty diesel vehicles have already been adopted for 2004 and later engines. Engine makers and aftertreatment suppliers are working on advanced emission control devices to meet more stringent standards, but many of these devices require low sulfur diesel fuel to be commercially available. Therefore, cutting on-road and off-road diesel fuel sulfur levels would reduce ambient SO_2 and fine PM levels, improve engine and aftertreatment system durability, and enable new technology to be commercially viable.

To determine the SO_2 and PM emission inventory impacts of lower sulfur on-road and off-road diesel fuel, the Engine Manufacturers Association (EMA) sponsored this study to evaluate two fuel control options. Current on-road diesel fuel has a fuel sulfur content on average of 300 parts per million (ppm), with off-road diesel 11 times that amount at 3300 ppm. Sulfur control Case A would reduce on-road and off-road sulfur levels to 30 ppm maximum by October 1, 2003. Case B would reduce on-road sulfur levels to the 30 ppm and off-road levels to 500 ppm by July 1, 2002. Case B would include a second phase for off-road diesel, reducing the sulfur level from 500 ppm to 30 ppm maximum by October 1, 2005. EMA's choice of 30 ppm sulfur for modeling purposes is meant to show the emission reductions of this level of control, and does not mean to imply that EMA believes that 30 ppm is sufficient to enable advanced aftertreatment technology.

AIR reviewed the existing EPA and California Air Resources Board (ARB) on-road and off-road models for predicting SO_2 and SO_4 PM emissions from diesel engines. There were many similarities between the models, but the EPA models appear to more completely account for sulfur than the ARB models. Therefore, for this study, AIR used the EPA PART5 model for on-road engines and the EPA NONROAD model for off-road engines to estimate these pollutants. The fractions of light heavy-duty and medium heavy-duty diesel vehicles equipped with catalysts in the PART5 model were updated with more recent information. AIR obtained on-road diesel vehicle activity information (miles per day by vehicle class) from EPA sources. Off-road activity is already included in the NONROAD model. The PART5 model includes indirect sulfates (i.e., those formed from reaction of SO_2 to sulfates in the atmosphere), but the NONROAD model does not. AIR therefore estimated indirect sulfates for NONROAD engines consistent with the EPA PART5 model methodology. The EPA estimate of indirect sulfates, as explained in the body of the text, is a significant underestimate of the impact that low sulfur diesel fuel will make on nationwide PM concentrations and sulfate deposition. More refined estimates are beyond the scope of this report.

The results of the analysis are shown in Figures 1 and 2, which show SO_2 and SO_4 PM emission reductions by calendar year for the two cases. The reductions in tons per day for each pollutant are shown for calendar years 2002 to 2010, and are shown separately for on-road and off-road engines. There are differences in the cases in the transitional years (2002-2005), but the long-term reductions are the same, and peak at almost 3000 tons per day (tpd) for SO_2, and 1100 tpd for SO_4 PM. Since the off-road current sulfur level is nearly 11 times that of the on-road sulfur level, the majority of the reductions come from off-road diesel. These reductions represent a 95% cut in these pollutants for on-road sources, and a 99% cut for off-road sources.

The 3000 tpd reduction in SO_2 in 2010 amounts to over 1 million tons per year. In 2010, total SO_2 from all sources after the 10 million ton per year acid rain program is completed will be about 15 to 17 million tons per year. Therefore, the 1 million ton per year reduction is very significant, or about 6 or 7 % of the total SO_2 in 2010.

Figure 1
National SO_2 Reductions

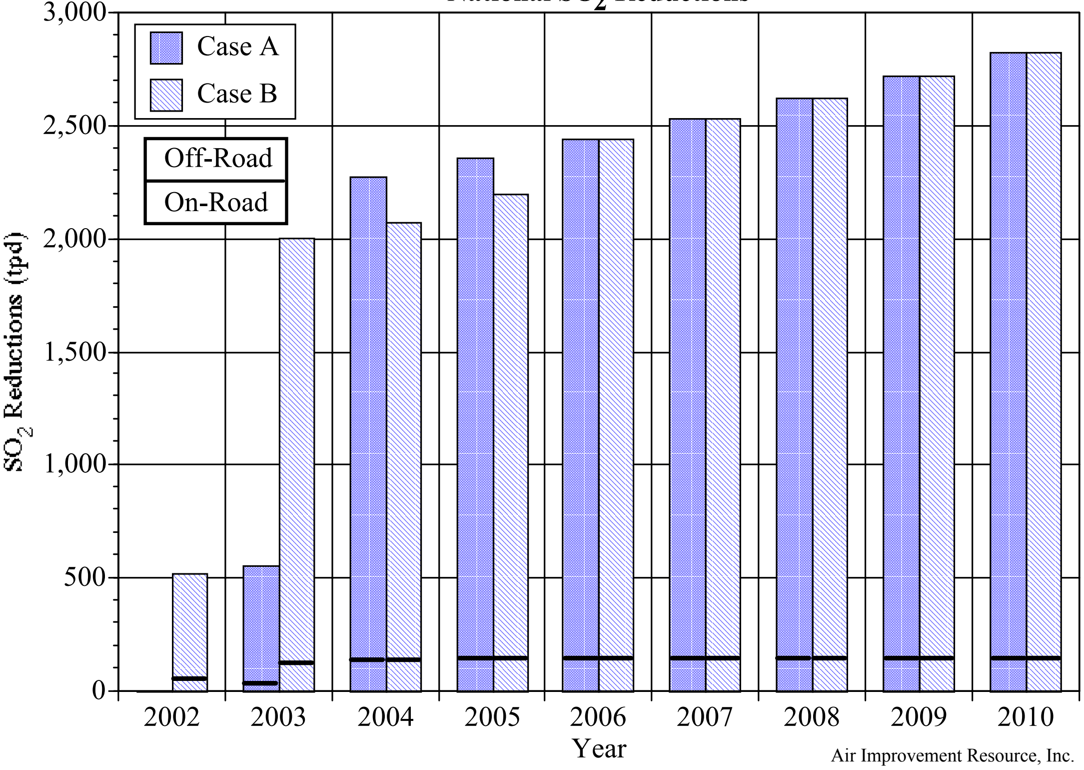
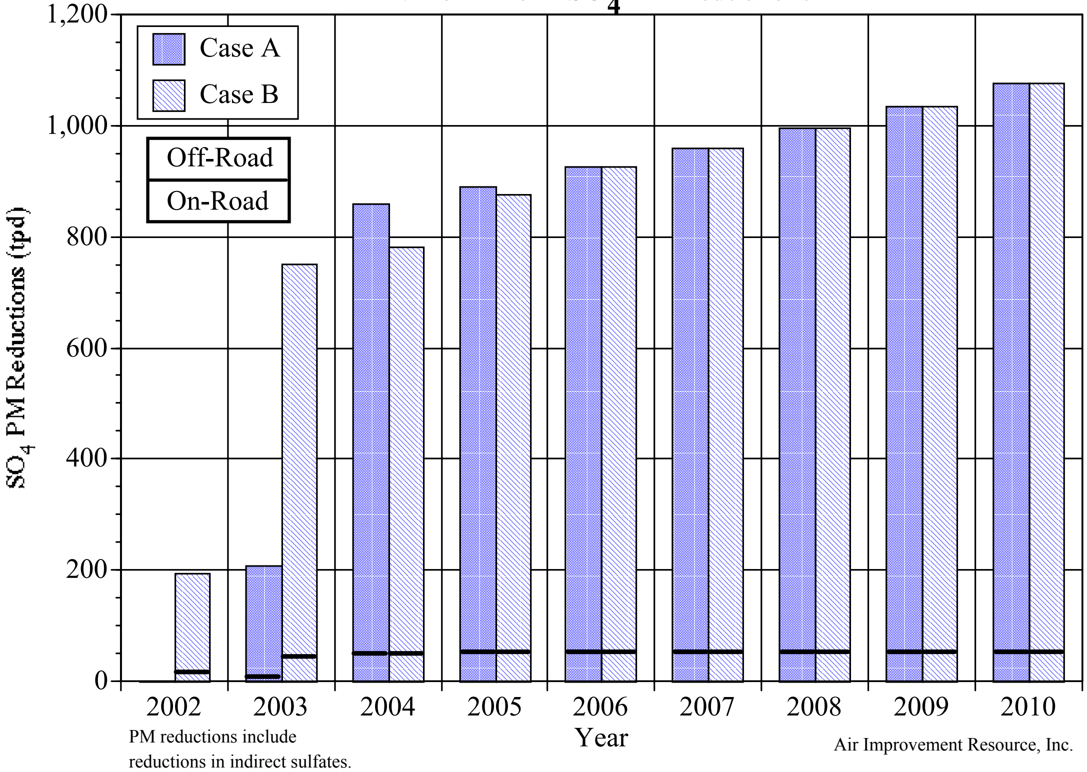


Figure 2
National Total SO_4 PM Reductions



PM reductions include
reductions in indirect sulfates.

Air Improvement Resource, Inc.

