Assessment of Biodiesel Scenarios for Midwest Freight Transport Emission Reduction

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Executive Summary

In 2007, petroleum-based fuel products supplied more than 95% of U.S. transportation energy (1). Driven largely by concerns over energy security, increased global demand, as well as air quality and climate change mitigation, state and federal policies are being developed and implemented to promote greater utilization of biofuels, which may offer benefits over petroleum-based fuels including opportunities for rural economic development. This study addresses the potential emissions benefits of biodiesel blending for use in heavy-duty diesel vehicles (HDDVs) in the Upper Midwestern United States (Michigan, Ohio, Illinois, Indiana and Wisconsin), a region of highly concentrated freight activity. The U.S. EPA's 9 Region Market Allocation Model (MARKAL), a state-of-the-art model that allows for regional-scale evaluation of transportation end-use emissions, is used to quantify PM and NOx emissions from HDDVs using biodiesel blends as a replacement for petroleum-based diesel. To evaluate effects of blending on greenhouse gas emissions, the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model is used for lifecycle analysis of greenhouse gases, including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). In this study, four alternative scenarios of HDDV biodiesel blend percentages, ranging from 20% (B20) to 2% (B2) biodiesel blends, are evaluated for their effects on HDDV emissions. These blends may be effectively used in current, unmodified diesel engines without maintenance and performance issues, thus offering a potential short-term, low-cost approach to reducing freight-related emissions.

Modeling results for all scenarios reflect an overall decline in PM_{10} and NOx emissions from heavy duty vehicles between 2010 and 2025 in the region, with a concurrent increase in GHGs. Furthermore, results demonstrate that the use of biodiesel blends, especially at higher blend levels, may further diminish GHG and PM_{10} emissions, while slightly increasing NOx emissions from heavy duty vehicles. However, at blend levels that require no modification to diesel engines (B20 and lower), the effect of biodiesel blending on NOx and PM emissions appear to be outweighed by major reductions in emission rates occurring as a result of improvements to vehicle exhaust controls, vehicle efficiency and fuel modifications over time.

1. Introduction

In 2007, petroleum-based fuel products supplied more than 95% of U.S. transportation energy (1). Driven largely by concerns over energy security, increased global demand, as well as air quality and climate change mitigation, state and federal policies are being developed and implemented to promote much greater utilization of biofuels, which may offer benefits over petroleum-based fuels. The Energy Independence and Security Act of 2007 was created in part to promote petroleum independence and greater utilization of alternative forms of energy. In March, 2010, the U.S. EPA published the Renewable Fuel Standard Program (RFS2) Final Rule, requiring 36 billion gallons of renewable fuel to be blended into transportation fuel by 2022, of which 1 billion gallons are designated from biodiesel. This study addresses the potential emissions benefits of biodiesel blending for use in heavy-duty diesel vehicles (HDDVs) in the Upper Midwestern United States (Michigan, Ohio, Illinois, Indiana and Wisconsin), a region of highly concentrated freight activity. A state-of-the-art integrated assessment model for energy, cost, and emissions was used, and we focus on criteria pollutants for which freight emissions are important, including particulate matter (PM) and nitrogen oxides (NOx), as well as greenhouses gases, including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). We evaluate four alternative scenarios of HDDV biodiesel blend percentages, ranging from 20% (B20) to 2% (B2) biodiesel blends. These blends may be effectively used in current, unmodified diesel engines without maintenance and performance issues, thus offering a potential short-term, low-cost approach to reducing freight-related emissions. Beyond their potential environmental benefits, biofuels in the Upper Midwest are viewed by many as supporting local farmers, reducing dependance on foreign oil, and strengthening the economies of these agricultural and manufacturing states.

1.1 Air Quality and Climate Impacts of Freight Transportation Emissions

The Bureau of Transportation Statistics has reported a steadily rising demand for freight transportation in the U.S., with a 2% annual increase in ton-miles of freight movement between 1990 and 2001 and forcasts of continued growth over the next several decades (2). In a study to examine the linkages between regional air quality and freight in the U.S., the Federal Highway Administration (FHWA) chose six extensive metropolitan areas (Los Angeles, Dallas-Fort Worth, Houston, Chicago, Detroit, and Baltimore) to serve as representative major multi-modal freight centers (3). Though trucking is the dominant freight mode in each of the centers, as a percentage of total on-road vehicle miles traveled (VMT), the Detroit region ranked first among the six centers, with 12.7% of total on-road VMT attributable to heavy-duty trucks, followed by Chicago (11.1%). Driving these high proportions of heavy duty traffic in the Midwest are the large volumes of long-distance trucks passing into and out of the region, particularly across the U.S.-Canada border (3).

Though the reliable and efficient movement of freight is vital to the economic well-being of the region, freight-related emissions pose a major challenge to public health and the environment. Heavy-duty vehicles are the largest contributors to U.S. freight-related NOx and PM_{10} emissions, emitting approximately 33% and 25% of all mobile source NOx and PM_{10} emissions, respectively (3). The above-mentioned FHWA study reported that among the six major metropolitan regions, freight trucks in the Detroit region contributed to the high of 63% of total on-road NOx emissions, while freight trucks from the Chicago area contributed the high of 63% of total on-road PM_{10} emissions (3). In addition to direct health effects, NOx reacts with volatile organic compounds (VOCs) to form ozone (O_3), which as been found to trigger asthma, reduced lung capacity and increased susceptibility to respiratory illnesses (4, 5, 6). Furthermore, NOx is a major contributor to wintertime fine $PM_{2.5}$, via the formation of nitrate particles. The total contribution of $PM_{2.5}$ from freight thus results from the secondary aerosols formed from NOx and – to a lesser extent – sulfur dioxide and VOC emissions, as well as from primary $PM_{2.5}$ emissions (e.g. exhaust smoke; dust released by brakes, etc.). This $PM_{2.5}$ has been found to be associated with asthma, difficult breathing, chronic bronchitis, myocardial infarction (heart attacks), and premature death (7). Both $PM_{2.5}$ and O_3 pose major challenges for regulators and public health officials in the Midwestern U.S., where over 28 million people live in areas not meeting the National Ambient Air Quality Standards (NAAQS) for these two pollutants (8).

In addition to regulated pollutants with direct health impacts, greenhouse gases (GHG) from trucking contribute significantly to total U.S. climate-related emissions. During the past few decades, vehicle efficiency improvements in the trucking sector have not kept pace with growth in demand, resulting in GHG emissions from trucking increasing by 80% between 1990 and 2007, while only increasing by 29% from all transportation activities during the same period (9). Growth in freight demand, coupled with an overall decline in energy efficiency within the freight sector are believed to have driven these trends. GHG emissions from freight trucks increased by 69% between 1990 and 2005, and accounted for almost 90% of the increase in freight GHGs, while vehicle efficiency declined between 1990 and 2005 (9). Climate policies are under discussion at local, state, and national levels, so any assessment of freight-related emission reduction options must consider GHGs along with currently regulated compounds.

