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Subcontractor Report

Impact of Biodiesel Fuels on Air Quality and Human Health

Summary Report
September 16, 1999–January 31, 2003

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EXECUTIVE SUMMARY

Biodiesel is derived from domestic renewable resources and can be used as an extender for petroleum based diesel fuels. One reason for the interest in biodiesel is because of its ability to reduce emissions from diesel engines for many air pollutant precursors, and the lower toxicity of the diesel particulate matter (PM) emissions. There have been numerous studies on the effects of biodiesel fuel on diesel engine emissions, however, the effects of biodiesel fuel use on air quality have not yet been quantified, although EPA is studying this issue. The National Renewable Energy Laboratory (NREL) contracted with ENVIRON International Corporation to conduct the "Impact of Biodiesel Fuels on Air Quality and Human Health" study. The study employed inventory and air quality modeling to analyze the impacts of biodiesel use in the on-road heavy-duty diesel vehicle (HDDV) fleet on:

- ambient ozone (O_3) concentrations in the Northeast Corridor, Lake Michigan, and the South Coast (Los Angeles) Air Basin (SoCAB) regions;
- carbon monoxide (CO) in Las Vegas, Nevada;
- particulate matter (PM) in the SoCAB; and
- air toxics, risk, and human health in the SoCAB.

Biodiesel test data were analyzed to determine the average effect that biodiesel (B100) and a 20%/80% biodiesel/diesel fuel blend (B20) would have on mass emissions from diesel vehicles. Table ES-1 summarizes the estimated average changes in mass emissions from diesel engines using biodiesel versus standard diesel that were used in the air quality modeling. The analysis of the diesel test data also found that diesel PM emissions from B100 and B20 biodiesel have, respectively, 20% and 5% less toxicity than standard diesel fuel.

Table ES-1. Average change in HDDV mass emissions due to use of a biodiesel fuel relative to a standard diesel fuel[1] (Lindhjem and Pollack, 2002).

Biodiesel Fuel	NOx	PM	CO	VOC	SO_2
B20	+2.4%	-8.9%	-13.1%	-17.9%	-20%
B100	+13.2%	-55.3%	-42.7%	-63.2%	-100%

[1] Standard diesel has sulfur content of < 500 ppm.

Three emissions scenarios were analyzed: (1) a standard diesel base case; (2) a 100% penetration of B20 biodiesel in the HDDV fleet; and (3) a 50% penetration of B20 biodiesel in the HDDV fleet. Table ES-2 summarizes the estimated peak pollution concentrations for the standard diesel and 100% B20 emission scenarios and the maximum increases and decreases that occurred anywhere in the region between the 100% B20 and standard diesel fuel scenarios. The difference between the 50% B20 and standard diesel scenarios were half that of the 100% B20 scenario. The increases or decreases in modeled ozone, CO, $PM_{2.5}$, and PM_{10} ambient concentrations due to the use of biodiesel are extremely small (<± 1%) for all air pollutants, regions, and averaging times studied. The use of biodiesel (100% B20) is estimated to reduce risk in the SoCAB associated with air toxics by approximately 5%. *The changes in air pollutant concentrations are below the resolution of the measurements that are typically reported to the State and EPA compliance databases, so that the impacts of biodiesel would not be measurable.*

Table ES-2. Change in peak estimated pollutant concentrations and maximum increase and decrease in daily maximum pollutant concentrations within the study area, and one in a million risk due to exposure to air toxics due to the use of a 100% penetration of B20 biodiesel in the HDDV fleet.

Location	Pollutant	Avg. Time	Units	Federal Standard	Peak Predicted Concentration			Maximum Change	
					Diesel	100% B20	Diff	Increase	Decrease
Northeast Corridor	Ozone	1-Hour	ppb	124	177	177	<1	+0.20	-0.25
Lake Michigan	Ozone	1-Hour	ppb	124	178	178	<1	+0.09	-0.53
Southern California	Ozone	1-Hour	ppb	124	176	176	<1	+0.25	-1.20
Northeast Corridor	Ozone	8-Hour	ppb	84	155	155	<1	+0.15	-0.20
Lake Michigan	Ozone	8-Hour	ppb	84	158	158	<1	+0.09	-0.40
Southern California	Ozone	8-Hour	ppb	84	145	144	<1	+0.15	-0.96
Las Vegas	CO	1-Hour	ppm	35	18.4	18.4	<1	0.00	-0.03
Las Vegas	CO	8-Hour	ppm	9	13.7	13.7	<1	0.00	-0.02
Southern California	PM_{10}	Annual	$\mu g/m^3$	50	75.8	75.6	<1	+0.04	-0.31
Southern California	PM_{10}	24-Hour	$\mu g/m^3$	150	187	186	<1	+0.62	-1.61
Southern California	$PM_{2.5}$	Annual	$\mu g/m^3$	15	52.7	52.4	<1	+0.04	-0.30
Southern California	$PM_{2.5}$	24-Hour	$\mu g/m^3$	65	178	178	<1	+0.62	-1.61
Southern California	Risk	Annual	1:Million	NA	1,257	1,191	-66	NA	NA

Acronyms and Abbreviations

B100	100% biodiesel
B20	20% biodiesel, 80% petroleum diesel
CAAA	Clean Air Act Amendments
CAMx	Comprehensive Air Quality Model with Extensions
CARB	California Air Resources Board
CO	carbon monoxide
DOE	U.S. Department of Energy
EC	elemental carbon
EMA	Engine Manufacturers Association
EMS	Emission Modeling System
EPA	U.S. Environmental Protection Agency
GEM	Gridded Emissions Model
HC	hydrocarbons
HDDV	heavy-duty diesel vehicle
I/O	indoor/outdoor
LVV	Las Vegas Valley
MATES II	Multiple Air Toxics and Exposure
NHAQS	National Ambient Air Quality Standards
NOx	nitrogen oxide
NREL	National Renewable Energy Laboratory
OC	organic carbon
OTAG	Ozone Transport Assessment Group
PAH	polyaromatic hydrocarbons
PM	particulate matter
SCOS	Southern California Ozone Study
SIP	State Implementation Plan
SoCAB	South Coast Air Basin
THC	total hydrocarbons
URF	unit risk factor
VOC	volatile organic compounds

1. INTRODUCTION

BACKGROUND

Biodiesel is derived from domestic renewable resources and can be used as an extender for petroleum based diesel fuels. One reason for the interest in biodiesel relates to the potential for a more environmentally benign fuel. One potential benefit of biodiesel is that it can biologically degrade, making spills and leaks less of a concern. But the potential for exhaust emission reductions from diesel vehicles and reductions in the toxicity of diesel particulate matter (PM) emissions are of the most interest. Several studies have shown that large reductions in hydrocarbon (HC), PM, and carbon monoxide (CO) emissions are expected from its use either as a neat fuel or as a blend with petroleum-derived fuels.