2.0 Introduction

EPA plans to release its Tier 2 NPRM early this year. The NPRM will not only call for lower exhaust emissions standards for cars and light trucks, it will also propose tighter sulfur limits for gasoline. The tighter sulfur limits will have the immediate impact of lowering in-use emissions of ozone-forming pollutants, carbon monoxide and particulate matter. Sulfur control is critical because sulfur forms sulfur dioxide (SO_2) in the engine during combustion, and SO_2 impairs the ability of the catalytic converter to reduce exhaust emissions, especially in all vehicles equipped with catalytic converters, especially in vehicles equipped with advanced emission control technology. Current gasoline sulfur levels in non-California states vary significantly, but the national average is about 340 ppm. (1) EPA is studying a number of scenarios, including reducing this by over 90% to an average of about 30 ppm, and the possibility of eventually phasing in a “sulfur free” fuel. Sulfur levels in gasoline in California are under 30 ppm, because California’s Phase 2 reformulated gasoline requirement contains an averaging limit of 30 ppm. California is also studying the possibility of further reducing the sulfur in its gasoline below 30 ppm to essentially a “sulfur free” fuel corresponding to the next level of emission reductions requirements, LEV II.

Sulfur in diesel fuel also affects engine emissions. Sulfur forms SO_2 during combustion, and some of the SO_2 reacts with additional oxygen and water to form sulfate (H_2SO4) particulate matter (PM). This PM is called “direct” PM. SO_2 also forms additional PM by complex reactions in the atmosphere, and this is referred to as “indirect” PM. In 1993, EPA implemented a 500 ppm nationwide cap for the sulfur limit of on-highway diesel fuel. California also implemented the same cap for diesel fuel sold in California. California further controlled total aromatics in diesel fuel to a maximum of 10%, although uit has implemented a mechanism to certify fuels with alternative formulations that achieve equivalent emissions performance. The current national average sulfur level for on-highway diesel fuel is about 300 ppm. (2) Currently, there is no sulfur cap for off-highway diesel fuel, and EPA estimates that off-highway diesel fuel has a sulfur level of almost 3300 ppm, or about *11 times* the on-highway level. (3) The adoption of Stage III/IV standards for 2000/2005 by Europe was accompanied by a phased reduction of sulfur to a 50 ppm cap. This was necessary for advanced diesel aftertreatment technology to function effectively.

Sulfur in diesel fuel also has an effect on exhaust emission aftertreatment expected to be used to meet lower NOx standards. The EPA has adopted stricter NOx standards for heavy-duty diesel engines starting in 2004, and many expect EPA to lower heavy-duty NOx standards further in the future. Many engine manufacturers will utilize exhaust gas recirculation (EGR), in combination with other strategies, to meet the 2004 NOx standards. However, in order for EGR to be effective at reducing NOx emissions, the exhaust gas must be cooled, and in the process of cooling the exhaust gas, sulfuric acid condenses in the EGR system. Thus, with current sulfur fuel, manufacturers must use premium components for EGR systems combined with shorter service intervals that increase overall maintenance costs.

In the longer term for heavy-duty diesel engines, if NOx standards are further tightened, it is unlikely that EGR systems alone will be able to enable engine manufacturers to meet lower standards. The diesel engine and emission control manufacturers are developing new technologies such as adsorption catalysts and other devices to reduce NOx from diesel engines. Like the catalytic converters used for gasoline vehicles, many of these advanced diesel technologies are also adversely impacted by SO_2.

Some oil companies, expecting control of gasoline sulfur levels under the Federal Tier 2 rule, also expect diesel fuel sulfur levels to be eventually reduced as well, and may desire for EPA to reduce gasoline and diesel fuel sulfur levels along a similar timeline. Recognizing this, EPA is requesting input from all parties on an advance notice of proposed rulemaking (ANPRM) on potentially controlling future diesel fuel sulfur levels. California would also like to reduce sulfur levels in diesel fuel.

The advantages of a lower sulfur on-highway and off-highway diesel fuel, then are summarized below:

- Lower SO_2 emissions from diesel engines, and reduced acidic deposition
- Lower directly emitted PM from diesel engines
- Lower indirect PM
- Improved visibility and ambient PM levels
- Increased EGR system life
- Increased engine life and reduced maintenance costs
- Allows for commercial application of advanced technology aftertreatment

Because of the need for lower sulfur on-highway and off-highway diesel fuel, the Engine Manufacturers Association (EMA) contracted with AIR to assess the SO_2 and SO_4 PM emission benefits of low sulfur diesel fuel in the nation, and in California. EMA also contracted with MathPro to perform a study of the costs of lower sulfur diesel fuel. EMA desired to study the emission reductions of two control cases, as shown in Table 1.

Table 1. Diesel Fuel Control Scenarios

Case	On-Road		Off-Road	
	Level	Date	Level	Date
A	30 max	10/1/2003	30 max	10/1/2003
B	30 max	7/1/2002	500 max	10/1/2002
			30 max	10/1/2005

Case A would limit all on- and off-road diesel sulfur to 30 ppm maximum starting on October 1, 2003. Case B would limit on-road diesel sulfur to 30 ppm maximum on July 1, 2002, and would provide for a two-phase reduction for off-road diesel to 500 ppm maximum on October 1, 2002, followed by a further reduction to 30 ppm maximum on October 1, 2005. EMA's choice of 30 ppm sulfur for modeling purposes is meant to show the emission reductions of this level of control, and does not mean to imply that EMA believes that 30 ppm is sufficient to enable advanced aftertreatment technology.

The remainder of this report is divided into four sections. *Section 3 Review of Methods to Estimate SO_2 and SO_4 Emissions From Diesel Engines* reviews the methods used by the EPA and California Air Resources Board to estimate SO_2 and SO_4 emissions in the various on-road and off-road models. *Section 4 Methods Used in This Analysis* discusses the modeling approach used in this analysis. *Section 5 Results* presents the emission inventories and emissions reductions from the various cases. *Section 6 Conclusions* discusses implications of the analysis and remaining uncertainties.

3.0 Review of Methods Used to Estimate SO_2 and SO_4 From Diesel Engines

EPA and ARB have two models each, which estimate SO_2 and SO_4 emissions from on- and off-highway diesel engines. These models are shown in Table 2.

Table 2. ARB and EPA Models

Source	Model Name	Vehicles Covered
EPA	PART5	On-Highway Vehicles
	NONROAD	Off-Road Vehicles
ARB	MVEI7G	On-Highway Vehicles
	OFFROAD	Off-Road Vehicles

The PART5 model was finalized shortly after MOBILE5 was finalized. EPA currently plans to update this model about a year after MOBILE6 is finalized (MOBILE6 is scheduled to be completed by the end of 1999). MVEI7G is ARB's current model for California; it is being updated at this time. The new model, EMFAC99, will be released sometime this spring. Both of the models for off-road engines are still under development, but both have been available for some time for review by interested parties. AIR has provided both organizations with comments on various parts of these models, but until now AIR has not reviewed in detail the methods used to estimate emissions specifically derived from the sulfur in diesel fuel.

The following sections review how each of these models estimate SO_2 and SO_4 emissions.

3.1 On-Road Models

3.1.1 EPA's PART5 Model

EPA's PART5 model estimates SO_2 and SO_4 emissions for the following diesel vehicle types:

- Light Duty Diesel Vehicles
- Light Duty Diesel Trucks (0-6000 lb GVW)
- 2B Diesel Trucks (6,001-10,000 lb GVW)
- Light-Heavy Duty Diesel Vehicles (10,001-19,500 lb GVW)
- Medium-Heavy Duty Diesel Vehicles (19,501-33,000 lb GVW)
- Heavy-Heavy Duty Diesel Vehicles (33,000+ lb GVW)

SO_2 and SO_4 emission rates are estimated for non-catalyst equipped vehicles with the following expressions:

$$SO_2 = (9.072 * Density * Sulfur * (1-Frac_{SO4}))/Fuel\ Economy \qquad (4)$$

Where

SO_2 is in g/mi
*9.072 is (453.6 g * 2)/100, where 2 is the number of grams of SO_2 formed per gram of S (64/32), and 100 converts sulfur from a wt % to a wt fraction*
Density is the assumed density of diesel fuel, 7.11 lb/gal
Sulfur is the wt percent of sulfur in on-road diesel fuel, assumed to be 0.05%, or 500 ppm
$Frac_{SO4}$ is the fraction of sulfur converted to SO_4 in the exhaust, 2%
Fuel Economy is the fuel economy in mpg for each model of each vehicle type

SO_4 = (31.10 * Density * Sulfur * $Frac_{SO4}$)/Fuel Economy

Where

SO_4 is in g/mi
*31.10 is (453.6 g/lb * 6.857)/100, where 6.857 is EPA's estimate of the g of $H_2SO_4 : 7H_2O$ per g of S, and 100 converts sulfur from wt % to a wt fraction*
Other terms are the same as for SO_2

In the above expressions, the PART5 model splits the fuel sulfur into either SO_2 or SO_4 using the assumed fraction of sulfur converted to SO_4 in the exhaust (2%). The expressions use fuel economy in mpg by vehicle type and model year to estimate SO_2 and SO_4 emissions in g/mi. Finally, EPA assumes that direct sulfate is emitted as sulfuric acid with associated water (7 water molecules per molecule of sulfuric acid).

In the above expression, EPA estimates that 6.857 is the ratio of sulfuric acid and 7 waters to sulfur ($[H_2SO_4 + 7H_2O]/S$). EPA estimated this number as the product of two other ratios: SO_4/S (96/32 = 3.0), and $(H_2SO_4 + 7H_20)/H_2SO_4$ (224/98 = 2.2857). Note that EPA uses SO_4 in the numerator of the first ratio and H_2SO_4 in the denominator of the second ratio. H_2SO_4 should have been used in the first ratio; then the 31.10 would be 31.75. This is not considered to be a major difference, so AIR used the EPA equation as is.