While current environmental regulations are expected to significantly curtail freight truck PM and NOx emissions, they are not expected to strongly impact GHG emissions (9). There are trade-offs when attempting to reduce both GHG and criteria air pollutants, as the control strategies are not necessarily complimentary. While emission controls can remove O_3 precursors and PM from vehicle exhaust streams, these controls lower the vehicle fuel efficiency, thereby increasing the rate of CO_2 emission.

Unlike other compounds, CO_2 is relatively inert and cannot be readily separated or captured. In the absence of control technology for CO_2 exhaust, freight transport emissions can only be mitigated by improving engine efficiency/reducing fuel consumption or switching to lower carbon-content alternative fuel. To achieve reductions in fuel consumption within the next decade, the scope of alternatives is further narrowed. Improvements in engine efficiency can reduce fuel use through multiple technology pathways. The slow rate of vehicle turnover, however, limits the penetration of new technology measures in the near-term. To lower the carbon-content of freight transportation fuel, one seemingly viable near-term alternative is to increase blending of biodiesel. Replacing pure petroleum diesel with blends of biodiesel and petroleum diesel would potentially yield reductions in GHGs, as well as PM and O_3 precursors.

1.2 Biodiesel Alternative

The use of biodiesel as a fuel option has emerged as a potential alternative to petroleum-based diesel in HDDVs. Biodiesel is produced from the base-catalyzed transesterification of vegetable oil, animal fat/oil, tallow or waste oil. Soybean (U.S.) and rapeseed (Europe) oils are the most common feedstocks for biodiesel production. In addition to domestic production, advantages of biodiesel include higher combustion efficiency, lower sulfur and aromatic content (10, 11), higher cetane number as well as a higher level of biodegradability (12). Additionally, engine dynamometer tests of tailpipe emissions have shown decreased hydrocarbon, carbon monoxide and particulate emissions from biodiesel relative to petroleum-based diesel (13). Furthermore, because the CO_2 emitted from biodiesel combustion is off-set by the CO_2 absorbed during plant growth, biodiesel may reduce GHG emissions relative to petroleum-based fuels, depending on the life-cycle emissions associated with feedstock production, transport and refining. (14).

In this study, we address the question of whether substituting biodiesel for petroleum-based diesel in Midwestern HDDVs may affect criteria pollutant and GHG emissions. When evaluating a potential emissions effect, it is important to consider the temporal and spatial scales upon which specific pollutants act. Greenhouse gases and air pollutants such as NOx and PM act on different time as well as spatial scales. While the atmospheric lifetime of CO_2 is 50-200 years (9), PM and NOx are much shorter-lived pollutants, with an atmospheric lifetime on the order of days. This temporal difference also impacts the spatial scale upon which these pollutants act; GHGs impact the global atmosphere, while NOx and PM generally act at a smaller spatial scale.

This study relied on leading tools for emissions quantification from regional energy systems. The U.S. EPA's 9 Region Market Allocation Model (MARKAL) is a state-of-the-art model that allows for regional-scale evaluation of PM and NOx emissions from transportation end-use, while the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model is used for lifecycle analysis of U.S. transportation fuels. We use these models (described in more detail below) to evaluate four different biodiesel blends that may be used in current, unmodified HDDV engines. **Section 2** of this report describes model features of EPA's 9R MARKAL model, as well as MARKAL-generated freight activity trends in the Midwestern region, upon which the model calculates emission projections. **Section 3** reports on the blending scenarios tested in this study and their effect on PM_{10} and NOx emissions. Application of the GREET model and evaluation of GHG emissions are also described in section 3, while **Section 4** presents a discussion and derives conclusions and implications of the use of biodiesel blends in HDDVs in the Midwest.

2. Biodiesel Scenario Assessment

2.1 U.S. EPA 9R MARKAL Model

The US EPA 9 Region MARKAL (MARKet ALlocation) model was used to develop Midwest energy scenarios, which formed the basis for evaluating the potential emission abatement effect of different biodiesel blends for heavy duty diesel vehicles. MARKAL, an economic optimization model, offers a complete model representation of the US energy sector, from resource to end-use demand, and calculates, using straightforward linear and mixed-integer linear programming techniques, the least-cost set of technologies over time to satisfy the specified demands, subject to various user-defined constraints. Model output includes a projection of the technological mix at 5-year projected intervals to 2050, estimates of total system cost, energy services (by type and quantity), criteria and GHG emissions, and energy commodity prices (15).

The MARKAL 9r database represents the major sectors in the U.S. energy system, including the commercial, industrial, residential, transportation, and electricity generation sectors. The primary sources of data populating the MARKAL database are the U.S. Department of Energy’s Annual Energy Outlook (AEO) and National Energy

Modeling System (NEMS), which were used to construct the energy supply, demand, and technology characterizations. National end-use demand (vehicle miles traveled, or VMT) for HDDVs was based on a linear extrapolation of AEO data and distributed regionally based on available state-level data (15). Projections and statistics for light duty vehicles (passenger cars and trucks) were extracted from AEO forecasts and from light-duty vehicle technology assumptions provided by the U.S. EPA Office of Transportation and Air Quality's Transportation and Climate Division (15). Data for heavy trucks and buses were carried over from the U.S. EPA MARKAL National Model database (18). Information for technologies not represented in the AEO and NEMS were derived from other widely recognized authoritative sources such as the Department of Energy Office of Transportation Technology's Quality Metrics report and the EPA's Air Quality and Emissions Trends Report (15, 16, 17). For this analysis, an updated version of the MARKAL model was used which included the renewable fuels mandate of the Energy Information and Security Act of 2007. This modified version incorporated changes to the biodiesel sector, allowing for biodiesel blend constraints to be applied to specific end-use heavy duty vehicle categories.

MARKAL models are widely-used for energy-environmental analysis. The model flexibility has allowed for applications from energy planning to policy analysis at the regional, national and even global level (19). The U.S. EPA 9R version of MARKAL model divides the United States into nine regions, based upon the nine US census divisions, which are also used by the U.S. Department of Energy's Annual Energy Outlook (AEO) (fig. 1). These boundaries allow for model representation of inter-regional trade, such that a fuel or energy carrier produced in one region can be used in a different region. Such a framework yields insight into the entire system response to important drivers and provides an ability to characterize scenarios at a regional level, which is critical for many air pollutants that act at a regional scale such as PM and NOx.