Diesel PM and, to a lesser extent, diesel HC exhaust emissions, have garnered much scrutiny for their inherent toxicity. Diesel fuels are typically characterized by heavy hydrocarbons, which produce, through partial combustion, a variety of compounds that are believed to be toxic. The State of California has listed diesel PM as a toxic substance, and recent U.S. Environmental Protection Agency (EPA) reports also discuss the toxicity of diesel PM. The recent Multiple Air Toxic Exposure Study (MATES-II) in the South Coast (Los Angeles) Air Basin (SoCAB) estimated that 70% of the risk due to air toxics in theSoCAB is due to diesel PM emissions (SCAQMD, 2000). Therefore, the potential to reduce overall toxic emissions through fuel substitution is of great interest given the reduced toxicity of PM using biodiesel.

Biodiesel has emission advantages when used in diesel engines because it can improve a number of important fuel properties, most importantly cetane, and oxygen content. Generally, these properties are thought to be responsible for improving emissions by improving ignition and distribution of oxidant. The effect of fuel substitution may be unique by engine type; the Engine Manufacturers Association (EMA) has theorized that newer engines may show less benefit because of more precise engine management (EMA, 1995). Nonroad diesel engine technology lags behind highway engine technology, so emission benefits may be greatest for nonroad engines, which also have higher base emissions of HC and PM.

Most of the potential problems typically cited for the introduction of biodiesel blends are related to the lack of a running history for their use. Unforeseen complications arising from materials compatibility, consistent fuel quality, gumming, low temperature effects, and various other long-term durability factors not specifically listed are feared with the use of biodiesel blends and may affect its penetration into the nonroad market. Most of these concerns do not affect the emission testing results in the laboratory; and the lack of cold temperature testing is typical of emission testing for diesel, gasoline, or other types of vehicles and engines.

Cost of an alternative fuel is always a concern, especially when the production facilities have neither been optimized nor can take advantage of economies of scale. The Department of Energy (DOE) estimates that a fuel blend of 20% biodiesel and 80% diesel (known as B20) would cost approximately 30 to 40 cents a gallon more than regular diesel. This cost differential is high enough to adversely affect the penetration of biodiesel in the market. For the most part, this price differential is due to the price of the base vegetable oil or tallow. In addition, there may be a small reduction in fuel economy because biodiesel has lower energy density than standard diesel fuels.

There have been several studies regarding the effects of biodiesel on exhaust emissions of nitrogen oxide (NOx), volatile organic compounds (VOC), CO, and PM. Almost all of these studies have examined emissions from heavy-duty diesel vehicle (HDDV) engines. However, the effects of biodiesel use on ambient air quality have not been quantified. Thus, the National Renewable Energy Laboratory (NREL) has retained ENVIRON International Corporation to estimate the air quality and resultant toxic impacts from the use of biodiesel in several cities in the United States.

PURPOSE

This document discusses the results of the NREL "Impact of Biodiesel Fuels on Air Quality and Human Health" study. This report provides a summary of the key results on the air quality and risk impacts from the use of biodiesel in the heavy-duty diesel vehicle (HDDV) fleet. Details on the air quality impacts from the use of biodiesel are found in the five Task Reports prepared for the NREL biodiesel study:

> Task 1 Report: "Incorporate Biodiesel Data into Vehicle Emission Databases for Modeling" (Lindhjem and Pollack, 2002), NREL report number: NREL/SR-540-33794;
>
> Task 2 Report: "The Impact of Biodiesel Fuels on Ozone Concentrations – Ozone Impacts in the Northeast Corridor, Chicago, Other Cities in the Eastern United States, and in the South Coast Air Basin Region of Southern California" (Morris, Mansell, Jia, and Wilson, 2002) , NREL report number: NREL/SR-540-33795;
>
> Task 3 Report: "The Impact of Biodiesel Fuels on Ambient Carbon Monoxide Levels in the Las Vegas Nonattainment Area" (Mansell, Morris, and Wilson, 2002) , NREL report number: NREL/SR-540-33796;
>
> Task 4 Report: "Effects of Biodiesel Fuel Use on Particulate Matter (PM) Concentrations in the South Coast Air Basin Region of Southern California" (Morris and Jia, 2002a) , NREL report number: NREL/SR-540-33797; and
>
> Task 5 Report: "Air Toxics Modeling of the Effects of Biodiesel Fuel use on Human Health in the South Coast Air Basin Region of Southern California" (Morris and Jia, 2002b) , NREL report number: NREL/SR-540-33798.

BIODIESEL EMISSION EFFECTS

The effect on emissions from truck and bus engines using biodiesel or a blend of biodiesel and standard diesel have been studied to investigate the effect on total hydrocarbon (THC), NOx, CO, and PM emissions. Some studies have also investigated the chemical compositional effects such as toxic compounds. The effect of biodiesel on emissions has been measured using both engine dynamometer and chassis dynamometer tests. An analysis of the data revealed that the engine dynamometer tests were more consistent and robust than the chassis tests so these were used to estimate the effects of biodiesel on tailpipe emissions from HDDVs. The engine dynamometer tests estimated the effects of biodiesel using both 2-stroke and 4-stroke engines for different model years that represent different levels of engine certification standards. These data were analyzed to obtain the mean effect of a 100% biodiesel (B100) and a 20%/80%

biodiesel/standard diesel fuel blend (B20) as shown in Table 1-1. The average of the biodiesel effect across engine types was used to estimate the overall effect that a B100 and B20 fuel would have on the HDDV fleet in the air quality modeling analysis. Details of the data used and the analysis are provided in the Task 1 report (Lindhjem and Pollack, 2002).

