WHITE PAPER

MARCH 2021

AIR QUALITY IMPACTS OF BIODIESEL IN THE UNITED STATES

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ACKNOWLEDGMENTS

This study was generously funded by the David and Lucile Packard Foundation and the Norwegian Agency for Development Cooperation.

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EXECUTIVE SUMMARY

Since the passage of the Clean Air Act in 1970, the U.S. Environmental Protection Agency (EPA) has enacted standards to reduce vehicle exhaust emissions. These standards set emission limits for pollutants that contribute to poor air quality and associated health risks, including nitrous oxide (NOx), hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM). Although the majority of the on-road vehicle fleet in the United States is fueled by gasoline, diesel combustion makes up an overwhelming share of vehicle air pollution emissions.

Air pollution emissions can be affected by blending biodiesel, composed of fatty acid methyl ester (FAME), into diesel fuel. Biodiesel increases the efficiency of fuel combustion due to its high oxygen content and high cetane number. Studies have found that biodiesel combustion results in lower emissions of PM, CO, and HC, likely for this reason. However, studies have consistently found that biodiesel blending increases NOx formation.

Industry analysts, academic researchers, and government regulators have conducted extensive study on the emissions impacts of biodiesel blending over the last thirty years. The EPA concluded in a 2002 report that, on the whole, biodiesel combustion does not worsen air quality compared to conventional diesel and reaffirmed that conclusion in a 2020 proposal and subsequent rulemaking. This determination based on literature published in 2007 and earlier, proposed that no additional fuel control measures are necessary to mitigate the air quality impacts of biofuels from the Renewable Fuel Standard (RFS).

This study presents a meta-analysis of air pollution changes from vehicles and engines running on biodiesel blends in the United States relative to a conventional diesel baseline. We draw from a comprehensive literature review of exhaust emissions testing and performance studies, dozens of them published after EPA's studies, and analyze changes in NOx, PM, CO, and HC for U.S.-relevant feedstocks. We assess the impacts that feedstocks, test cycles, and diesel quality have on the exhaust emissions from biodiesel combustion. Unlike previous meta-analyses, we also assess the impacts of fuel injection systems, engine horsepower, and emission control technologies on biodiesel exhaust emissions.

When analyzing the entirety of the available literature, we find that a 20% biodiesel blend (B20) increases NOx emissions by 2% compared to conventional diesel, in agreement with EPA's 2002 finding. However, this estimate includes many literature studies that are no longer relevant due to evolving developments in the industry. We find that the biodiesel NOx effect has increased in recent years with the introduction of ultra-low sulfur diesel (ULSD) and common-rail fuel injection systems. When we restrict our meta-analysis to only studies reflecting these conditions, we find that the biodiesel NOx effect for B20 increases to 4%.

Table ES-1 summarizes the percent change in emissions, or biodiesel emissions effect, with 20 percent biodiesel blends compared to pure diesel fuel, based on our analysis. We also present results from EPA's 2002 study, follow-up 2010 regulatory impact assessment (RIA), and another meta-analysis for comparison. Under modern conditions, we also find that a 20% biodiesel blend (B20) increases HC and CO by 7% and 10%, respectively, and does not reduce PM compared with conventional diesel. This new finding presents a striking contrast with the conclusions in EPA's 2002 meta-analysis that biodiesel sharply reduces emissions of all these pollutants.

Table ES-1. Biodiesel exhaust emissions study comparison. Data reported in percent change in emissions between B20 and petroleum diesel fuel.

Pollutant	EPA (2002)	EPA (2010)	Hoekman & Robbins (2012)	This study (all data)	This study (modern conditions)
NOx	2%	2%	1%	2%	4%
PM	-10%	-16%		-6%	Insignificant
HC	-21%	-14%		-4%	7%
CO	-11%	-13%		Insignificant	10%

Our findings illustrate that our understanding of the air quality impacts of biodiesel should change in response to the large volume of new evidence that has been published since EPA's reports. Our results show that the air quality impacts of biodiesel combustion are worse than was previously believed. These updated results should inform EPA's future rulemakings pursuant to the Renewable Fuel Standard.