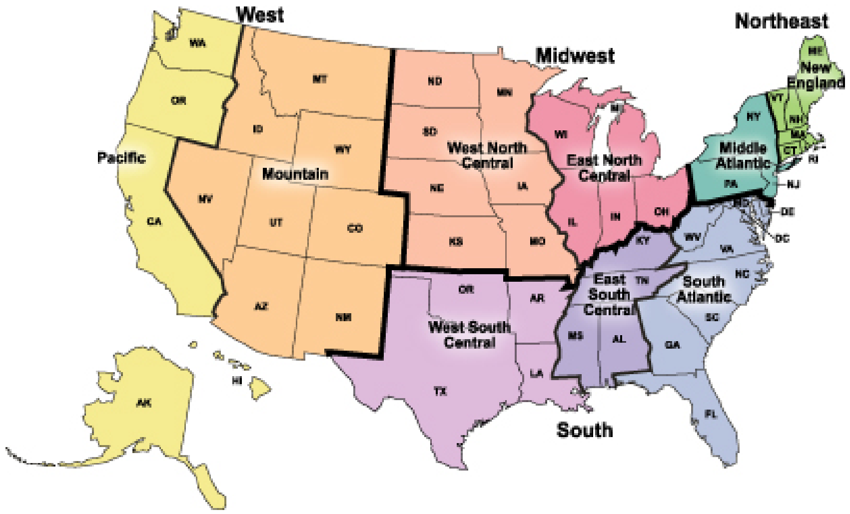
R1	New England	
R2	Middle Atlantic	
R3	East North Central	
R4	West North Central	
R5	South Atlantic	
R6	East South Central	
R7	West South Central	
R8	Mountain	
R9	Pacific	

Figure 1: EPA US 9R regions. (15)

2.2 Characterization of Freight Activity

The reference scenario, or baseline, anticipates that VMT will increase by approximately 38% between 2010 and 2015 in the “East North Central” (region 3, or R3) model domain corresponding to the Upper Midwest focus of our analysis (fig. 2). Likewise, fuel use among heavy duty vehicles is assumed to increase by 18% (fig. 3). These assumptions are based on AEO fuel consumption estimates which are used as inputs to MARKAL 9R. AEO projections are based on regionally reported fuel use from the State Energy Data Report, and growth in VMT is based upon projections of dollars of industrial output (20), and largely driven by growing international trade, and modern manufacturing and distribution supply chain practices such as express delivery.

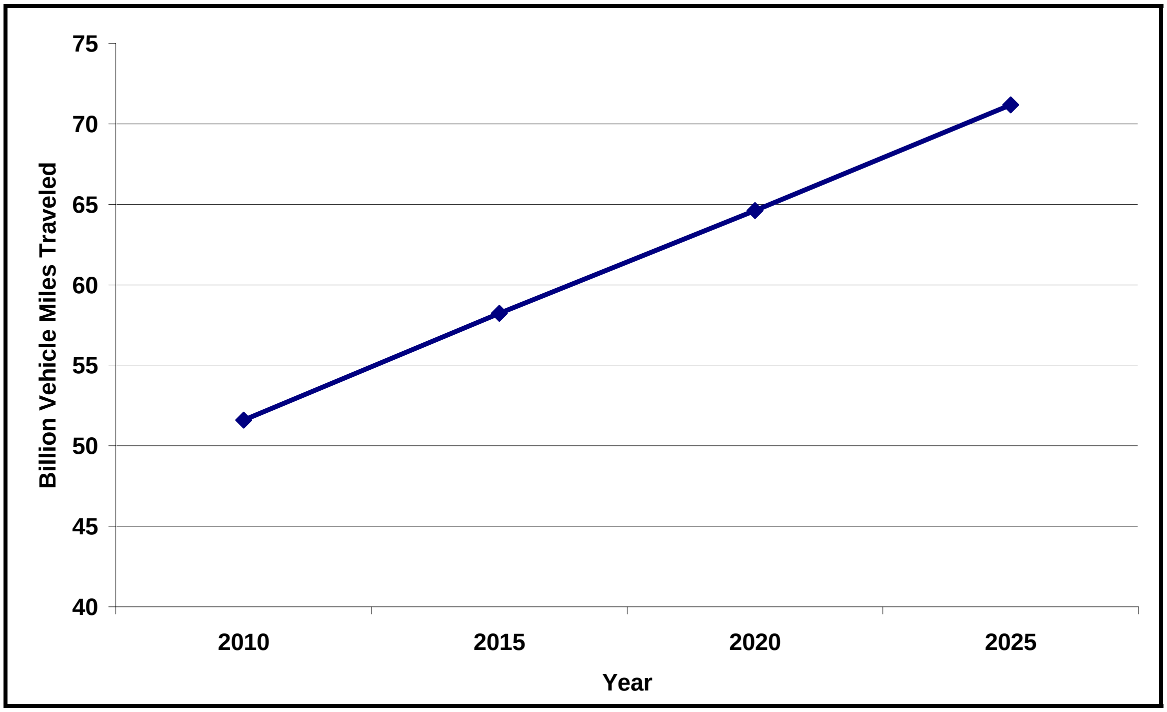


Figure 2: Projected heavy duty vehicle VMT, region 3.

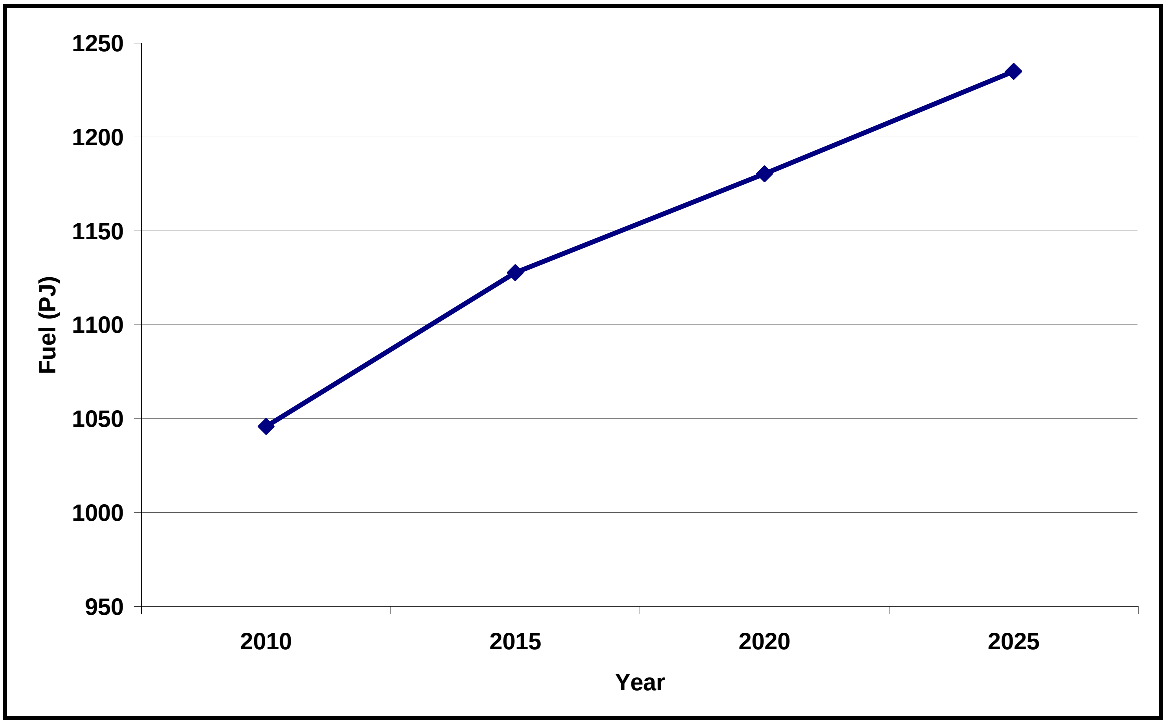


Figure 3: Projected heavy duty vehicle fuel use in region 3, 2010-2020.