For the non-catalyst-equipped vehicle s, all of the above factors are constant except fuel economy, which varies by vehicle type and model year. To estimate fleet SO_2 emission factors, the model combines the model year emission factors with travel fractions in the same manner that MOBILE5 does for HC, CO and NOx.

Direct PM emissions include sulfates, carbon, and a soluble organic fraction (SOF). EPA bases the PART5 PM estimates on total direct PM from its available test data. This data is assumed to have been gathered using a test fuel that matches the sulfur level of in-use fuel (500 ppm). To estimate the emission rates of the different PM types, EPA subtracts the estimated sulfates from total PM, and then splits the remainder (carbon + SOF) using an estimated SOF fraction.

For catalyst-equipped diesel vehicles, EPA assumes that the fraction of sulfur converted to sulfates increases to 3% from 2%. EPA estimates that 90% of the 1995 and later LHDVs, 75% of the 1995 and later MHDVs, and 100% of the 1991 and later buses are equipped with catalysts.

Fuel economy values assumed in the model for diesel vehicles are shown in Figures 3 (LDDV and LDDT) and 4 (HDDVs). The fuel economy values show a significant increase in fuel economy from the 1989 model year to the 1990 model year, which is not expected. The reason for this increase is an artifact of how the EPA referenced the fuel economy values to the MOBILE3 Fuel Consumption Model: EPA used 1975 fuel economy values for 1975-1989 vehicles, and a projection for 1990 for 1990 and later vehicles. (5) The fuel economy values should show more of a constant increase from 1975-1989, which has been acknowledged by the EPA. This has a tendency to overstate PM emissions, until the 1975-1989 vehicles are retired. AIR did not change the fuel economy values, but this should be addressed by the EPA in PART6, and the fuel economy values should probably be based on recent Truck Inventory and Use Surveys (TIUS).

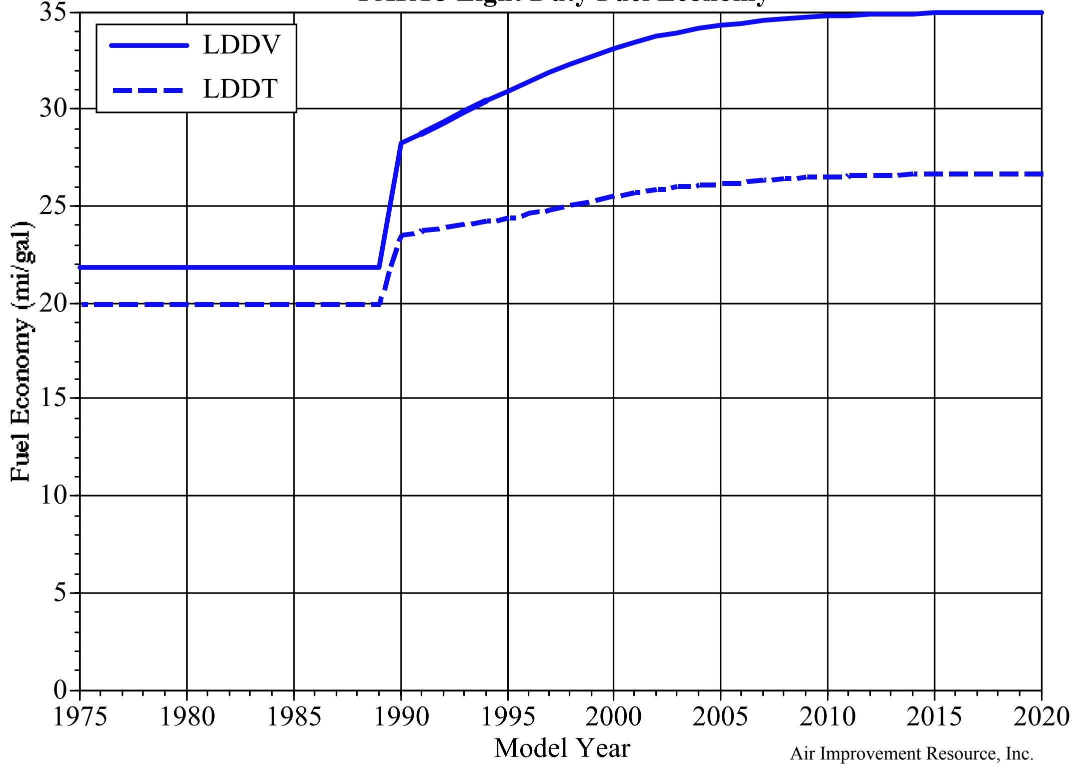
The PART5 model also estimates indirect sulfates, that is, sulfates that are formed in the atmosphere from SO_2. The model uses the following expression:

$$\textit{Indirect } SO_4 = \textit{Indirect } Frac_{SO4} * SO_2 * 1.92$$

Where

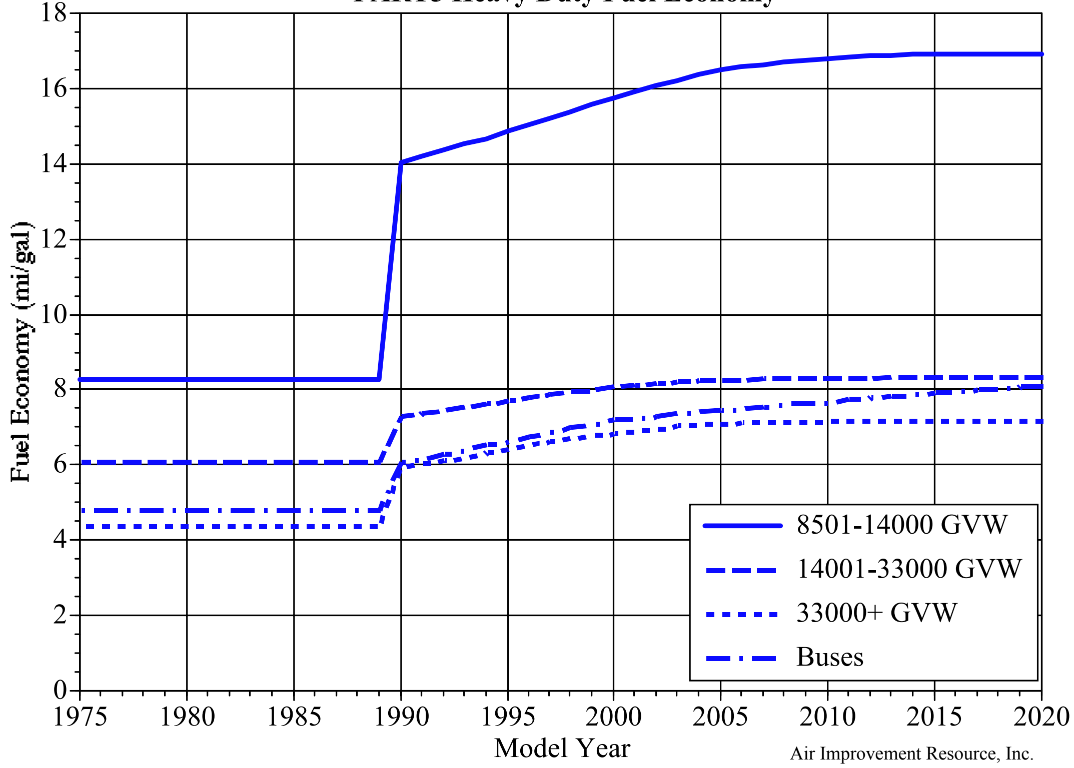
Indirect SO_4 *is in g/mi*
Indirect $Frac_{SO4}$ *is the fraction of* SO_2 *that reacts to form* SO_4 *in the atmosphere, or 12%*
SO_2 *is in g/mi (from earlier expression)*
1.92 is the g of ammonium sulfate (NH_2SO_4) *and ammonium bisulfate* (NH_4HSO_4) *(50/50) produced per g of* SO_2

Figure 3
PART5 Light Duty Fuel Economy



Air Improvement Resource, Inc.

Figure 4
PART5 Heavy Duty Fuel Economy



Air Improvement Resource, Inc.

EPA estimates that 12% of SO_2 is converted in urban areas to sulfate PM.[1] The source of this estimate is an EPA analysis of nationwide SO_4 to SO_2 ambient levels from SO_2 and SO_4 monitors across the U.S. (6) This analysis was performed for the 1990 diesel fuel sulfur rule, which lowered diesel fuel sulfur levels to 500 ppm. EPA assumes that the SO_2 that reacts in the atmosphere forms either ammonium sulfate or ammonium bisulfate. In its analysis, EPA cites reaction rates in California as high as 6% per hour in the spring, summer, and fall, in which all of the SO_2 would be expected to have formed sulfates within about 18 hours. However, to better represent non-California states, EPA developed the 12% figure from ambient sulfate and SO_2 data in 10 non-California cities. The ambient data were year-round, rather than being in the spring or summer when reaction rates are probably significantly higher. Also, EPA's analysis assumes that sulfate and SO_2 deposition in the 10 cities occurs at the same rate (EPA assumes that because of the small size of the sulfate that it disperses like a gas). If SO_4 deposition occurs faster than SO_2 deposition, then the 12% conversion rate is underestimated.