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INTRODUCTION

The U.S. Census Bureau (2016) estimates that approximately 80 percent of Americans live in urban areas where densely populated conditions contribute to increased smog and ozone formation. Vehicle emission standards introduced since the 1970s have mitigated air quality concerns (Chambliss et al., 2013), but on-road diesel vehicles continue to be the primary source of nitrous oxide (NOx) emissions. In the United States, 40% of anthropogenic NOx release is estimated to come from on-road vehicles; together with non-road vehicles, the transportation sector accounts for 60% of NOx release (U.S. EPA, 2016). A report by Anenberg et al. (2017) finds that NOx emissions account for 100,000 deaths from premature mortality worldwide. Particulate matter (PM) is another pressing health concern, as PM exposure can lead to premature mortality and respiratory and cardiovascular disease. Other tailpipe emissions including CO, a byproduct of incomplete combustion, and unburned HCs also have adverse health effects such as restricted oxygen flow in the bloodstream and increased cancer risk (U.S. EPA, 2015a).

The U.S. Bureau of Transportation Statistics (2015) estimates that while diesel vehicles only account for 4 percent of the on-road fleet in the United States, they are also responsible for over half of on-road NOx emissions. Although diesel usage remains a small portion of energy consumption across the energy sector, it is expected to continue to serve as the primary fuel for trucking and long-haul freight transportation in the coming decades (U.S. EIA, 2019).

Close to 2 billion gallons of biodiesel is used annually in the United States, primarily in on-road heavy-duty applications (U.S. EIA, 2020). Biodiesel use is driven by the biomass-based diesel (BBD) volume obligation in the Renewable Fuel Standard (RFS), intermittent availability of federal tax credits, and state and local policies. In the United States, biodiesel is sourced from numerous feedstocks including soybean oil, animal fats, used cooking oil (UCO), and canola oil (U.S. EIA, 2020). The U.S. Environmental Protection Agency (EPA) estimates that biodiesel is blended into the national fuel mix at 5% blend levels (B5), on average, although the regional breakdown varies due to state-specific biodiesel subsidies and mandates. For example, Minnesota adopted the country's highest blend mandate in 2018, requiring B20 to be sold at all diesel pumps from April through September (Biodiesel Content Mandate, 2019). Future growth of the U.S. biodiesel market will be dependent upon state and federal level biofuel policies. At the federal level, the national BBD blending obligation set annually by the EPA has increased 83 percent from 2010 to 2019 (U.S. EPA, 2015b) and is expected to continue to increase through at least 2022.

How biodiesel affects the air quality impacts of diesel fuel combustion is thus a question of increasing importance. The EPA is required by the 2007 Energy Independence and Security Act (EISA) to conduct a study to determine whether renewable fuel required by the RFS will adversely impact air quality. In 2020, EPA released this study, known as the "anti-backsliding study" (U.S. EPA, 2020) which relied heavily on data from the 2010 Regulatory Impact Assessment (U.S. EPA, 2010) and corresponding MOtor Vehicle Emissions Simulator (MOVES) database. Relative to EPA's 2002 assessment (U.S. EPA, 2002), the RIA broadened its scope to include the effects of newer model engines and technologies on biodiesel emissions. However, older data was supplemented with literature published between 2002 and 2007, omitting the effects of biodiesel and ultra-low sulfur diesel blends, advanced emission control technologies such as diesel particulate filters (DPFs), and common-rail fuel injection systems largely phased in after this period.

BACKGROUND

This study assesses the air quality impacts of biodiesel exhaust emissions in the United States. It offers an update to two U.S. meta-analyses on biodiesel emissions conducted in the last twenty years: the EPA's seminal 2002 study on biodiesel emissions impacts (U.S. EPA, 2002) and a Hoekman and Robbins (2012) study on the biodiesel NOx effect in medium- and heavy-duty engines. Both studies identify a small but statistically significant increase in biodiesel NOx emissions relative to conventional diesel fuel. The EPA study also finds that HC, CO, and PM decrease proportionally to biodiesel blend level. These studies attribute these changes in emissions in part to biodiesel's physical properties, including its high oxygen content, bulk modulus, and cetane number (CN).