During the same time period, VMT demand from light duty vehicles and buses is expected to grow, although less-so, by 20% and 10%, respectively. Overall, the referece scenario projection for total on-road transportation increases by approximately 22% between 2010 and 2025 in region 3. Relative to total on-road transportation VMT, the heavy duty vehicle sub-sector constitutes 10-11.5% of total VMT, while light duty vehicles make up 88-90% and buses contribute less than 0.25% to total demand.

The US EPA 9R MARKAL model further classifies each transportation sub-sector, allowing for the effect of vehicle technology to be considered. Vehicle miles traveled and fuel use in Table 1 reflects the phase-out of current technologies and the concurrent build-up of future heavy duty vehicles.

Transport Mode	**2010**	**2015**	**2020**	**2025**
	Fuel Use (petajoules)			
Buses	26.7	27.5	28.4	29.2
Heavy Duty Diesel Vehicles	1046	1127.7	1180.3	1235
Light Duty Vehicles	2665.3	2703.5	2669.3	2709.7
Total	3738	3858.7	3878	3973.9
HDDV Percentage of Total	**27.98%**	**29.22%**	**30.44%**	**31.08%**
	Billion Vehicle Miles Traveled			
Buses	1.2	1.3	1.3	1.3
Heavy Duty Diesel Vehicles	51.6	58.2	64.6	71.2
Light Duty Vehicles	453.4	482.4	513.4	544.9
Total	506.2	541.9	579.3	617.4
HDDV Percentage of Total	**10.19%**	**10.75%**	**11.16%**	**11.53%**

Table 1: Sub-sector projected fuel use and VMT.

Fuel economy standards for light duty vehicles reflect current law through model year 2010. For model years 2011 through 2015, fuel economy standards reflect National Highway Transportation Safety Administration’s proposed standards. For model years 2016 through 2020, the standards reflect the U.S. Energy Information Administration’s assumed increases that ensure a light vehicle combined fuel economy of 35 mpg is achieved by model 2020. For model years 2021 though 2030, fuel economy standards are held constant at model year 2020 levels (20). Vehicle efficiencies, fuels and emissions for various transportation sub-sectors are largely driven by national-scale regulations. The Energy Bill passed by the Senate in 2007 included a provision that increased the average new car efficiency to 35 miles per gallon by 2020, an increase of approximately 40% over the existing CAFÉ standards (15). Efficiency standards are represented in the MARKAL database as added constraints that specify minimum fleet efficiencies. In addition, “degradation factors” are used to convert new vehicle tested fuel economy values to "on-road" fuel economy values, which serve to adjust tested fuel economy values to account for the difference experienced between fuel economy performance realized in the CAFE test procedure compared fuel economy realized under normal driving conditions (20). In the reference scenario, the HDDV fleet-averaged fuel efficiency increases from 6.6 miles per gallon in 2010 to 7.7 miles per gallon in 2025, based on the adoption of newer high efficiency vehicles over time.

3. Evaluating the Emissions Impacts of Biodiesel Blending Scenarios

The emissions reduction potential from increasing blend levels of biodiesel for HDDVs was analyzed by comparing a reference scenario of petroleum-based diesel to four alternative scenarios where HDDV biodiesel blend percentage changed as follows:

- Scenario 1 – 100% of Region 3 HDDV fuel using a 20% biodiesel-80% petroleum diesel blend (B20)
- Scenario 2- 100% of Region 3 HDDV fuel using a 10% biodiesel-90% petroleum diesel blend (B10)
- Scenario 3- 100% of Region 3 HDDV fuel using a 4% biodiesel-96% petroleum diesel blend (B4)
- Scenario 4- 100% of Region 3 HDDV fuel using a 2% biodiesel-98% petroleum diesel blend (B2)

Blends of 20% biodiesel and lower were considered in the analysis, as these levels can be effectively used in current, unmodified diesel engines without maintenance and performance issues such as cold weather gelling.

3.1 Effect of Biodiesel Blending on PM_{10} and NOx Emissions

Vehicle emissions generally depend upon the type and quantity of fuel consumed, and quantity is a function of travel demand (VMT), vehicle choice and associated engine efficiency. However, emission drivers are also pollutant-dependent. While carbon and sulfur emissions are more fuel-dependent, NOx emissions are generated by heat in the combustion process, resulting in the widespread use of catalytic converters due to regulations limiting NOx emissions. In MARKAL, the vehicles' NOx emissions rates are based largely on regulations. Total NOx emissions are driven by vehicle choice, as projected by MARKAL, and the resulting quantity of fuel required to satisfy VMT demand (15). Table 2 displays MARKAL petroleum-based diesel emission factors for PM_{10} and NOx for all HDDV technologies.

MARKAL emission factors take into consideration AEO projections of freight transportation energy use, which assume vehicle efficiencies improve based largely on federal regulations, including the EPA's heavy duty highway vehicle emissions rules that took effect in 2007 affecting PM and NOx emissions (15). Though $PM_{2.5}$ is more relevant from a health perspective than PM_{10}, we were not able to evaluate the effects of biodiesel blending on $PM_{2.5}$, as the current version of MARKAL provides more detailed analysis of PM_{10}. The MARKAL model calculates emissions from HDDVs based upon emissions factors for HDDVs operating with petroleum-based diesel, however, though PM_{10} and NOx emissions factors vary with the biodiesel blend level, the MARKAL database currently does not have representative emission factors for HDDVs operating on various biodiesel blends. Therefore, blend-specific emission factor adjustments for NOx and PM_{10} were generated as described below, and used to adjust model emission results.

Heavy Duty Diesel Vehicle Technology*	**Pollutant Emission Factors (kt/petajoule)**	
	NOx	**PM_{10}**
HDDVs, 2000	0.661	0.013
HDDVs + 20% miles per gallon, 2010	0.023	0.001
HDDVs + 40% miles per gallon, 2020	0.029	0.001
Existing Fleet of HDDVs	0.734	0.024

Table 2: MARKAL emission factors for all heavy duty diesel vehicle technologies. *Percent efficiency improvement, model year.

Particulate matter and NOx emissions were adjusted according to biodiesel blend level by applying the following equation:

$$\begin{array}{c}\text{Predicted change in emissions of biodiesel blend} \\ \text{relative to petroleum-based diesel} \\ = \{\exp[a \times (\text{vol\% biodiesel})] - 1\} \times 100\% \text{ (eq 1),}\end{array}$$

where the coefficient $a = 0.0009794$ for NOx and -0.006384 for PM_{10}. These equations, taken from the EPA's *Comprehensive Analysis of the Emissions Impacts of Biodiesel*, were based on a statistical regression analysis which correlated the concentration of biodiesel in conventional diesel fuel with changes in regulated and unregulated pollutants in heavy duty highway engines (13), and can be used to predict the percent change in emissions, given the concentration of biodiesel blend.

Equation 1 was used to calculate biodiesel blend adjustment factors for PM_{10} and NOx (table 3). As a result, NOx emission factors for B20 were 2% higher than petroleum-based diesel, while PM10 emission factors for B20 were 12% lower than petroleum-based diesel (table 3).