Overall, our concern with the 12% figure is that it could be low, particularly in the spring and summer when meteorological conditions favor secondary PM formation, and human exposure is greater.

3.1.2 ARB's MVEI7G Model

MVEI7G, ARB's model for on-road vehicles, utilizes the EMFAC emission factor models and the BURDEN activity model to produce emissions for California in tons per day. The MVEI7G model estimates all on-highway emission rates (HC, CO, NOx, CO_2, PM, SO_2) for the following vehicle classes:

- Passenger cars
- Light duty trucks (0-6000 lb GVW)
- Medium duty trucks (6-8500 lb GVW)
- Light-heavy-duty trucks (8,500-14,000 lb GVW)
- Medium-heavy-duty trucks (14,000-33,000 lb GVW)
- Heavy-heavy-duty trucks (33,000+ lb GVW)
- Buses

In the MVEI7G model, SO_2 emissions in tons per day are estimated with the following expression:

$$SO_2 = (Fuel * Density * Sulfur * Frac_{SO2})/(2*10^9) \quad (7)$$

Where

SO_2 is in tons per day

---

[1] The remaining SO_2 is assumed to be converted into sulfates in nonurban areas, or deposited onto surfaces in urban or nonurban areas without reacting. However, SO_2 and SO_4 that is deposited contribute to acid deposition.

Fuel is fuel consumption in 000s of gal/day
Density is the assumed density of diesel fuel, 7.07 lb/gal
Sulfur is the assumed sulfur content of diesel fuel, or 500 ppm starting in 1993
Frac$_{SO2}$ *is the g of* SO_2 *produced per gram of S (64/32)*
*2** 10^9 *converts from ppm to a wt fraction and from lbs to tons*

In the above expression, all of the fuel sulfur is assumed to react to form SO_2. Fuel consumption in gal/day by vehicle class is estimated with fuel economy estimates by vehicle class and activity (miles per day). ARB fuel economy by vehicle class is shown in Figures 5 (LDDVs and LDDTs) and 6 (HDDVs). The above expression is similar to EPA's expression, however, there are three differences in the input data and assumptions:

- ARB assumes that all of the fuel sulfur reacts to form SO_2, where EPA assumes that 98% reacts to form SO_2

Figure 5
ARB Light Duty Fuel Economy

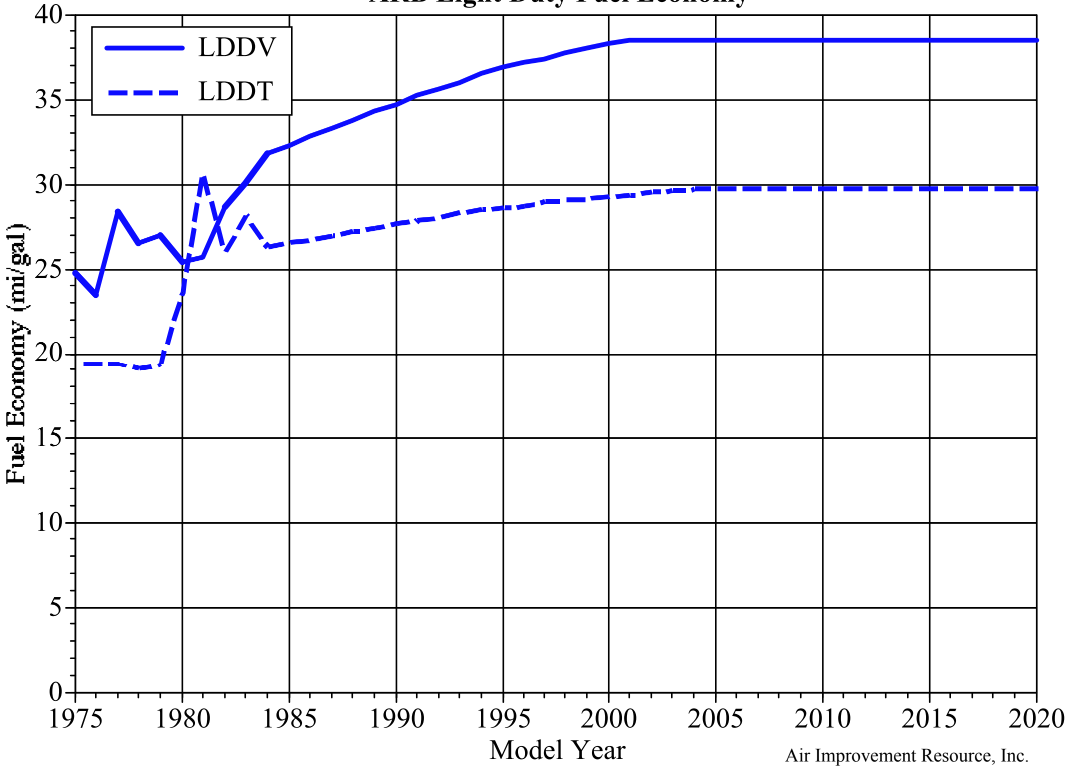
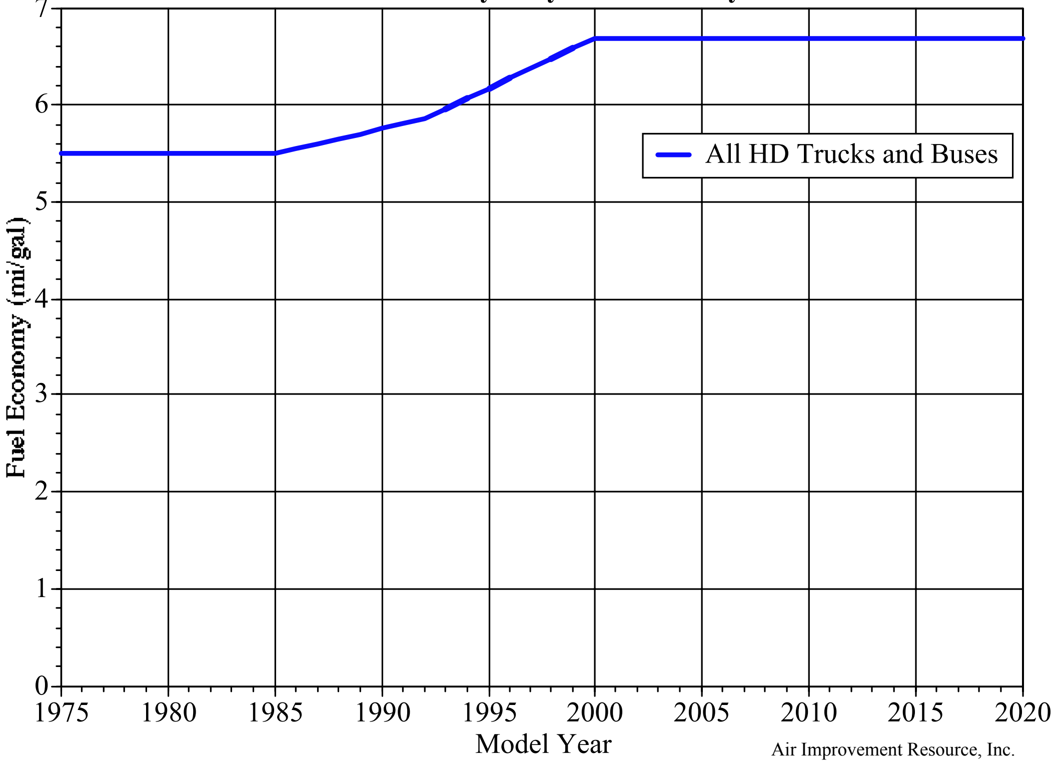


Figure 6
ARB Heavy Duty Fuel Economy



Air Improvement Resource, Inc.