While the high oxygen content of biodiesel is expected to improve combustion properties, other fuel characteristics result in increased NOx. Biodiesel has low compressibility, so it enters the combustion chamber earlier than conventional diesel. This extends the period of time between fuel injection and fuel ignition, known as the "ignition delay." Extended ignition delay increases air-fuel mixing (i.e. premixed combustion) inside the combustion chamber which can lead to rapid rises in pressure and temperature compared to when pure diesel fuel is used (Lee et al., 1998). The formation of NOx increases exponentially with temperature increases, so a longer ignition delay corresponds with increased NOx. This is known as the biodiesel NOx effect. Engine parameters, including fuel injection rate, spray quality, and injection pressure, also play a role in air pollutant formation from vehicle tailpipes. For example, high pressure injection systems increase NOx by raising temperatures in the combustion chamber while improved fuel atomization allows more complete combustion, reducing the formation of HC and CO in exhaust gas streams.

This study investigates the impact of these parameters on the biodiesel NOx effect as well as on CO, HC, and PM emissions from biodiesel blends. We also investigate the effects of engine test cycles and emission control technologies. Lastly, we consider the impact the sulfur content of baseline diesel fuel and type of fuel injection system used has on the biodiesel emissions effect.

METHODOLOGY

This analysis uses the same methodology and dataset as O'Malley and Searle (2020). This dataset is comprised of 131 biodiesel exhaust emissions studies conducted between 1983 and 2018, which include analysis of a wide range of feedstocks, engines, test cycles, and emission control technologies. A complete summary table of studies is provided in Appendix B. Of the dataset, 104 studies assess feedstocks that are prominent in the U.S. biodiesel market, including soybean oil, canola (rapeseed) oil, and animal fats. We classify these feedstocks based on production data from the Energy Information Authority's (EIA) Monthly Biodiesel Production Report (U.S. EIA, 2020) and filter results to only include the primary feedstocks in the U.S. fuel market when data is sufficient. We also place an emphasis on studies conducted on vehicles adherent to modern emission standards.

Although diesel is only minimally used in light-duty applications across the United States, data for light-duty and single cylinder engines are also included in our analysis. Light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs) differ by weight class and use of emission control technologies. For example, HDVs typically utilize selective catalytic reduction (SCR) systems to reduce NOx, and diesel oxidative catalysts (DOCs) and diesel particulate filters (DPFs) to reduce PM. Smaller cars, however, utilize lean NOx traps (LNTs) to reduce NOx in conjunction with DOCs and DPFs to mitigate other conventional pollutants (M. Williams & Minjares, 2016). Grouping data by vehicle weight class, we find no significant difference among the emissions effect for LDV versus HDV test results.

Throughout this study, we perform simple linear regressions on the concentration of NOx, CO, PM, and HC emissions in vehicle exhaust (i.e. dependent variable) against the biodiesel blend level (i.e. independent variable) for the entire literature. We adopt this methodology in order to utilize a wider range of test results on varying blend levels. Including more studies across blend levels increases the sample size and improves the accuracy of predictions than assessing each blend level separately. We also perform multiple linear regressions to determine the statistical significance of multiple interacting explanatory variables. For these regressions, we check for multicollinearity with an R^2 threshold of 0.65.

We perform additional regressions on select datasets, filtered by feedstock properties, engine configurations and test cycles, and baseline fuel sulfur quality. We do not remove any outliers from any analyses. In all graphs, we show trendlines only for statistically significant trends at $p<0.05$. The shaded cones encasing trendlines show standard error. Our companion study (O'Malley and Searle, 2020) provides more information on study methodology.