	PM_{10}	**NOx**
B20	- 11.99%	1.98%
B10	- 6.18%	0.98%
B4	- 2.52%	0.39%
B2	- 1.27%	0.20%

Table 3: Percent emission change of biodiesel blend relative to petroleum-based diesel.

PM_{10} and NOx emissions for petroleum-based diesel for all heavy duty diesel vehicle technologies were calculated based on reference scenario projections for fuel use and VMT. . Results of the reference scenario (assuming 100% petroleum-based diesel) project an approximately 2-fold decrease in NOx as well as PM_{10} from total HDDVs in region 3 between 2010 and 2025, reflecting federal regulations and advanced emission control technologies such as particle filter traps (fig.s 4, 5).

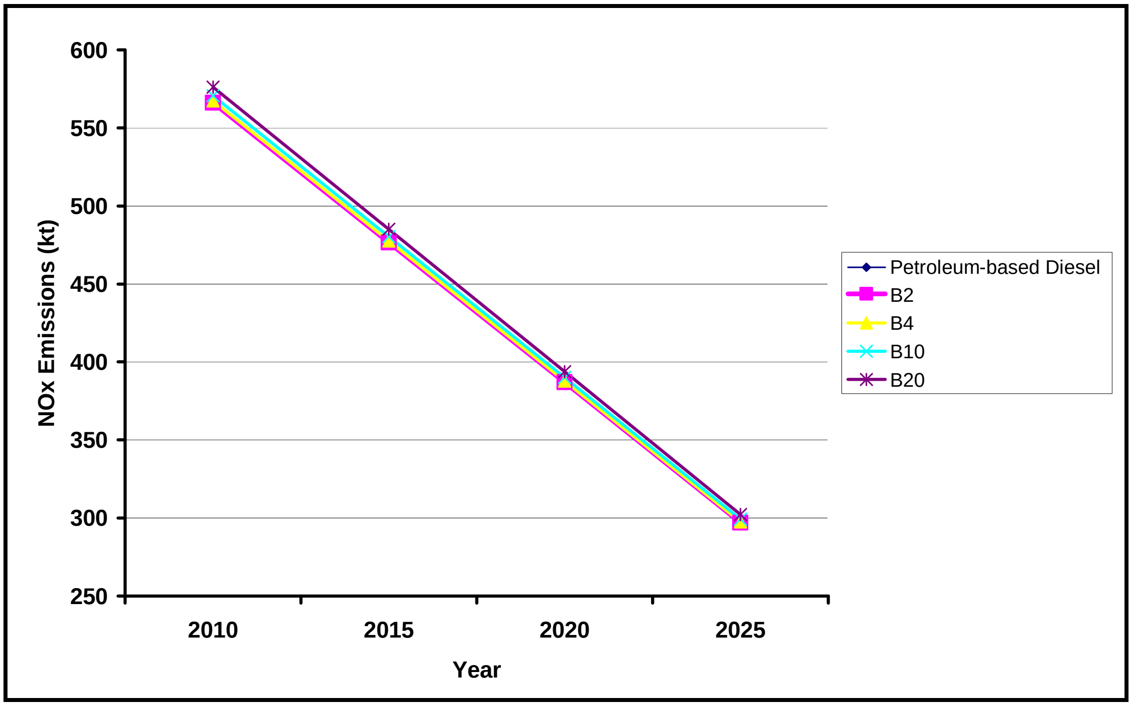


Figure 4: Projected NOx emissions from region 3 heavy duty diesel vehicle fleet reflecting a decrease in total emissions from 2010 to 2025.

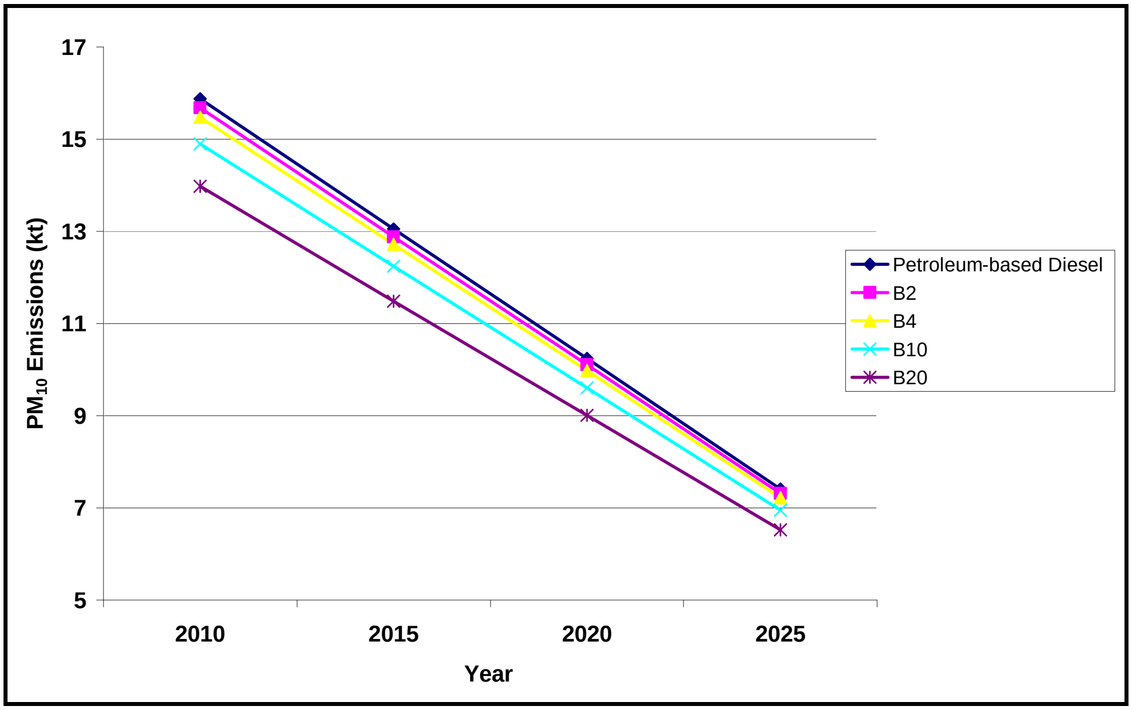


Figure 5: Projected PM10 emissions from region 3 heavy duty diesel vehicle fleet reflecting a decrease in total emissions from 2010 to 2025.

To estimate emissions for the B2, B4, B10 and B20 biodiesel blend scenarios, emission factors were adjusted and applied to calculate the effect of biodiesel blend on emissions from the total heavy duty diesel vehicle fleet as described above. Overall, biodiesel has a small linear effect on NOx emissions, increasing NOx by approximately 0.2-2.0% between 2010 and 2025, and a more moderate impact on PM_{10}, decreasing these emissions by 1.25-12% (tables 4, 5). Due to the approximately linear emission factor adjustment, higher blend levels (B20, B10) affect emission rates more dramatically than do lower blend levels (B2, B4), with limited influence on NOx and PM_{10} emissions relative to petroleum-based diesel at these blend levels.