EPA's Office of Transportation and Air Quality has been compiling a biodiesel effects database over the last several years. EPA's work extended over a longer time period than the emissions analysis for this study, and their database is therefore more comprehensive. EPA included No. 1 and No. 2 diesel fuel in their database as well as related blends that can be used in a typical heavy-duty diesel engine without engine modifications. EPA's draft analysis of their data, which was released as this report was being finalized, is based on statistical regressions, which can then be used to estimate the percent change in exhaust emissions as a function of the concentration of biodiesel in conventional diesel fuel (EPA, 2002). Table 1-1 compares the average emissions effects used in this study with the EPA estimated biodiesel effects. Although the EPA analysis is based on a more comprehensive data base, the estimated emissions effects are very similar to the averages estimated for this study.

Table 1-1. Emission effects by technology type from engine dynamometer testing for biodiesel fuels compared against a standard diesel fuel. Recent EPA analysis is provided for comparison.

Engine Type/ Model Year	Fuel Pair	Engines	NOx	PM	CO	THC
20% Biodiesel Emission Effects						
2-Stroke < 1991	D-2 / B-20	6	3.2%	-1.8%	-13.9%	-20.9%
2-Stroke 1991+	D-2 / B-20	2	3.9%	-17.8%	-12.0%	-17.5%
4-Stroke <1991	D-2 / B-20	3	2.9%	-15.7%	-13.6%	-12.2%
4-Stroke 1991-3	D-2 / B-20	4	-0.9%	-15.7%	-12.0%	-2.8%
4-Stroke 1994+	D-2 / B-20	5	2.8%	-9.8%	-15.2%	-24.0%
Overall Average	D-2 / B-20	17	2.4%	-8.9%	-13.1%	-17.9%
EPA (2002) Average		43	2.0%	-10.1%	-11.0%	-21.1%
100% Biodiesel Emission Effects						
2-Stroke 1991+	D-2 / B-100	1	19.6%	-33.0%	-42.4%	-72.7%
4-Stroke 1991-3	D-2 / B-100	2	13.3%	-68.3%	-41.8%	-38.7%
4-Stroke 1994+	D-2 / B-100	5	9.9%	-36.6%	-41.5%	-76.3%
Overall Average	D-2 / B-100	5	13.2%	-55.3%	-42.7%	-63.2%
EPA (2002) Average			10.3%	-47.2%	-48.1%	-67.4%

Diesel PM includes several known toxic compounds that fall into a class known as polyaromatic hydrocarbons (PAH) and nitro-PAH compounds. Studies that measured the PAH and nitro-PAH compounds in standard diesel and B20 and B100 biodiesel fuel blends were compared to obtain an estimate of the reduction in these toxic compounds in the biodiesel as shown in Table 1-2.

Table 1-2a. Relative fraction (x 10^6) of selected PAH compounds to PM emissions from Sharp (1998) and Durbin (1999).

Compounds	Standard Diesel		B20		B100	
	Sharp	Durbin	Sharp	Durbin	Sharp	Durbin
Benzo(a)anthracene	1.59	1.01	1.51	0.43	1.37	1.11
Chrysene	2.21	1.01	1.32	0.65	1.04	0.89
Benzo(b)fluoranthene	0.96	0.50	0.97	0.22	0.77	0.22
Benzo(k)fluoranthene	1.01	*	0.92	*	0.73	*
Benzo(a)pyrene	1.12	0.25	0.69	1.72	0.49	0.00
Indeno(1,2,3-cd)pyrene	0.72	0.00	0.56	0.00	0.60	0.00
Dibenz(a,h)anthracene	0.21	0.00	0.19	0.00	0.13	0.00
Benzo(g,h,i)perylene	0.94	0.00	0.88	0.00	0.93	0.00
Total	**8.76**	**2.77**	**7.04**	**3.02**	**6.06**	**2.22**

* Included in Benzo(b)fluoranthene.

Table 1-2b. Relative fraction (x 10^6) of selected Nitro-PAH compounds to PM emissions.

Compounds	D2	B20	B100
2-Nitrofluorene	0.14	0.11	0.09
1-Nitropyrene	0.11	0.11	0.02
7-Nitrobenz(a)anthracene	0.01	0.00	0.00
6-Nitrochrysene	0.00	0.00	0.00
6-Nitrobenz(a)pyrene	0.01	0.00	0.00
Total	**0.27**	**0.22**	**0.11**

OVERALL EFFECTS OF BIODIESEL FUEL USE ON EMISSIONS AND TOXICITY

The overall effects of the use of biodiesel on emissions in the HDDV fleet are assumed to be the average effect from the engine dynamometer test data provided in Table 1-1. Based on the data in Table 1-2 and the dilution effect of the biodiesel fuel, the toxicity of the PM emissions from B100 and B20 fuels were assumed to be 20% and 5% less, respectively, than a standard diesel fuel.

2. EFFECTS OF BIODIESEL ON AMBIENT OZONE CONCENTRATIONS

The effect of biodiesel use on ozone air quality was evaluated in the SoCAB, lower Lake Michigan (Chicago), Northeast Corridor (New York, Philadelphia, Baltimore, and Washington, DC), and other cities in the Eastern United States . The largest impacts on ambient ozone concentrations due to the use of biodiesel are expected to be due to changes in NOx emissions from diesel vehicles. Studies, such as the Ozone Transport Assessment Group (OTAG), have concluded that regional NOx controls are one of the most effective control strategies for reducing regional ozone concentrations in the eastern United States. However, in some cases, NOx controls result in increased ozone levels, particularly in the urban cores of large cities. The assessment of ozone impacts due to biodiesel must therefore include the effects of the fuel on regional ozone and ozone transport as well as the effects within urban areas. The ozone air quality modeling conducted as part of this study therefore takes into account both urban-scale and regional-scale ozone formation through the use of high-resolution (4 - 5-km) urban-scale modeling of the cities under study as well as coarser-scale (12-km) regional-scale modeling.

The 1-hour ozone National Ambient Air Quality Standard (NAAQS) has a threshold of 0.12 ppm (124 ppb) that is not to be exceeded more than once per year over three consecutive years (i.e., with complete data capture a violation occurs if the fourth highest daily maximum 1-hour ozone concentration at a monitor exceeds 0.12 ppm). More recently EPA has promulgated a more stringent 8-hour ozone standard that is based on a three-year average of the fourth highest annual daily maximum 8-hour ozone concentration with a threshold of 0.08 ppm (84 ppb). EPA is currently formulating the implementation policy for the 8-hour ozone NAAQS.