Figure 7
Light Duty Fuel Economy Comparison

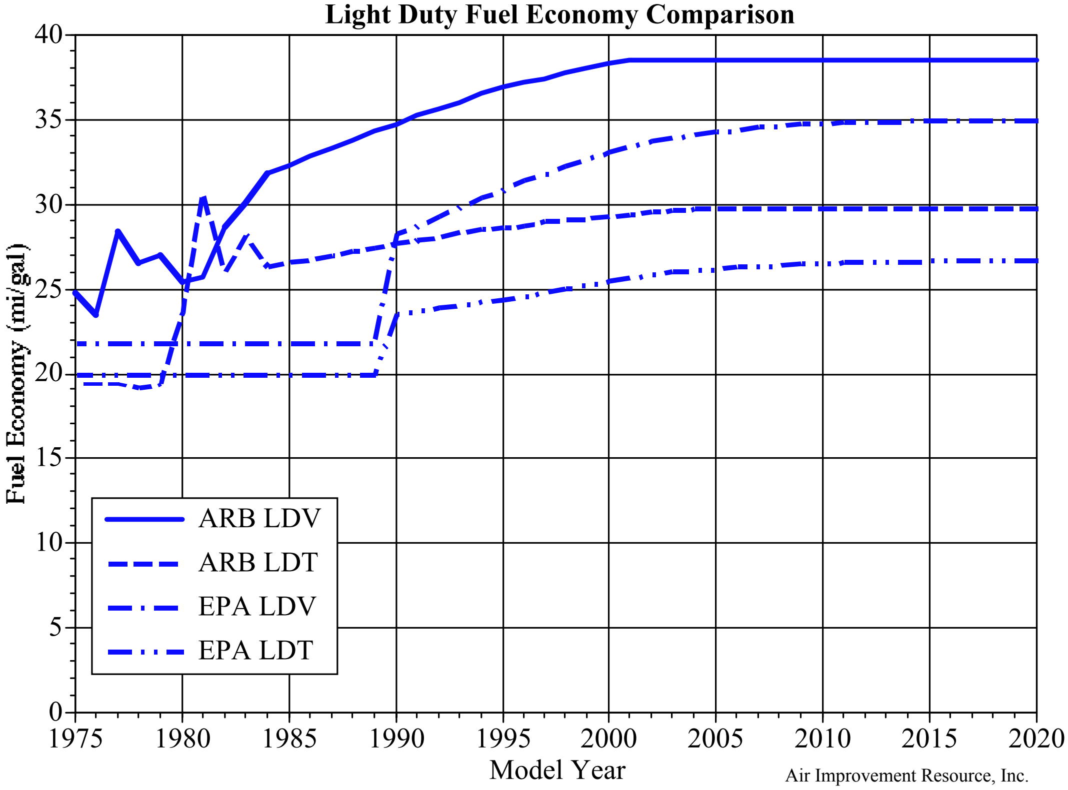
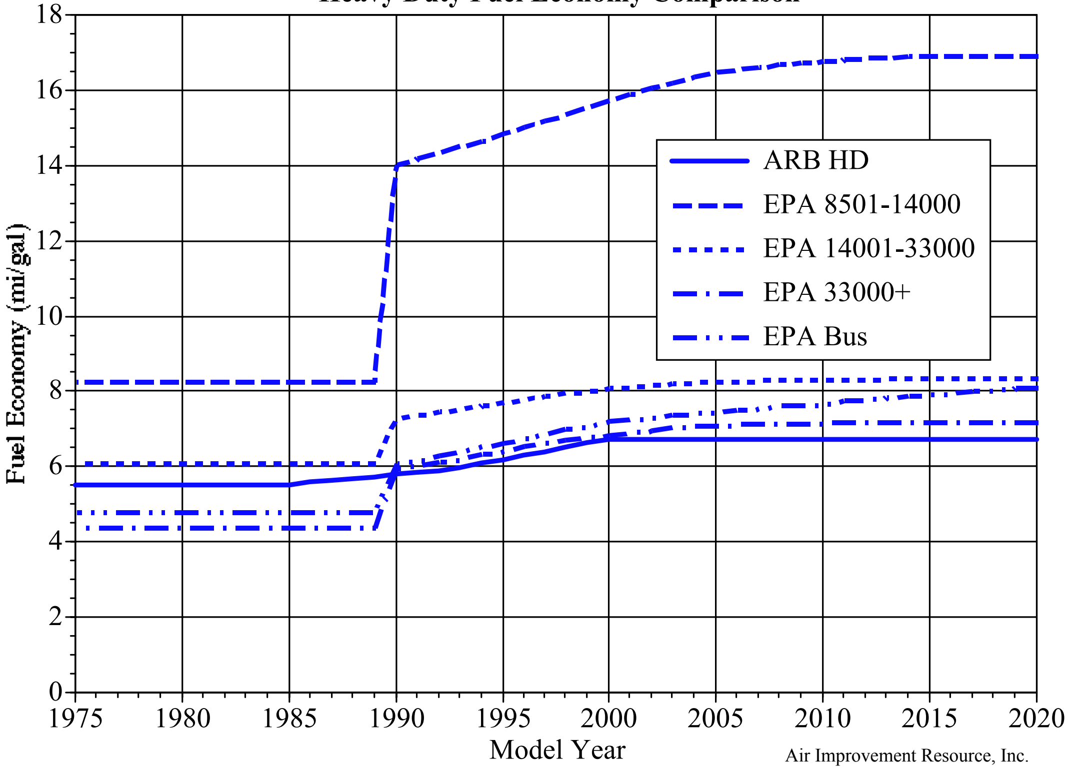


Figure 8
Heavy Duty Fuel Economy Comparison



- There is a small difference in the assumed diesel fuel density (ARB – 7.07 lb/gal, EPA- 7.11 lb/gal)

- There are significant differences in estimated fuel economy by vehicle class, as shown in Figures 7 and 8. For light duty vehicles and light duty trucks, the EPA values are lower than the ARB values. The trends (increasing fuel economy with time) are similar. For the heavy-duty vehicles, ARB uses a single value for all heavy-duty vehicles, while EPA uses separate values by vehicle class. Because of this, it is difficult to compare the heavy-duty vehicle fuel economy estimates.

For sulfate particulate, ARB relies on its PM emission rates from test data. In this sense, ARB is double-counting the sulfur that forms sulfate particulate, because it does not subtract the sulfur that forms sulfate PM when estimating SO_2 emissions.

3.2 Off-Highway Models

3.2.1 EPA's Draft NONROAD Model

EPA's Draft NONROAD model estimates HC, CO, NOx, SO_2, and PM emissions (including sulfates) for the nation, for the following equipment types:

- Agriculture
- Airport Ground Support
- Lawn and Garden
- Light Commercial
- Logging
- Recreation
- Other Oil Field Equipment
- Transport Refrigeration Units

The model does not yet include vessels and rail operations, but the final version is expected to include these equipment types.

For SO_2 emissions, the model uses the following expression:

$$SO_2 = (BSFC * (1-Frac_{SO4}) - HC) * Sulfur * 2 \qquad (8)$$

Where

SO_2 *is in g/hp-hr*
BSFC is the in-use adjusted fuel consumption in lb/hp-hr
453.6 is the conversion factor from g to lb
$Frac_{SO4}$ *is the fraction of sulfur converted to sulfate, assumed to be 2.2%*
HC is the in-use adjusted HC emissions in g/hp-hr

Sulfur is the wt fraction of sulfur in nonroad diesel fuel, 0.0033%, or 3300 ppm
2 is the g of SO_2 formed per g of S

The equation above includes corrections for the fraction of sulfur that is converted to direct PM and for the fraction of sulfur remaining in the unburned fuel. There are two differences in the above expression and the expression used for on-highway diesel vehicles:

- In the NONROAD model, EPA is assuming that 2.2% of the sulfur is converted to SO_4, where the PART5 model assumes this percentage is 2.0%

- EPA also appears to be correcting for the sulfur in the unburned, or partially burned fuel

It is not clear why the NONROAD model assumes a conversion of 2.2%, while the onroad model PART5 assumes a conversion of 2.0% for noncatalyst-equipped vehicles. Also, EPA assumes that the fraction of sulfur in the unburned, or partially burned fuel is the same as in the raw fuel. First the HC emissions are probably at least partially burned, and there is no evidence that the fraction of sulfur in the partially burned fuel is the same as in the raw fuel. While this assumption and resulting adjustment is questionable, since HC emissions from diesel vehicles are very low, the adjustment has little effect on the overall SO_2 emission rate.

For SO_4 emissions, EPA utilizes test data of a number of engines on different test fuels, but adjusts the total PM to a sulfur level of 3300 ppm. Thus, there appears to be no double counting of sulfur.

Unlike the PART5 model, the NONROAD model does not estimate indirect sulfates. The reasons for this are not clear.

3.2.2 ARB Draft OFFROAD Model

In ARB's OFFROAD model, SO_2 emissions are estimated very similarly to the method ARB uses in its MVEI7G on-road model, except that fuel consumption by equipment type is estimated by multiplying fuel consumption in g/hp-hr by activity in total hp-hr. ARB assumes that all of the diesel fuel sulfur reacts to form SO_2, but the PM emissions ARB uses includes SO_4, so sulfur appears to be double-counted in this model as well. The OFFROAD diesel fuel sulfur level is assumed to be 2800 ppm.

3.3 Comparison of Models

A comparison of some of the input parameters for all four models is shown in Table 3. In the last column, we have indicated that for the EPA models, the sulfate PM is based on the fuel sulfur level and the assumed percent of sulfur converted to SO_4, and that for ARB, the sulfate PM is based on test data, which could have varying sulfur levels.

Table 3. Input Parameter Comparison for the Various Models						
Model	Base Sulfur Level (ppm)	% Sulfur Convert to SO_2	% Sulfur Convert to SO_4	Indirect SO_4 Estimated?	Fuel Density (lb/gal)	Exhaust SO_4 PM Based On
PART5 – EPA	500	98.0	2.0	Yes – 12%	7.11	Amount converted
MVEI7G – ARB	500	100.0	0.0	No	7.07	Test data
NONROAD – EPA	3300	97.8	2.2	No	NA	Amount converted
OFFROAD – ARB	2800	100.0	0.0	No	NA	Test data

NA = not applicable

4.0 Modeling Method Used in This Analysis

4.1 Models Used

Since both of the EPA models seem to effectively split the fuel sulfur into SO_2 and SO_4 without double counting, AIR will use the EPA models to estimate nationwide SO_2 and SO_4 emission inventories. It is recognized, however, that these two models are not exactly consistent with each other, in the following respects:

- The NONROAD model does not yet include indirect sulfates
- There is a difference in the assumed percent of sulfur converted to SO_4. The SO_4 conversion is 2.2% for off-road engines, and 2.0% for on-road engines. The reason for this difference is not clear.
- The NONROAD model corrects for the sulfur in unburned or partially burned HC, while PART5 does not. The models should be made consistent, but the small size of this adjustment probably does not make much difference.