	2010	**2015**	**2020**	**2025**
Petroleum-Based Diesel	565.0	475.6	386.3	296.4
B2	566.1	476.5	387.0	296.9
B4	567.2	477.4	387.8	297.5
B10	570.6	480.3	390.1	299.3
B20	576.2	485.0	393.9	302.2

Table 4: Total NOx emissions (kt) of biodiesel blend scenarios relative to reference-case scenario (100% petroleum-based diesel).

	2010	2015	2020	2025
Petroleum-Based Diesel	15.9	13.1	10.2	7.4
B2	15.7	12.9	10.1	7.3
B4	15.5	12.7	10.0	7.2
B10	14.9	12.2	9.6	7.0
B20	14.0	11.5	9.0	6.5

Table 5: Total PM10 emissions (kt) of biodiesel blend scenarios relative to reference-case scenario (100% petroleum-based diesel).

Overall NOx emissions are projected to decrease over time. When total on-road transportation emissions are broken down by sub-sector, it is apparent that an increasing *proportion* of the total on-road NOx emissions will be from heavy duty vehicles, as the contribution from light-duty vehicles are expected to decrease from approximately 28% to 14% of total on-road NOx emissions. Buses are projected to emit a minor and declining proportion (fig. 6). Though NOx emissions are expected to decrease across all vehicle sub-classes, light-duty vehicle emissions are projected to decrease more rapidly due to regulations on NOx emission limits as well as incorporation of advanced engine technologies such as hybrid power. Hybrid and plug-in hybrid vehicles are modeled as emitting below the regulated amount since these vehicles are assumed to be operated in electric mode for some fraction of their operating cycle, emitting no NOx (15).

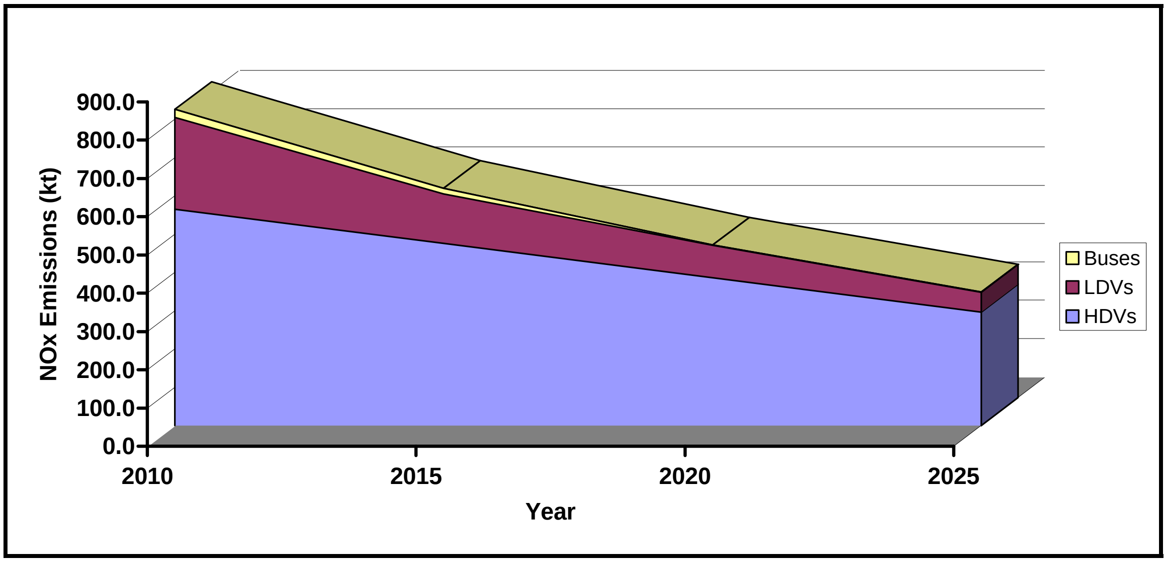


Figure 6: Sub-sector contribution to NOx on-road transportation emissions, reference case (Petroleum-based diesel).

In contrast to NOx, emission projections indicate the contribution from heavy duty diesel vehicles to PM_{10} will decline between 2010 and 2025 (fig. 7). Between 2010 and 2015, the proportion of PM_{10} from light duty vehicles will grow from approximately 47% to 69%. Heavy duty vehicle PM_{10} contributions are expected to decrease from 52% to 31%, and bus emissions from 1% to 0.08% in 2025. In addition to the implementation of cleaner diesel fuel regulations, the reduction in PM_{10} emissions from heavy duty vehicles relative to other sub-classes likely reflects the effectiveness of diesel engine retrofit control devices such as diesel particle filters, which work most effectively on engines built after 1995 and have been shown to have a PM emissions reduction potential of 90% (21).

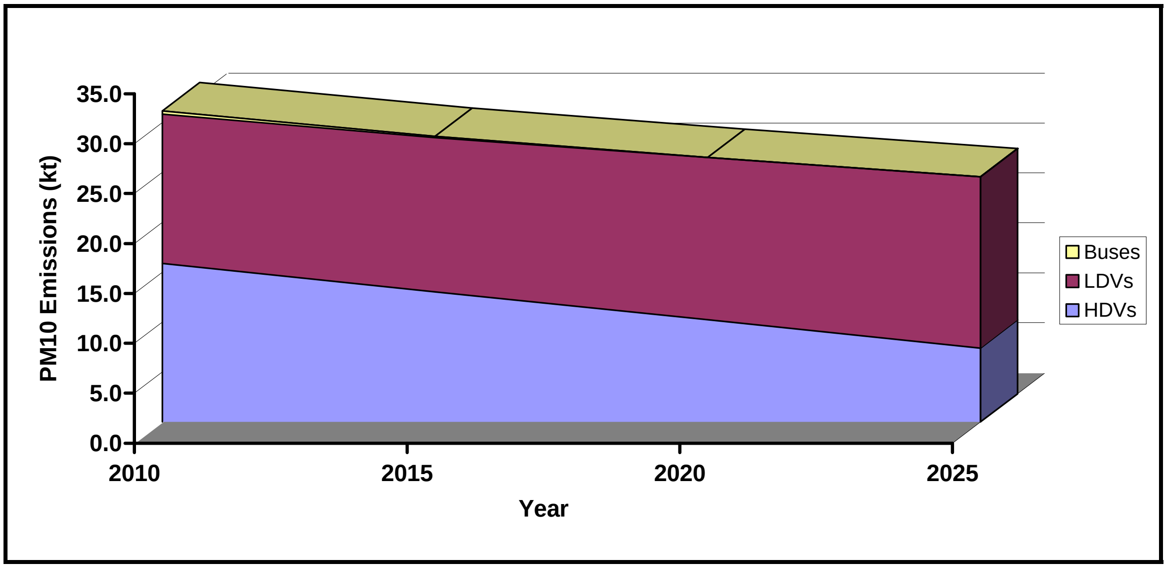


Figure 7: Sub-sector contribution to PM10 on-road transportation emissions, reference case (Petroleum-based diesel).