The assessment of the impacts of biodiesel use on ozone concentration is made with respect to both 1-hour and 8-hour ozone concentrations (Morris, Mansell, Jia, and Wilson, 2002). An analysis of daily peak ozone concentrations in each urban area is made along with displays of spatial distributions of daily maximum ozone concentrations. These results are used to evaluate the effects of biodiesel use on the 1-hour and 8-hour ozone concentrations and attainment of the NAAQS. As part of the assessment, ozone exposure metrics are also calculated and evaluated as a measure of the biodiesel impacts on ozone air quality and human health.

MODEL AND DATABASES USED

The Comprehensive Air Quality Model with Extensions (CAMx) was selected to conduct the air quality modeling because (a) it is state-of-science, (b) it is publicly available, (c) it uses two-way grid nesting so that both urban- and region-scale issues can be addressed, (d) the databases are available, and (e) it has been used recently for regulatory decision making (e.g., EPA NOx SIP Call Rule and Dallas-Fort Worth and Houston/Galveston SIPs).

An enhanced July 1995 OTAG database was used to model the eastern United States; the July 1995 OTAG 36/12-km database was enhanced by adding two 4-km fine grids, one covering the lower Lake Michigan region and the other covering the Northeast Corridor, to better simulate urban ozone formation.

The EPA 2007 State Implementation Plan (SIP) Call emissions inventory was used for the eastern United States and the baseline (standard diesel) scenario with the MOBILE5 mobile source emissions was updated to incorporate some of the MOBILE6 emission effects.

A new SoCAB database for the August 3-7, 1997 Southern California Ozone Study (SCOS) episode was used for ozone modeling of Southern California.

The California Air Resources Board (CARB) latest emissions inventory for 1997 based on the EMFAC2000 mobile source emissions model was used for the baseline (standard diesel) emissions scenario.

EFFECTS OF BIODIESEL USE

The incorporation of biodiesel effects in the emission inventory used in this study was accomplished by applying the 1995 version of the Emission Modeling System (EMS95) for the eastern US and the ARB's Gridded Emissions Model (GEM) for the SoCAB. Biodiesel effects were accounted for in the HDDV fleet only, and only the effects of B20 were considered. Under Task 1 of the NREL study, engine test data were analyzed and the average effects of using biodiesel rather than a standard diesel fuel on HDDV tailpipe emissions of ozone precursors were estimated as shown in Table 2-1 (Lindhjem and Pollack, 2002).

Table 2-1. Overall average change in mass emission effects due to use of biodiesel fuels in HDDVs over using a standard diesel fuel.

Biodiesel Fuel	NO_x	CO	VOC
B20	+2.4%	-13.1%	-17.9%
B100	+13.2%	-42.7%	-63.2%

Three emission scenarios were analyzed for 2007 in the eastern United States and 1997 for the SoCAB:

- Standard diesel baseline scenario;
- 100% penetration in the HDDV fleet of a B20 biodiesel fuel scenario; and
- 50% penetration in the HDDV fleet of a B20 biodiesel fuel scenario.

EMISSION SUMMARY RESULTS

Table 2-2 summarizes the on-road mobile source NOx, VOC, and CO emission inventory in terms of the fractional contribution to the total inventory, the fractional contribution to the anthropogenic component, and the fraction of the on-road mobile inventory due to HDDV for the Lake Michigan and Northeast Corridor high-resolution (4-km) modeling domains, the 12-km eastern United States OTAG domain, and the SoCAB high-resolution (5-km) domain. While the on-road mobile component represents a considerable percentage of the overall inventory, the HDDV contribution is relatively small, with the exception of the HDDV NOx emissions, which account for approximately one third of the on-road mobile inventory.

The resulting changes in the emission inventory for a representative episode weekday are presented in Table 2-3 for the two biodiesel emission scenarios and for the Lake Michigan, Northeast Corridor, eastern United States, and SoCAB domains. The use of biodiesel fuel with the HDDV fleet is estimated to cause a very small change (<1%) in all ozone precursor emissions.

Table 2-2. Summary of on-road mobile and HDDV emission contributions.

2007 SIP Call Base Case and Eastern US OTAG 12-km Domain			
	NOx	**VOC**	**CO**
Mobile % of Total Inv.	30%	2.2%	49%
Mobile % of Anthro.	37%	17%	49%
HDDV % of Mobile Inv.	35%	4.7%	4.5%
2007 SIP Call Base Case and Lake Michigan 4-km Domain			
	NOx	**VOC**	**CO**
Mobile % of Total Inv.	28%	7.4%	48%
Mobile % of Anthro.	40%	156%	48%
HDDV % of Mobile Inv.	32%	4.6%	4.7%
2007 SIP Call Base Case and Northeast Corridor 4-km Domain			
	NOx	**VOC**	**CO**
Mobile % of Total Inv.	42%	2.6%	42%
Mobile % of Anthro.	46%	14%	42%
HDDV % of Mobile Inv.	36%	7.3%	6.3%
1997 EMFAC2000 Base Case and South Coast Air Basin 5-km Domain			
	NOx	**VOC**	**CO**
Mobile % of Total Inv.	63%	29%	87%
Mobile % of Anthro.	63%	33%	87%
HDDV % of Mobile Inv.	41%	6.5%	8.3%

Table 2-3. Summary of ozone precursor emission effects due to B20 biodiesel fuel use.

Emission Component	100% B20 Biodiesel 2007 EUSA OTAG 12-km Domain			50% B20 Biodiesel 2007 EUSA OTAG 12-km Domain		
	%Change NOx	**%Change VOC**	**%Change CO**	**%Change NOx**	**%Change VOC**	**%Change CO**
On-Road Mobile	0.84%	-0.85%	-0.59%	0.42%	-0.42%	-0.29%
Total Anthropogenic	0.32%	-0.14%	-0.29%	0.16%	-0.07%	-0.15%
Total	**0.25%**	**-0.02%**	**-0.29%**	**0.13%**	**-0.01%**	**-0.15%**
	2007 Lake Michigan 4-km Domain			**2007 Lake Michigan 4-km Domain**		
	%Change NOx	**%Change VOC**	**%Change CO**	**%Change NOx**	**%Change VOC**	**%Change CO**
On-Road Mobile	0.78%	-0.83%	-0.60%	0.39%	-0.41%	-0.30%
Total Anthropogenic	0.31%	-0.13%	-0.29%	0.16%	-0.07%	-0.14%
Total	**0.22%**	**-0.06%**	**-0.29%**	**0.11%**	**-0.03%**	**-0.14%**
	2007 Northeast Corridor 4-km Domain			**2007 Northeast Corridor 4-km Domain**		
	%Change NOx	**%Change VOC**	**%Change CO**	**%Change NOx**	**%Change VOC**	**%Change CO**
On-Road Mobile	0.86%	-1.31%	-0.82%	0.43%	-0.65%	-0.41%
Total Anthropogenic	0.40%	-0.19%	-0.35%	0.20%	-0.09%	-0.17%
Total	**0.36%**	**-0.04%**	**-0.35%**	**0.18%**	**-0.02%**	**-0.17%**
	1997 SoCAB 5-km Domain			**1997 SoCAB 5-km Domain**		
	%Change NOx	**%Change VOC**	**%Change CO**	**%Change NOx**	**%Change VOC**	**%Change CO**
On-Road Mobile	0.79%	-0.27%	-0.075%	0.39%	-0.14%	-0.04%
Total Anthropogenic	0.50%	-0.09%	-0.07%	0.25%	-0.05%	-0.03%
Total	**0.50%**	**-0.08%**	**-0.07%**	**0.25%**	**-0.04%**	**-0.03%**