These differences should be corrected when the next version of each model is finalized. Certainly the biggest issue is the omission of estimating indirect sulfate particulate from the NONROAD model, and this analysis will include indirect sulfates for NONROAD vehicles, using the same fraction of SO_2 reacted (12%) as in the PART5 model for onroad vehicles.

It should also be recognized that the NONROAD model is still being developed by EPA, although many parts of the model have receive substantial review and comment. One area that is still undergoing review by the EPA that could impact these estimates is nonroad diesel fuel consumption. Some have commented that the off-road diesel fuel consumption appears to be too high relative to other sources. If true, this could mean that the activity is too high, the populations are too high, or both. EPA is currently reviewing these comments and conducting additional analyses. If the fuel consumption in the model is too high, then the inventories and reductions as estimate from this analysis will also be too high. However, the emission reductions from nonroad sources are still expected to be very significant.

AIR has several other concerns with the EPA models, as follows:

1. The indirect sulfate conversion of 12% in PART5 may be very low. As mentioned earlier in this report, it was estimated by EPA on an annual average basis, and does not represent an episodic condition (late Spring, Summer, early Fall) in which the SO_2 conversion may be significantly higher. EPA's 12% estimate is for urban areas. The SO_2 that does not react in the immediate urban area is transported downwind and reacts in rural areas, contributing to acid deposition, fine PM, and visibility problems in downwind areas.

2. The catalyst fractions in PART5 should be updated. This is discussed further in the next section.

3. The direct sulfate conversion of 3% for current catalyst-equipped vehicles may be low. AIR has examined evidence that the conversion rate may be much higher than 3%. The level of conversion is very sensitive to the catalyst formulation. All of this evidence is on current and past diesel catalyst formulations. It is very likely that future diesel catalyst formulations that must reduce NOx emissions by 50-60% will likely have much higher SO_2 conversions. In this analysis, however, we have used EPA's estimate of 3%.

4.2 Human Exposure and the Source of SO_2

AIR also believes that there could be a significant difference in the level of human exposure to sulfate from diesel engines, versus from tall stack stationary sources. In the case of tall stacks located near urban areas, SO_2 emitted can be blown many miles before it reacts to form sulfate PM. In the case of diesel engines, however, direct sulfate, indirect sulfate, and SO_2 emissions are much closer to ground level, thereby increasing human exposure. This difference is not reflected in the models or inventories.

4.3 Model Modifications

First, for on-road engines, many 2b, light-heavy-duty, and medium heavy-duty vehicles are now equipped with oxidation catalysts. The PART5 model assumes the fraction equipped for these vehicles is zero. In a previous analysis that AIR conducted for the Canadian Vehicle Manufacturers Association (CVMA), AIR estimated that 90% of 1995 and later 2b and light heavy duty vehicles are equipped with oxidation catalysts, and that 75% of 1995 and later medium duty vehicles are equipped with catalysts. (9) As noted earlier, EPA estimates that the fraction of sulfur that is converted to sulfates increases from 2% to 3% with an oxidation catalyst. Therefore, AIR adjusted the fraction of sulfur converted to sulfates in the model for 1995 and later 2bs, LHDDVs, and MHDDVs. The increased sulfate conversion fractions are shown in Table 4.

Table 4. Sulfate Conversion and Catalyst Fractions for Heavy Duty Diesels

Vehicle Type	Sulfate Conversion Fraction		Catalyst Fraction
	1994 and earlier MY	1995 and later MY	1995 and later MY
2b and LHDDV	0.02	0.029	0.9
MHDDV	0.02	0.0275	0.75
HHDDV	0.02	0.02	0

Second, since the NONROAD model currently does not include indirect sulfates, AIR included indirect sulfates to be consistent with the PART5 model. This was accomplished by estimating the SO_2 to indirect SO_4 inventory ratio for the on-road vehicles, and using this ratio with the NONROAD SO_2 inventory to estimate the indirect sulfates from NONROAD sources.

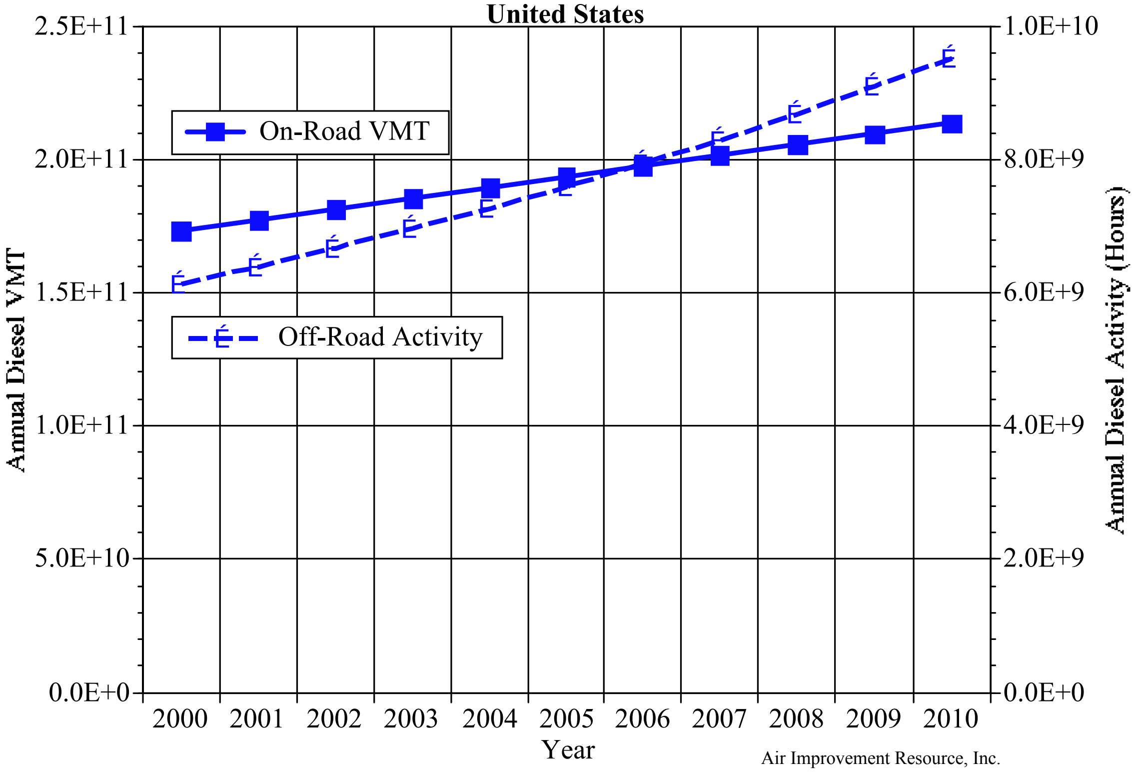
Third, AIR modified both of the models to input diesel fuel sulfur level, to aid in modeling the various control scenarios.

4.4 Activity

The NONROAD model already includes all of the populations and activities, so that it can estimate nationwide inventories in tons directly. However, the PART5 model outputs emissions in g/mi, so we must find a source of diesel vehicle miles traveled (VMT). AIR performed an analysis of the benefits of gasoline sulfur controls for AAMA, in which we obtained projected VMT for the 2007 calendar year by vehicle type and state for all 50 states from the EPA. (10,11) EPA has used this VMT to project nationwide emission inventories from on-highway mobile sources. To obtain VMT by diesel vehicle type for other calendar years, AIR applied a 2% linear growth factor. For years prior to 2007, the VMT values were reduced by 2% per year. For years after 2007, the VMT was increase by 2% per year.

The on-road and off-road total activity for calendar years 2000-2010 is shown in Figure 9.

Figure 9
Diesel On-Road VMT and Off-Road Activity
United States



4.5 Diesel Fuel Scenarios

EMA's diesel fuel control scenarios are shown in Table 5.

Table 5. Diesel Fuel Control Scenarios

Case	On-Road		Off-Road	
	Level	Date	Level	Date
Base	300	NA	3000	NA
A	30 max/15 nom	10/1/2003	30 max/15 nom	10/1/2003
B	30 max/15 nom	7/1/2002	500 max/300 nom	10/1/2002
			30 max/15 nom	10/1/2005

The PART5 model assumes on-road diesel sulfur level is 500 ppm, and the NONROAD model assumes the sulfur level is 3300 ppm. AIR evaluated on-road national sulfur levels using AAMA's fuel surveys, and the population-weighted average was very close to 300 ppm, therefore, 300 ppm was used in PART5 for on-road fuel in the base case. EMA specified a 3000 ppm nominal value for the baseline for off-road diesel fuel, so 3000 ppm was used in the off-road modeling.

Control Case A implements a 30 ppm cap for both on-road and off-road fuel on 10/1/2003. With a 30 ppm cap, AIR believes many refiners would sell fuel below the cap, therefore, we assumed a 15 ppm nominal level for all modeling of a 30 ppm cap. The 10/1/2003 implementation date was modeled by assuming for 3/4s of the year, the fuel sulfur level was at 300 ppm, and for the last quarter, it was at the nominal level.

Control Case B implements the 30 ppm cap for on-road engines 15 months earlier than Case A, but for off-road engines the first phase drops to a 500 ppm cap. The 500 ppm cap is modeled at a nominal value of 300 ppm. This is further reduced to a 30 ppm cap (15 ppm nominal) in 2005.