RESULTS AND DISCUSSION

Figure 1 shows the results of our analysis of the average impacts of biodiesel blending on conventional air pollutants. Including all studies from our literature review on common U.S. feedstocks, we calculate the average biodiesel emissions effects to be 9% for NOx, -30% for PM, and -19% for HC. There was no statistically significant trend for CO emissions regressed on biodiesel blend level. Our analysis included studies with blend rates as low as 1% biodiesel in conventional diesel fuel up to 100% blends (pure biodiesel). Biodiesel blend level is shown on the x-axis. The y-axis shows the percent change in emissions of NOx, PM, and HC when combusting biodiesel blends in vehicles and engines compared to the emissions when combusting conventional diesel fuel. For example, a datapoint at 50% blend level (x-axis) and 5% emissions effect (y-axis) for NOx would mean that study found that a vehicle emits 5% higher NOx when operating on a 50% biodiesel blend than when operating on conventional diesel. We expect the emissions effect to vary proportionally with blend level. We note that there is very high variability in the data, as illustrated in the standard error cones, even for the trends that are statistically significant. This is likely due to the additional factors that vary across studies which impact the emissions effect. Thus, we analyze the effects of feedstock physical properties, engine test cycles, and modern advancements across the diesel industry on biodiesel exhaust emissions formation in the following sections.

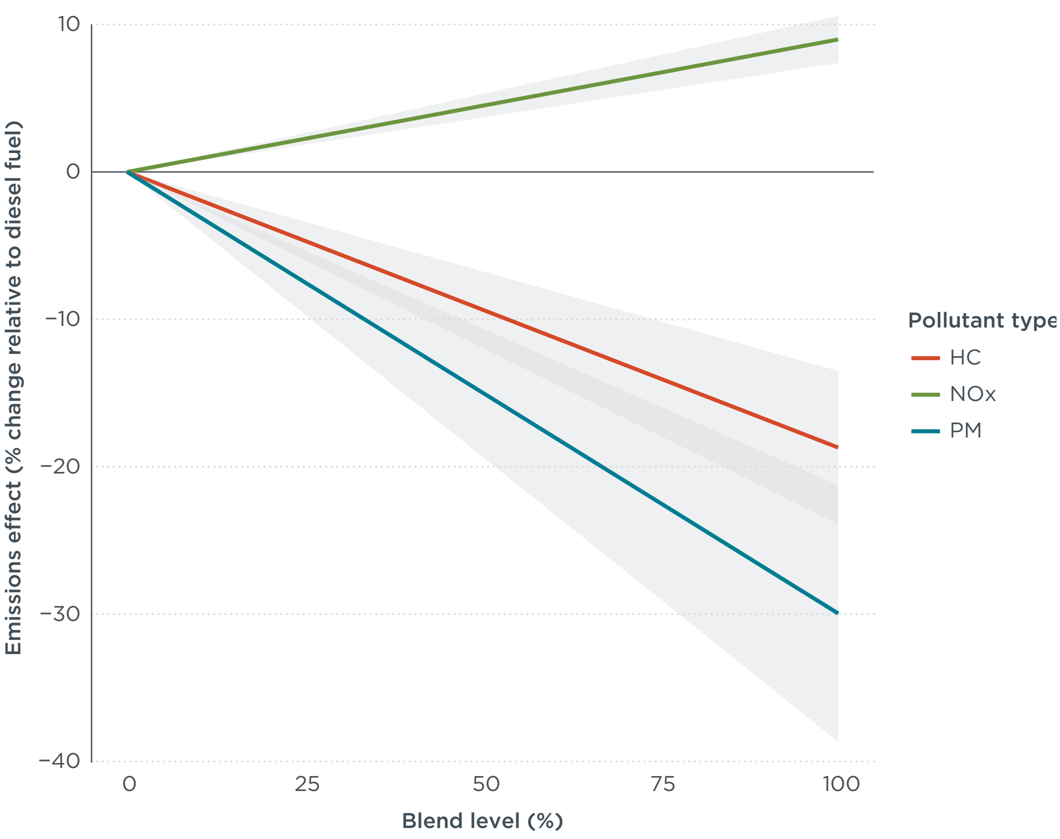

Figure 1. Average impacts of biodiesel blending on conventional air pollutants in United States.

BIODIESEL FEEDSTOCK PROPERTIES

Feedstock properties have a significant impact on total emissions formation and the biodiesel emissions effect. Physical properties such as density and viscosity alter the level of air-fuel mixing inside the combustion chamber; this in turn influences the efficiency of combustion as well as temperature and pressure conditions inside the combustion chamber (Heywood, 2001). Feedstock properties also influence the timing of combustion.