OZONE MODELING RESULTS

The CAMx, version 3.02, air quality model was exercised for the 7-18 July, 1995 episode on the enhanced 36/12/4-km OTAG modeling domain for the 2007 SIP Call Base Case and the 100% and 50% B20 penetration into the HDDV fleet emission scenarios. Of the 12 episode days modeled, the July 11-15, 1995 period was analyzed in detail to evaluate the effects of biodiesel fuel use on urban and regional ozone air quality; the July 7-10, 1995 period is used to initialize the model and eliminate the influence of the initial concentrations, whereas the July 16-18, 1995 is a clean out period when ozone is relatively low so is not regulatory relevant. Modeling results were evaluated separately in the Lake Michigan and Northeast Corridor 4-km modeling domains and for selected urban areas in the eastern United States within the 12-km OTAG modeling domain. The August 3-7, 1997 SCOS episode was simulated by CAMx version 3.10 for the three 1997 emissions scenarios in the SoCAB. Results for August 3, 1997 were not analyzed as it was used as an initialization day.

Tables 2-4 and 2-5 summarize the maximum increases and decreases in daily maximum 1-hour and 8-hour ozone concentrations, respectively, in each of the three regions due to using biodiesel fuel in HDDVs. In the Lake Michigan region, the maximum increase and decrease in daily maximum ozone concentrations anywhere in the modeling domain for the 100% B20 emissions scenario are +0.09 and –0.53 ppb, respectively. The maximum increases and decreases in daily maximum ozone concentrations in the Northeast Corridor are +0.20 and –0.25 ppb, respectively. Similar numbers for the SoCAB are +0.22 and –1.20 ppb. Thus, the maximum changes in daily maximum 1-hour and 8-hour ozone concentrations due to the introduction of biodiesel fuels in the HDDV fleet in the Lake Michigan, Northeast Corridor, and SoCAB regions are very small.

The use of a 100% or 50% penetration in the HDDV results in very small changes, both increases and decreases, in the peak daily maximum 1-hour and 8-hour ozone concentrations in the SoCAB and Northeast Corridor, Lake Michigan, and other cities in the eastern United States (see Morris, Mansell, Jia, and Wilson, 2002). The changes in 1-hour and 8-hour ozone peaks due to use of the biodiesel fuel are always < 1 ppb.

Table 2-4. Maximum increases and decreases in daily maximum 1-hour ozone concentrations (ppb) in the Lake Michigan, Northeast Corridor, and South Coast Air Basin regions.

	50% B20 Biodiesel (ppb)		**100% B20 Biodiesel (ppb)**	
Date	**Max Increase**	**Max Decrease**	**Max Increase**	**Max Decrease**
2007 Lake Michigan Domain				
July 11, 1995	+0.03	-0.16	+0.05	-0.33
July 12, 1995	+0.07	-0.10	+0.09	-0.19
July 13, 1995	+0.05	-0.12	+0.09	-0.24
July 14, 1995	+0.07	-0.09	+0.09	-0.18
July 15, 1995	+0.04	-0.26	+0.08	-0.53
2007 Northeast Corridor Domain				
July 11, 1995	+0.06	-0.08	+0.11	-0.14
July 12, 1995	+0.07	-0.12	+0.13	-0.25
July 13, 1995	+0.12	-0.06	+0.15	-0.07
July 14, 1995	+0.15	-0.04	+0.20	-0.09
July 15, 1995	+0.10	-0.10	+0.18	-0.20
1997 South Coast Air Basin Domain				
August 4, 1997	+0.09	-0.48	+0.17	-0.95
August 5, 1997	+0.10	-0.56	+0.19	-1.1
August 6, 1995	+0.11	-0.60	+0.22	-1.2
August 7, 1995	+0.13	-0.49	+0.26	-0.98

Table 2-5. Maximum increases and decreases in daily maximum 8-hour ozone concentrations (ppb) in the Lake Michigan, Northeast Corridor, and South Coast Air Basin regions.

Date	50% B20 Biodiesel (ppb)		100% B20 Biodiesel (ppb)	
	Max Increase	Max Decrease	Max Increase	Max Decrease
2007 Lake Michigan Domain				
July 11, 1995	+0.02	-0.14	+0.04	-0.28
July 12, 1995	+0.03	-0.09	+0.07	-0.17
July 13, 1995	+0.04	-0.11	+0.09	-0.21
July 14, 1995	+0.03	-0.09	+0.07	-0.18
July 15, 1995	+0.03	-0.20	+0.07	-0.40
2007 Northeast Corridor Domain				
July 11, 1995	+0.05	-0.07	+0.10	-0.13
July 12, 1995	+0.05	-0.10	+0.11	-0.20
July 13, 1995	+0.07	-0.04	+0.12	-0.07
July 14, 1995	+0.07	-0.04	+0.14	-0.07
July 15, 1995	+0.06	-0.04	+0.15	-0.08
1997 South Coast Air Basin Domain				
August 4, 1997	+0.06	-0.34	+0.12	-0.68
August 5, 1997	+0.07	-0.39	+0.15	-0.77
August 6, 1995	+0.08	-0.48	+0.15	-0.96
August 7, 1995	+0.08	-0.42	+0.15	-0.83

CONCLUSIONS

Measured ozone is typically reported to EPA's AIRS ozone compliance database to the nearest 1 ppb. The maximum estimated increase and decrease in daily maximum 1-hour or 8-hour ozone concentrations due to the use of either a 100% or 50% penetration of a B20 fuel in the HDDV fleet in any of the areas studied is +0.26 ppb and –1.20 ppb for 1-hour ozone and the 100% B20 fuel scenario in the SoCAB region. As the maximum ozone increase (+0.26 ppb) is well below 1 ppb, the use of biodiesel is estimated to have no measurable adverse impact on 1-hour or 8-hour ozone attainment in Southern California and the Eastern United States.