5.0 Results

5.1 On-Road Results

On-road SO_2, direct SO_4, and indirect SO_4 PM inventories in tons per day for the Base Case (i.e., 300 ppm S) are shown in Table 6. SO_2 ranges from 132 tpd in 2000 to 151 tpd in 2010. Total SO_4 PM is around 50 tpd. It should be recalled that this is only urban PM; urban + rural PM is likely to be much higher due to continued reaction of SO_2 in other areas. Emission reductions from the Base Case for Cases A and B are shown in Table 7, and are shown graphically in Figures 10 and 11. Once the low sulfur requirement is fully phased-in, SO_2 and SO_4 PM are reduced by 95%, or about 140 tpd and 50 tpd, respectively.

Table 6. Base Case SO_2 and SO_4 Inventories From On-Road Diesel Vehicles (tons per day)

Year	SO_2	Direct SO_4 PM	Indirect SO_4 PM	Total SO_4 PM
2000	131.7	9.9	37.9	47.8
2001	134.8	10.3	38.8	49.1
2002	136.6	10.5	39.3	49.6
2003	138.4	10.6	39.8	50.2
2004	140.0	10.8	40.3	51.1
2005	141.8	11.0	40.8	51.9
2006	143.4	11.3	41.3	52.6
2007	145.1	11.5	41.8	53.3
2008	146.8	11.7	42.3	54.0
2009	148.6	11.9	42.8	54.7
2010	150.5	12.0	43.3	55.3

Table 7. On-Road Emission Reductions from Cases A and B (tons per day)

	Case A				Case B			
Year	SO_2	Direct SO_4 PM	Indirect SO_4 PM	Total SO_4 PM	SO_2	Direct SO_4 PM	Indirect SO_4 PM	Total SO_4 PM
2000	0	0	0	0	0	0	0	0
2001	0	0	0	0	0	0	0	0
2002	0	0	0	0	64.9	5.0	18.7	23.7
2003	32.9	2.5	9.5	12.0	131.4	10.1	37.9	48.0
2004	133.0	10.3	38.3	48.6	133.0	10.3	38.3	48.6
2005	134.7	10.5	38.8	49.3	134.7	10.5	38.8	49.3
2006	136.2	10.7	39.2	49.9	136.2	10.7	39.2	49.9
2007	137.8	10.9	39.7	50.6	137.8	10.9	39.7	50.6
2008	139.5	11.1	40.2	51.2	139.5	11.1	40.2	51.2
2009	141.2	11.3	40.7	51.9	141.2	11.3	40.7	51.9
2010	143.0	11.4	41.2	52.6	143.0	11.4	41.2	52.6

5.2 Off-Road Results

Off-road SO_2, total PM, and Indirect SO_4 PM in tons per day for the Base Case, Case A, and Case B are shown in Table 8. SO_2 and PM inventories are directly from the model, and the Indirect SO_4 emissions were estimated from SO_2 with the same ratio of SO_2/SO_4 as from on-road mobile sources. The PM emissions include nonsulfate PM as discussed earlier. Emission inventory reductions for the two cases are shown in Table 9, and are shown in Figures 12 and 13.

Table 8. Base Case Nonroad Vehicle SO_2, PM, and Indirect SO_4 Inventories (tpd)

Year	SO_2	PM	Indirect SO_4
2000	1870	856	538
2001	1935	875	557
2002	2005	897	577
2003	2078	923	598
2004	2155	951	621
2005	2235	982	644
2006	2318	1016	668
2007	2405	1051	693
2008	2496	1089	719
2009	2592	1131	747
2010	2693	1174	776

Table 9. Nonroad SO_2 and PM Emission Reductions (tpd)								
	Case A				Case B			
Year	SO_2	Direct SO_4 PM	Indirect SO_4 PM	Total SO_4 PM	SO_2	Direct SO_4 PM	Indirect SO_4 PM	Total SO_4 PM
2000	0	0	0	0	0	0	0	0
2001	0	0	0	0	0	0	0	0
2002	0	0	0	0	451	40	130	170
2003	517	46	149	195	1871	167	538	705
2004	2144	193	618	811	1939	174	559	733
2005	2224	201	641	842	2064	187	641	828
2006	2307	210	666	876	2307	210	666	876
2007	2393	220	689	909	2393	220	689	909
2008	2484	230	715	945	2484	230	715	945
2009	2579	241	743	984	2579	241	743	984
2010	2678	252	772	1024	2678	252	772	1024

Table 9 indicates that Case will reduce SO_2 by 2100 tpd in 2004, expanding to 2700 tpd in 2010. Total sulfate PM is reduced by 600 tpd in 2004, expanding to over 1000 tpd in 2010. The reductions for Case B are approximately the same, except that they start one year earlier.

5.3 Total Program Emission Reductions

Total on-highway and off-highway SO_2 and SO_4 PM reductions for the two cases are shown in Table 10. Nationwide SO_2 reductions are almost 3000 tpd and total PM SO_4 reductions are in excess of 1000 tpd.

Table 10. Total Nationwide SO_2 and PM Emission Inventory Reductions (tpd)				
	Case A		Case B	
Year	SO_2	Total PM	SO_2	Total PM
2000	0	0	0	0
2001	0	0	0	0
2002	0	0	516	194
2003	541	207	2002	753
2004	2277	860	2072	782
2005	2359	891	2199	878
2006	2443	926	2443	926
2007	2531	960	2531	960
2008	2624	996	2624	996
2009	2720	1036	2720	1036
2010	2821	1077	2821	1077