3.2 Effect of Biodiesel Blending on GHG Emissions

Greenhouse gas emissions were evaluated from a lifecycle perspective, as is appropriate for biofuels where the majority of greenhouse gas impact occurs as a result of feedstock production and fuel refining. Though the MARKAL model can be considered a “lifecycle model” in the respect that emissions can be considered from production through end-use, the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model is more comprehensive for generating life-cycle GHG emission factors for both biodiesel and petroleum diesel (14). While GREET emission factors are typically reported in grams per mile for passenger cars and light duty trucks, the underlying assumptions were used to create fuel-based emission factors which could be applied to heavy duty freight transport. Emission factors in table 6 are expressed in terms of grams per mega-joule (gCO_2-eq./MJ) and include CO_2-equivalent contributions from CO_2, CH_4, N_2O, VOC, and CO.

Process Step	Soy Biodiesel g CO_2-eq./MJ	Low Sulfur Diesel g CO2-eq./MJ
Feedstock Production	10.4	7.0
Fuel refining	12.3	10.3
Vehicle Operation	1.6	75.8
Total	**24.3**	**93.0**

Table 6: Life-cycle greenhouse gas emission factors based on GREET model.

Heavy duty vehicle GHG emissions were estimated by multiplying MARKAL end-use fuel consumption (table 1) by the GREET greenhouse gas emission factors for evaluated blends, listed in table 7.

Fuel Blend	g CO2-eq./MJ
100% Petroleum Diesel	93.0
2% Biodiesel Blend	91.6
4% Biodiesel Blend	90.3
10% Biodiesel Blend	86.2
20% Biodiesel Blend	79.3

Table 7: Life-cycle greenhouse gas emission factors for biodiesel blends.

Results reflect an overall increase in GHG emissions from total HDDVs through 2025, with biodiesel blends decreasing emissions by 1.5-14.7% (fig. 8). GHG emissions are closely tied to freight energy use, both of which are increasing due to an increase in demand outpacing improvements in energy efficiency in the trucking sector. The EPA’s inventory of Greenhouse Gases and Sinks reports that while total transportation is responsible for 28% of GHG emissions, 21% of those emissions are from freight trucks (9). Energy use and GHG emissions from freight transportation have grown at approximately twice the rate of light duty transportation emissions over the last 15 years. The overall decline in energy efficiency within the freight sector, along with prosperous growth in freight demand reflect a growing reliance on freight transport with faster and more reliable service but higher energy intensity. Though the bulk of on-road GHG emissions are from light duty vehicles, the proportion from this sub-class declines by 3.5% between 2010 and 2025 in the reference case, while the proportion of emissions from heavy duty vehicles increase 3% during the same period. Emissions from buses are relatively slight and are projected to remain roughly constant (fig. 9).

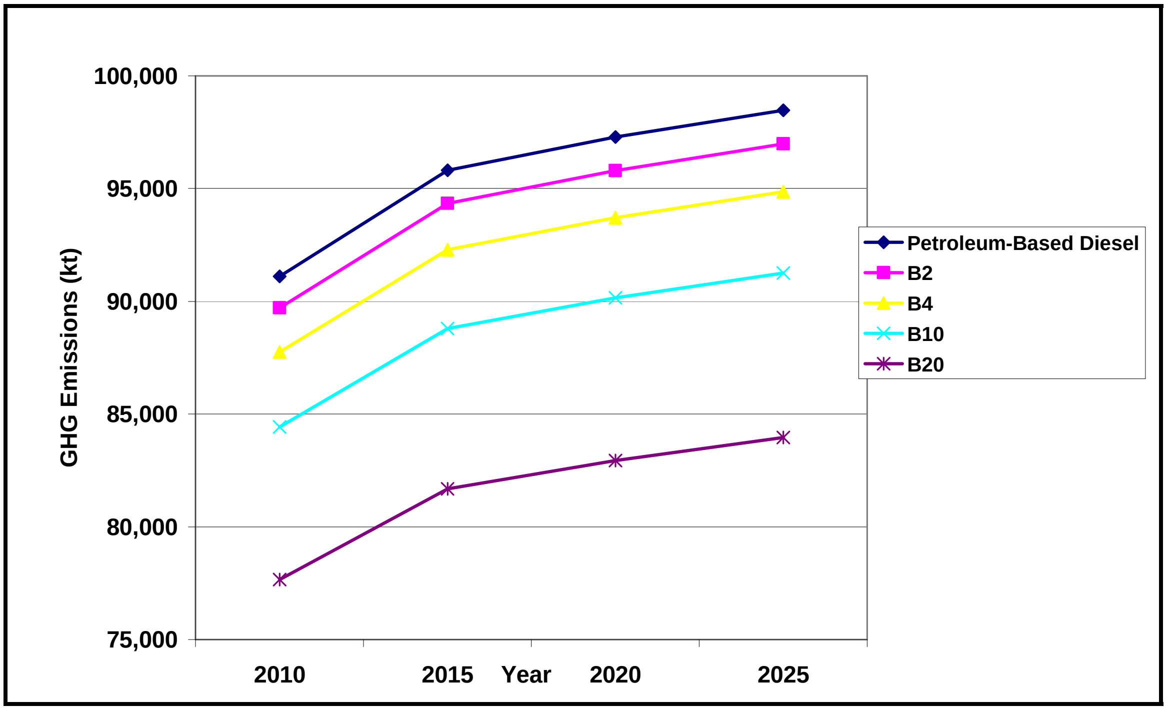


Figure 8: Projected GHG emissions from region 3 heavy duty diesel vehicle fleet reflecting an increase in total emissions from 2010 to 2025.

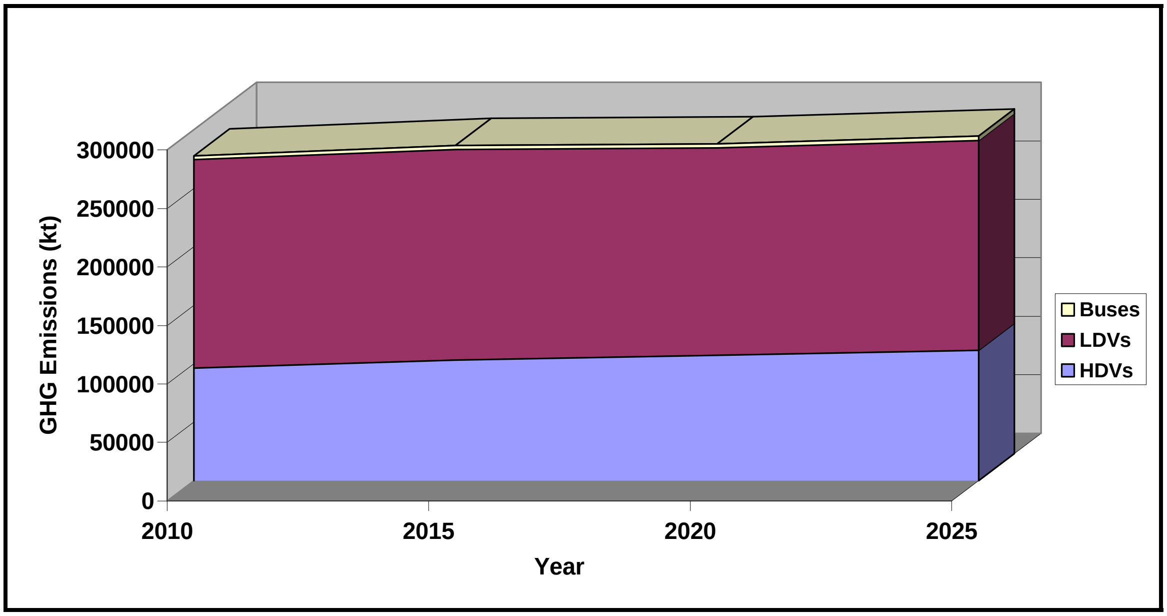


Figure 9: Sub-sector contribution to GHG on-road transportation emissions, reference case (Petroleum-based diesel).