3. BIODIESEL EFFECTS ON AMBIENT CO CONCENTRATIONS

INTRODUCTION

Carbon monoxide (CO) air pollution is generated by a variety of combustion processes ranging from industrial sources, to household heating, to motor vehicles. Due to the sheer number of automobiles, the vast majority (typically 90%) of area-wide CO emissions in congested urban areas come from on-road motor vehicles. Numerous urban centers in the western United States have experienced elevated CO air pollution episodes due to climatic influences, particularly during cold, dry, stagnant winter evenings and mornings. During these periods, CO emissions are trapped near the ground where they build up in direct response to hourly variations in traffic volume during the commute hours. Two NAAQS have been established for CO: a one-hour standard of 35 parts-per-million (ppm), and an eight-hour standard of 9 ppm. The 1990 Clean Air Act Amendments (CAAA) specify that regions exceeding the CO NAAQS more than three times in a three-year period are to be classified as nonattainment areas. The CAAA required CO nonattainment areas to develop SIPs which list various control strategies that, by appropriate demonstration, are estimated to lead to attainment of the CO NAAQS by the date required in the CAAA.

OVERVIEW OF APPROACH

CO modeling databases for the Las Vegas Valley (LVV) developed for Clark County, Nevada (Emery et al., 1999) were selected for use in assessing the impacts of biodiesel use on ambient CO concentrations for the following reasons:

- Clark County was designated an 8-hour CO nonattainment area in the CAAA;
- The databases were used in recent (1999) SIP CO modeling;
- The database year (1996) was more recent than that used for CO SIP modeling in other areas; and
- The databases and models used were publicly available.

Two LVV CO modeling databases were used in the SIP modeling: December 8-9, 1996 and December 19-20, 1996. Because biodiesel would occur in a future-year, the biodiesel CO assessment was performed for the year 2001, the only future year for which emissions projection data were readily available.

Based on an analysis of engine dynamometer test data for a standard diesel, B100, and a B20, Lindhjem and Pollack (2002) estimated that the mean effect on fleet average HDDV emissions of a B20 fuel would be to reduce CO emissions by 13.1 percent. Three different emission scenarios were analyzed in 2001 using the two 1996 LVV CO episodes:

- 2001 Base Case diesel (CARB standard diesel);
- 100% penetration of a B20 fuel in the HDDV fleet; and
- 50% penetration of a B20 fuel in the HDDV fleet.

Table 3-1 summarizes the CO emissions in the LVV for the 1996 and 2001 base case simulations. Although on-road mobile sources contribute the most to CO emissions in the LVV area (> 90%), the HDDV fraction contributes less than one percent (0.7%) to the total on-road mobile CO emissions. The percent reduction in CO emissions due to the 100% B20 and 50% B20 biodiesel emissions scenarios from the 2001 standard diesel base case for the HDDV, on-road mobile, and total emissions are shown in Table 3-2. Although the biodiesel results in substantial reductions in CO emissions from the HDDV fleet (7%-13%), because the HDDV contributes such a small fraction of the total CO emissions, the CO reductions from on-road mobile sources (0.08%-0.19%) and total emissions in the LVV area (0.09-0.18%) are quite small.

Table 3-1. Base year 1996 and base year 2001 CO emissions by emission component for the Las Vegas Valley.

Emissions Component	Emissions (tons/day)			
	December 9		December 20	
	1996	2001	1996	2001
Area	12.7	14.3	12.7	14.3
Surface Points	22.6	22.6	22.6	22.6
Elevated Points	2.1	2.1	2.1	2.1
On-Road Mobile	415.2	366.6	511.8	451
Total	452.6	405.6	549.2	490

Table 3-2. Reductions from base year 2001 CO emissions by emission component for the Las Vegas Valley due to a 100% and 50% penetration of a B20 biodiesel fuel in the HDDV fleet.

Emissions Component	Emissions Reductions (%)			
	December 9		December 20	
	50% B20	100% B20	50% B20	100% B20
HDDV	6.55	13.1	6.55	13.1
On-Road Mobile	0.095	0.190	0.084	0.168
Total	0.089	0.178	0.082	0.164

BIODIESEL CO IMPACT ASSESSMENT

Table 3-3 displays the peak estimated 1-hour and 8-hour CO concentrations in the LVV area for the standard diesel base case and the two biodiesel emission scenarios. The use of biodiesel is estimated to reduce the peak CO concentrations as well as CO concentrations throughout the LVV area (see Mansell, Morris, and Wilson, 2002). However, these reductions are extremely small, ranging from 0.01 to 0.03 ppm (< 0.2%).

Table 3-3. Peak estimated 1-hour and 8-hour CO concentrations in the Las Vegas Valley for the 2001 Base Case, 100% B20, and 50% B20 emission scenarios and the differences in CO concentrations between the biodiesel fuel scenarios and standard diesel base case.

	Std. Diesel	50% B20		100% B20	
Episode	**Peak (ppm)**	**Peak (ppm)**	**Difference (ppm)**	**Peak (ppm)**	**Difference (ppm)**
1-Hour CO Dec 8-9	17.90	17.89	-0.01	17.87	-0.02
8-Hour CO Dec 8-9	9.39	9.38	-0.01	9.37	-0.02
1-Hour CO Dec 19-20	18.38	18.36	-0.02	18.35	-0.03
8-Hour CO Dec 19-20	13.73	13.72	-0.01	13.71	-0.02

4. BIODIESEL IMPACTS ON PM CONCENTRATIONS

There are several areas in the United States that are currently in nonattainment for particulate matter of 10 µm or less (PM_{10}). The PM_{10} NAAQS consists of an annual standard of 50 µg/m^3 that is not to be exceeded and a 24-hour average standard of 150 µg/m^3 that is not to be exceeded more than once per year over three consecutive years (i.e., fourth highest in 3 years). In addition, there is a new fine particulate matter ($PM_{2.5}$) standard that will result in new areas being in nonattainment for PM. The form of the $PM_{2.5}$ standard is similar to the PM_{10} standard with annual and 24-hour average thresholds of 15 and 65 µg/m^3, respectively. The use of biodiesel is estimated to reduce several precursors to PM (e.g., PM, SO_2, and VOC), but increase others (NOx). Thus, the net affect of biodiesel fuel use on ambient PM levels is unclear based on analyzing changes in emissions alone, so it was assessed using air quality modeling.