Figure 10
On-Road National SO_2 Reductions

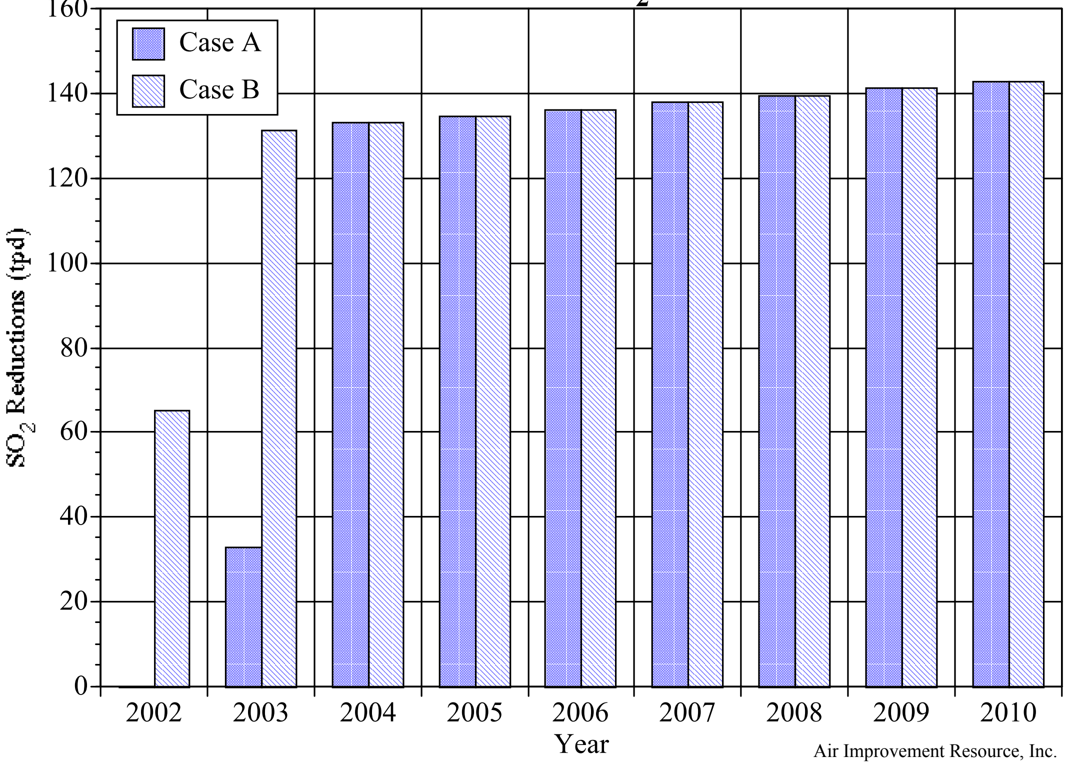


Figure 11
On-Road National Total SO_4 PM Reductions

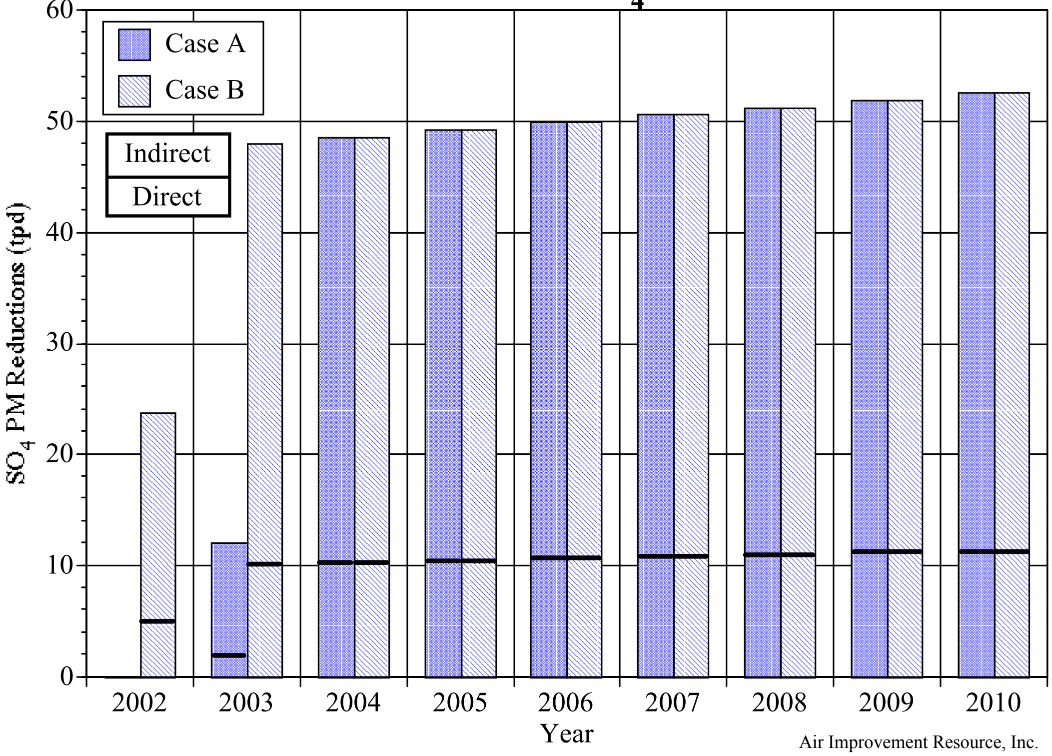
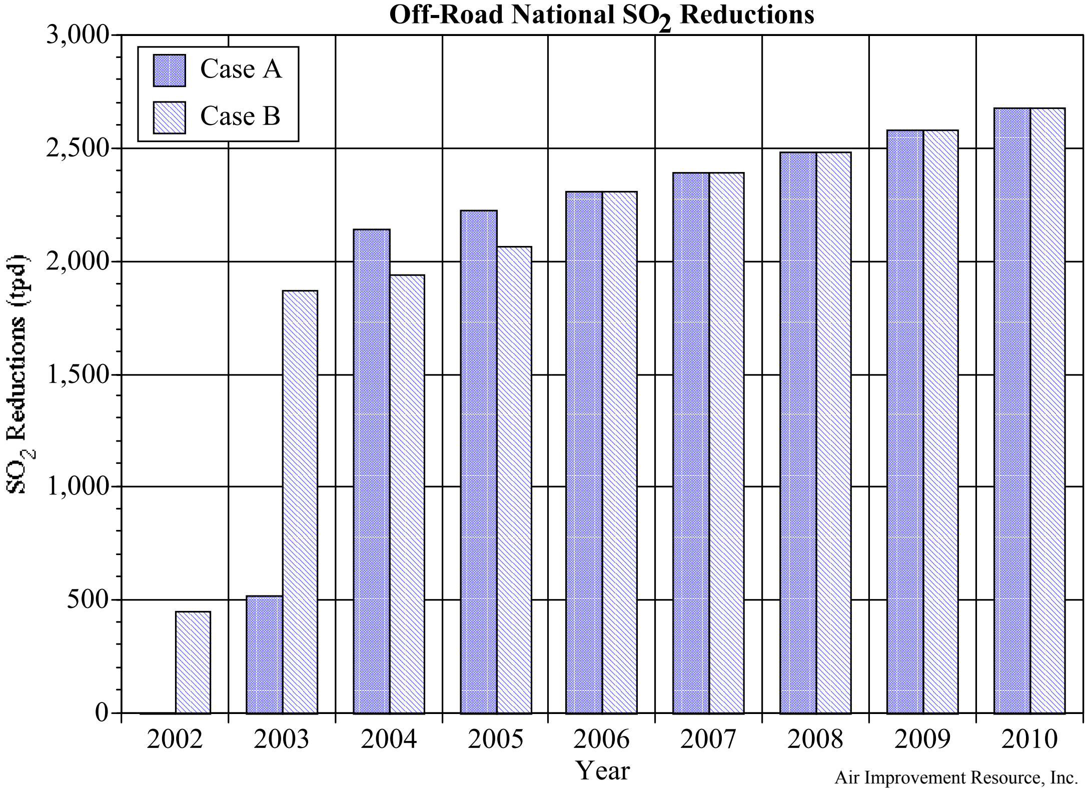
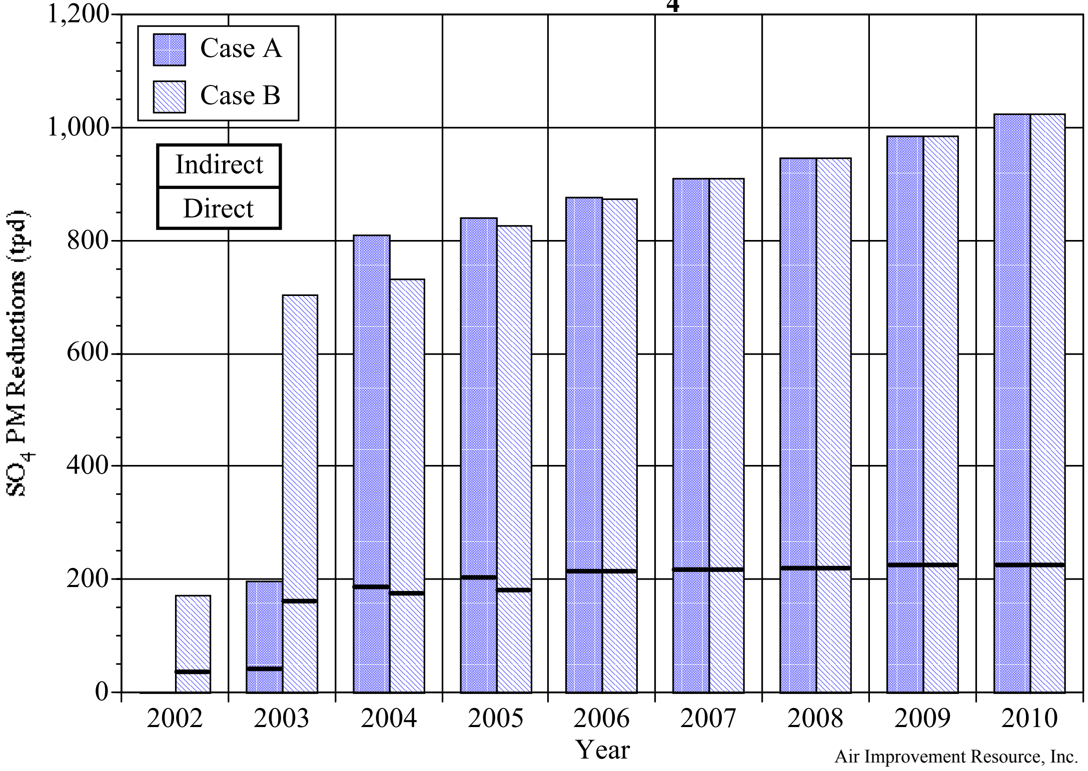


Figure 12
Off-Road National SO_2 Reductions



Air Improvement Resource, Inc.

Figure 13
On-Road National Total SO_4 PM Reductions



Air Improvement Resource, Inc.

6.0 Conclusions

This analysis has shown that a low sulfur on-road and off-road diesel specification would result in significant reductions in SO_2 and SO_4 PM emission inventories. The reductions in PM inventories are probably greater than estimated here because of the low assumed reaction of SO_2 to sulfate PM in this analysis. The PM reductions are certainly much greater in the summertime, when meteorological conditions favor much more rapid PM formation. Because sulfur oxides from diesel engines are emitted relatively close to the ground (compared to stationary sources), the reductions in SO_2 and fine sulfate PM inventories should result in lower ambient fine PM levels, improved visibility, and reduced human exposure to these pollutants. Finally, reducing diesel sulfur levels would improve EGR system life in diesel engines, reduce engine wear and maintenance costs, and allow for commercial application of more advanced diesel aftertreatment control devices.

7.0 References

1. EPA's MOBILE5 Model.

2. AIR derived this figure from AAMA's 1996 Annual Fuel Survey data.

3. EPA's Draft NONROAD Model.

4. "Draft User's Guide to PART5: A Program For Calculating Particle Emissions From Motor Vehicles," Office of Mobile Sources, EPA, February 1995.

5. Conversation with Lois Platte, U.S. EPA, OMS, March 3, 1999.

6. "Regulatory Impact Analysis: Control of Sulfur and Aromatic Content of On-Highway Diesel Fuel," EPA Publication 420-R-90-103, U. S. EPA, Office of Air and Radiation, Office of Mobile Sources, June 1990.

7. "Methodology for Estimating Emissions From On-Road Vehicles, Volume IV: BURDEN7G," ARB, November 1996.

8. "Exhaust Emission Factors for Nonroad Engine Modeling – Compression Ignition," Report No. NR–009A, EPA, revised June 15, 1998.

9. "On-Highway Emission Benefits of Vehicle and Fuel Controls in Ontario," AIR Report for Canadian Vehicle Manufacturers Association, February 12, 1996.

10. "Nationwide and State-by-State Emission Benefits of a Gasoline Sulfur Limit," AIR, AWMA, December 1998.

11. "Comparison of Emission Benefits of AAMA and API Sulfur Proposals in the U.S.: Summary Tables," AIR for AIAM, December 1998.