4. Discussion and Implications

The overall aim of this project was to clarify whether the use of biodiesel blends in heavy duty diesel vehicles may aid in the reduction of freight-related emissions in the Midwest. The reference case scenario reflects an overall decline in PM_{10} and NOx emissions from heavy duty vehicles between 2010 and 2025 in the region, with a concurrent increase in GHGs. Our modeling results suggest that the use of biodiesel blends, especially at higher blend levels, may diminish GHG and PM_{10} emissions relative to the reference scenario, though NOx emissions from heavy duty vehicles could increase slightly. At blend levels that require no modification to diesel engines (B20 and lower), the estimated impact of biodiesel on NOx and PM emissions appear to be largely outweighed by major emission reductions resulting from improvements to vehicle exhaust controls, vehicle efficiency and perhaps fuel modifications over time, as discussed in section 2.

The long-term regional availability of soy-based biodiesel is dependent on many factors and presents some uncertainty in the magnitude of potential biodiesel deployment. The MARKAL 9R database relies upon data from the U.S. Department of Agriculture (22, 23, 24) to inform the potential current production of biodiesel feedstocks. The model's baseline assumptions would limit the availability of soybean oil-based biodiesel that could be uniformly used in 100% of heavy duty diesel vehicles in region 3, effectively capping the blend at 4%. It has been noted (26) that U.S. resources are available to produce about 1.7 billion gallons of biodiesel annually, though in 2008 production reached 682 million gallons of B100, a significant fraction of which was exported (27). Several sources of additional feedstock could be developed in the near term, including corn oil recovered from dry-mill ethanol production, aquaculture of algae and a number of other terrestrial crops such as camelina, pennycress, canola rotation with wheat, and jatropha. Furthermore, future increases in soybean yields and oil content could also increase feedstock oil production (28), potentially allowing for higher blend levels to be spread across larger regions.

Regardless of the uncertainty in total biodiesel production potential, the possibility exists to concentrate higher blend levels within smaller regions, such as in urban areas that may be out of compliance with National Ambient Air Quality standards. For example, given MARKAL's baseline assumptions of soy biodiesel availability, roughly 13% of HDDVs in region 3 could run on B20 by 2025. In this instance, our regional estimates of emissions mitigation would be the same because the emission factor adjustment is linear, however, any corresponding air quality impacts could potentially be localized. The results of this study do not suggest that such an urban biodiesel concentration is warranted, given the currently limited understanding of associated HDDV emission rates. Biodiesel blend level was negatively correlated with $PM_{10.}$ So while concentrating biodiesel blends in PM_{10} non-attainment areas may be justifiable, PM_{10} is not a critical concern in the Midwest.[1] $PM_{2.5}$ is of greater concern, and therefore a better understanding of biodiesel's impact on fine particulate is needed.

While the projected influence on HDDV NOx emission was limited, increasing biodiesel blend levels could potentially lead to slightly higher NOx emissions and ozone formation. Currently, numerous areas in the Midwest are designated non-attainment areas for the 2008 ozone standards, including the Chicago metro area, Northern, Central and Southern regions in Indiana, several regions in Michigan including the Flint metropolitan area and the Southeastern region, many counties in Ohio as well as portions of Eastern Wisconsin. Ozone is formed when NOx reacts with volatile organic compounds (VOCs) in the presence of sunlight in the atmosphere. Studies have shown that in urban areas, ozone formation is rate-limited by VOCs, while in lower-NOx emitting rural areas, formation is mostly rate-limited by the presence of NOx, depending upon meteorological conditions (25).

Our analysis considered end-use emissions at the regional scale, but did not consider resulting air pollution concentrations. Air quality analysis would be necessary to evaluate pollutant-specific implications of localizing biodiesel use. Such an assessment would require allocating emissions at a finer spatial scale and subsequent pollutant fate

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[1] Michigan and Illinois have PM_{10} maintenance areas.

and transport modeling. This type of study would require consideration of local meteorology, and would preferably incorporate vehicle-specific emission factors that consider anticipated driving conditions.

Results of this study were highly dependent upon emission factor adjustments developed for biodiesel blends. Studies in published literature have reflected significant variation in emissions from biodiesel use, particularly for NOx. Factors that have been observed to affect NOx emissions from biodiesel include source of biodiesel feedstock material (i.e. soybean oil, rapeseed oil, animal fats) (13), engine design (29), driving cycle (30) and average load (31). Furthermore, engines equipped with adsorbent and catalyst systems to achieve a NOx standard of 0.2 g/bhp-h by 2010 are currently being phased in, and there are limited data demonstrating how the catalyst may behave with biodiesel blends. Likewise, data are limited on the emissions performance of heavy duty diesel engines equipped with diesel particle filters, use of which is enabled by the 2006 phasing-in of ultra low sulfur diesel. Therefore, many of these factors will need to be re-evaluated with these emergent technologies (28).

While the GREET model provides well-accepted representative emission factor values, there is considerable uncertainty associated with life-cycle greenhouse gas emission estimates for biodiesel. The life-cycle greenhouse gas emission factor estimates could vary substantially, based on the assumptions used for the feedstock production scenarios. For example, the GREET model does not endogenously model the flux of carbon and nitrogen from soil, but rather uses a single exogenously-modeled value for a representative production scenario. These terms are highly sensitive to crop rotation and fertilizer application and are the subject of considerable ongoing research. Further, the direct and indirect conversion of non-agricultural lands for crop production is not included in the estimates used in this report. The importance of land use change emissions has received considerable attention during the development of California's Low Carbon Fuel Standard (32). This is a valid consideration, particularly for scenarios requiring dramatic increases in biodiesel from current production levels.

The reduction of emissions from on-road transportation has been one of the drivers for biodiesel development in recent years. Our results show that using biodiesel blends in heavy duty diesel vehicles in the Midwestern region has the potential to decrease GHG and PM_{10} emissions, but could potentially increase NOx emissions. Overall, the estimated effect of biodiesel blends was limited relative to the larger emissions-reductions anticipated from technology and mandates in transportation sub-sectors. Much of the newly emerging heavy duty vehicle technologies have yet to be tested in the context of biodiesel blend use, an important factor that requires further research attention. Further, alternative policies such as imposing greenhouse gas regulation, improving trucking fleet fuel efficiency, reducing freight idling, switching to more fuel efficient modes of freight movement, or analyzing combinations of such alternatives merit additional research.

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