PM MODELING APPROACH

The SoCAB region of southern California was selected to assess the effects of biodiesel use because: (1) it is currently a PM_{10} nonattainment area; and (2) ammonium nitrate (for which NOx is a precursor) is a major component of the PM. Thus, the SoCAB would provide a conservative (i.e., tending toward overstating any adverse effects) assessment of the impacts of biodiesel fuel on PM because the one PM precursor that biodiesel fuel increases (NOx) is a precursor to ammonium nitrate, which is a major component to PM in the SoCAB. Outside of California, ammonium nitrate is usually a minor contributor to ambient PM. The CAMx photochemical and PM grid model were applied to the SoCAB for an April 1998 through March 1999 annual modeling period to estimate the effects a 100% and 50% penetration of B20 in the HDDV fleet has on ambient PM levels. The effects of biodiesel were separately assessed for particulate sulfate, nitrate, ammonium, elemental carbon (EC), organic carbon (OC), other fine particulate, coarse matter, total PM_{10} mass, total $PM_{2.5}$ mass, and exposure to PM_{10} and $PM_{2.5}$ (Morris and Jia, 2002).

PM MODELING RESULTS

The average effect of using a B20 and B100 biodiesel fuel over a standard diesel fuel was based on an analysis of test data and is shown in Table 4-1. This effect was assumed to occur in the HDDV fleet in the air quality modeling.

Table 4-1. Average change in HDDV mass emissions due to use of a biodiesel fuel over use of a standard diesel fuel (Lindhjem and Pollack, 2002).

Biodiesel Fuel	NOx	PM	CO	VOC	SO_2
B20	+2.4%	-8.9%	-13.1%	-17.9%	-20%
B100	+13.2%	-55.3%	-42.7%	-63.2%	-100%

Table 4-2 summarizes the NOx, VOC, SOx, and PM emissions in the SoCAB domain for the standard diesel and 100% B20 biodiesel emission scenarios and for the summer and winter periods. The difference between the 50% B20 and standard diesel scenario are half that of the 100% B20 scenario. For the standard diesel base case, on-road diesel vehicles account for 22.0%, 0.5%, 0.4%, 7%, and 0.7% of the NOx, VOC, CO, SOx, and PM emissions in the SoCAB, respectively. The change in total NOx, VOC, CO, SOx, and PM emissions in the SoCAB from all sources due to the 100% B20 scenario are, respectively, +0.5%, -0.1%, -0.1%, -1.3%, and –0.1%.

Table 4-2. Summary of domain-wide total on-road diesel (Total DSL), area plus point sources, and total NOx, VOC, CO, SOx, and PM emissions in the SoCAB (tons per day) for the 1997 standard diesel Base Case and 1997 100% penetration of B20 biodiesel scenarios.

	1998 Summer Baseline					1998 Summer 100% B20 Biodiesel				
	NOx	**TOG**	**CO**	**SOx**	**PM**	**NOx**	**TOG**	**CO**	**SOx**	**PM**
Total DSL	336.5	13.5	35.3	7.7	8.0	344.5	11.3	30.9	6.2	7.3
On-Road	932.9	860.5	6912.3	38.1	23.7	940.9	858.2	6907.8	36.6	23.1
Area+Point	571.1	1489.3	1466.9	73.3	1076.0	571.1	1489.3	1466.9	73.3	1076.0
Total	1504.0	2349.8	8379.2	111.4	1099.7	1512.0	2347.5	8374.8	110.0	1099.1
						% Change				
Total DSL						2.38	-16.57	-12.55	-19.30	-8.30
Total						0.53	-0.10	-0.05	-1.33	-0.06
	1999 Winter Baseline					**1999 Winter 100% B20 Biodiesel**				
Total DSL	364.1	14.8	31.7	5.4	7.9	372.7	12.4	27.7	4.3	7.3
On-Road	1009.4	944.5	6204.4	26.7	23.6	1018.0	942.0	6200.4	25.7	23.0
Area+Point	503.7	1484.3	1528.4	72.1	1070.7	503.7	1484.3	1528.4	72.1	1070.7
Total	1513.1	2428.8	7732.8	98.8	1094.3	1521.7	2426.3	7728.8	97.8	1093.7
						% Change				
Total DSL						2.36	-16.58	-12.53	-19.31	-8.30
Total						0.57	-0.10	-0.05	-1.05	-0.06

Table 4-3 summarizes the estimated maximum increases and decreases in total PM_{10} and $PM_{2.5}$ mass and PM components due to a 100% penetration of a B20 fuel in the HDDV fleet. The results for the 50% B20 penetration are approximately half those of the 100% B20 penetration scenario. The maximum increases and decreases in $PM_{2.5}$ and PM_{10} mass concentrations are extremely small. The largest effect is for particulate nitrate that exhibits both small increases and decreases due to the B20 fuel. The decreases in nitrate occur in the more populated portions of the SoCAB, whereas the increases occur east of the SoCAB in the desert (see Morris and Jia, 2002). The 100% B20 biodiesel fuel scenario is estimated to reduce exposure to annual and 24-hour exceedances of the PM_{10} standard by 4% and 7%, respectively, over use of a standard diesel fuel.

Table 4-3. Estimated maximum increases and decreases in PM concentrations (μg/m^3) in the SoCAB due to a 100% penetration of B20 biodiesel in the HDDV fleet.

	Annual Average		Maximum 24-Hour Average	
PM Species	**Maximum Increase**	**Maximum Decrease**	**Maximum Increase**	**Maximum Decrease**
Sulfate	0.00	-0.03	0.00	-0.07
Nitrate	+0.04	-0.09	+0.58	-1.12
Ammonium	+0.01	-0.03	+0.15	-0.34
EC	0.00	-0.06	0.00	-0.10
OC	0.00	-0.15	0.00	-0.27
Other PFIN	0.00	-0.01	0.00	-0.01
Other PCRS	0.00	-0.01	0.00	-0.01
PM_{10} Mass	+0.04	-0.31	+0.62	-1.61
$PM_{2.5}$ Mass	+0.04	-0.30	+0.62	-1.61

5. IMPACTS OF BIODIESEL FUEL ON AIR TOXICS AND RISK

Diesel particulate matter has been declared a toxic substance by the state of California, and reports from the EPA have also identified it as a toxic compound. In the recent MATES-II study in the SoCAB of Southern California, 70% of the air toxic risk in the SoCAB was identified as being associated with diesel PM (SCAQMD, 2000). The use of biodiesel not only reduces the level of diesel PM mass emissions, but also reduces their toxicity. The impacts from the use of biodiesel in the HDDV fleet on air toxics and risk is discussed below.

EFFECTS OF BIODIESEL ON DIESEL PM EMISSIONS MASS AND TOXICITY

An analysis of engine test data has found that B20 fuel reduces tailpipe diesel PM emissions by approximately 9% and reduces the toxicity of the diesel PM by approximately 5% (Lindhjem and Pollack, 2002). These effects were accounted for in air toxics modeling for the SoCAB region of Southern California for three emission scenarios:

- Standard diesel emissions based on the EMFAC2000 mobile source emissions model;
- 100% penetration of a B20 biodiesel fuel in the HDDV fleet; and
- 50% penetration of a B20 biodiesel fuel in the HDDV fleet.

Table 5-1 summarizes the diesel PM emissions (lb/day) in the SoCAB for the standard diesel Base Case and the two B20 biodiesel fuel scenarios. The 100% penetration of a B20 biodiesel fuel in the HDDV fleet is estimated to reduce diesel PM emissions from the HDDV fleet by approximately 9%. As the HDDV fleet contributes approximately 53% of the total diesel PM emissions in the SoCAB, this represents an overall reduction in diesel PM emissions in the SoCAB of approximately 5% for the 100% B20 biodiesel fuel scenario. The effects of the 50% B20 biodiesel fuel scenario are half that of the 100% B20 scenario. Note that no diesel PM emission reductions are assumed for other non-HDDV diesel engines due to the biodiesel fuel. This is a conservative assumption (i.e., understating the benefits of biodiesel fuel use) as the distribution of biodiesel fuel to the HDDV fleet would certainly result in penetration into some other on-road and non-road diesel engines that would produce additional diesel PM emission reductions.

Table 5-1. Diesel particulate matter emissions in SoCAB modeling domain for the three emission scenarios (lb/day).

Source Category	Standard Diesel (lb/day)	100% B20 Biodiesel		50% B20 Biodiesel	
		(lb/day)	(%)	(lb/day)	(%)
HDDV	23239.6	21171.3	(-8.9)	22205.4	(-4.4)
Other On-Road	1668.9	1668.9	(0.0)	1668.9	(0.0)
Other Diesel	19061.1	19061.1	(0.0)	19061.1	(0.0)
Total	43969.6	41901.3	(-4.7)	42935.4	(-2.4)

The air toxics modeling accounted for six air toxics compounds: diesel PM, four organic air toxics (benzene, 1, 3-butadiene, formaldehyde, and acetaldehyde) and hexavalent chromium. According to the MATES-II study, these six air toxic compounds accounts for over 90 percent of the risk associated with exposure to air toxic compounds in the SoCAB (SCAQMD, 2000).

EFFECTS OF BIODIESEL FUEL ON AIR TOXICS RISK

As used in the MATES-II study, species-dependent unit risk factors (URFs) were applied to the air toxics estimates to estimate the one in a million risk of premature death due to long-term exposure to air toxics as follows:

- Benzene: 2.9×10^{-5} $(\mu g/m^3)^{-1}$
- 1,3-Butadiene: 1.7×10^{-4} $(\mu g/m^3)^{-1}$
- Acetaldehyde: 2.7×10^{-6} $(\mu g/m^3)^{-1}$
- Formaldehyde: 6.0×10^{-6} $(\mu g/m^3)^{-1}$
- Standard Diesel Particles: 3.0×10^{-4} $(\mu g/m^3)^{-1}$
- B20 Diesel Particles: 2.85×10^{-4} $(\mu g/m^3)^{-1}$

In the MATES-II study, risk was calculated using "front-yard" exposures that assumed no indoor/outdoor effects on exposure to the ambient air toxics concentrations. For this analysis, risk was estimated using both outdoor "front-yard" exposures as well as two simple representation of indoor/outdoor (I/O) effects on diesel PM: (1) using an annual I/O factor applied to the annual average diesel PM concentrations; and (2) using an hourly I/O factor by time of day for several different conditions (at home, at work, outside, and in a car) that is applied to the hourly air toxics concentrations and accumulated for the annual simulation. Table 5-2 summarizes the estimated average one in a million risk of premature death due to exposure to air toxic compounds for the standard diesel base case and 100% and 50% B20 biodiesel fuel scenarios. The 100% penetration of a B20 biodiesel fuel in the HDDV fleet is estimated to reduce risk of premature death due to exposure to air toxics in the SoCAB by 5%-6%. The reduction in risk for the 50% B20 scenario relative to standard diesel is about half that (approximately 2%).

Table 5-2. Average risk (out of a million) of premature death due to exposure to air toxics for the standard diesel base case and the 50% and 100% penetration of B20 biodiesel in the HDDV fleet emission scenarios calculated with no indoor/outdoor (I/O) effects and accounting for I/O effects on an annual average and hourly basis.

Scenario	Std Diesel Risk	50% B20 Fuel Risk	50% B20 Fuel (%)	100% B20 Fuel Risk	100% B20 Fuel (%)
No I/O Effects	1,950	1,910	(-2.1)	1,835	(-5.9)
Annual I/O Effects	1,284	1,261	(-1.8)	1,216	(-5.3)
Hourly I/O Effects	1,257	1,235	(-1.8)	1,191	(-5.3)

In conclusion, the use of a B20 fuel in the HDDV fleet is estimated to reduce the per million risk of premature death due to exposure to air toxics in the SoCAB by approximately 2% and 5% for the 50% and 100% HDDV fleet penetration B20 scenarios, respectively.

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This document discusses the results of the NREL "Impact of Biodiesel Fuels on Air Quality and Human Health" study. This report provides a summary of the key results on the air quality and risk impacts from the use of biodiesel in the heavy-duty diesel vehicle fleet.

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