While biodiesel in general has different properties than conventional diesel, physical properties also differ among biodiesel feedstocks. A list of common biodiesel feedstocks and the properties of the biodiesel produced from these feedstocks is provided in Table 1. The properties of palm and coconut oil are also included for comparison, although their consumption in U.S. biodiesel markets is negligible. The average biodiesel properties in Table 1 are compiled from studies presented in the Appendix B with the exception of unsaturation and chain length, which are drawn from Hoekman et al. (2012), and bulk modulus of compressibility. Bulk modulus or "elasticity" measures a material's resistance to compression. Biodiesel is comprised of various long chain fatty acids dependent on the primary feedstock which undergo transesterification to form mono-alkyl esters (FAME). Therefore, to calculate the bulk modulus of biodiesel, we multiply the bulk modulus of mono-alkyl esters, measured at 1000 psi and 100° F, by their composition profiles in each biodiesel feedstock (Boehman et al., 2004; Shahabuddin et al., 2013).

Table 1. Biodiesel (FAME) properties overview.

Feedstock	Cetane number	Density (kg/m³)	Viscosity (mm²/s)	Unsaturation[†]	Chain length	Bulk modulus at 1000 psi and 100º F
Diesel	50.37	0.836	3.08	N/A	N/A	1477
Soybean	51.29	0.857	3.54	1.50	17.90	1648
Rapeseed	56.45	0.859	4.42	1.31	17.90	1642
UCO	54.64	0.860	4.64	1.06	18.50	1626
Animal fat	56.65	0.876	3.83	0.59	17.30	1608
Palm	57.81	0.851	5.01	0.62	17.20	1607
Coconut	58.68	0.875	4.39	0.12	13.40	1552

Notes: Cetane number, density, and viscosity data is sourced from the literature in Appendix B and averaged by feedstock type. Unsaturation and chain length data is adapted from Hoekman et al. (2012). Bulk modulus is calculated from data sourced from Boehman et al. (2004) and Shahabuddin et al. (2013).

Cetane number (CN), defined as the inverse of the delay between fuel injection into the combustion chamber and ignition, is one of the most frequently studied biodiesel properties. Fuels with a high CN ignite sooner than fuels with a low CN, providing less time for air-fuel mixing. The shorter ignition delay with high CN fuels reduces fuel residence time inside the chamber, limiting rapid increases in fuel pressure and temperature due to premixed burn (Hoekman & Robbins, 2012). Because NOx increases exponentially with temperature, shorter ignition delay limits NOx formation (Hoekman & Robbins, 2012; Lee et al., 1998). Other studies have found that if ignition delay is held constant through alternative strategies such as exhaust gas recirculation (EGR), CN has little effect on NOx emissions (Ickes et al., 2009).

Biodiesel generally has a higher CN than conventional diesel. Thus, CN is not the main parameter causing the biodiesel NOx effect, but one might expect higher CN biodiesels to produce lower NOx than lower CN biodiesels (Lee et al., 1998). However, we regress the biodiesel NOx effect on CN using our entire dataset and find that these two parameters are positively correlated, in contrast with much of the literature. We speculate that other fuel and vehicle parameters may influence this result.

Other fuel properties such as bulk modulus, density, and viscosity can affect emissions formation. As discussed above, high bulk modulus advances fuel injection and extends the ignition delay period, resulting in rapid temperature and pressure increases and high NOx formation. Monyem et al. (2001) identify a linear relationship between injection timing and NOx formation regardless of the type of fuel used. For the five diesel and biodiesel fuels studied in their experiment, advanced injection timing resulted in an average 23% increase in NOx emissions relative to standard injection timing. Other studies have found that common-rail injection systems better control for the effects of advanced injection due to biodiesel's high bulk modulus (Hoekman & Robbins, 2012).

Viscous fuels can also advance injection timing by building up pressure in the fuel pump (Lapuerta et al., 2012). This leads to an increase in NOx emissions. However, viscous fuels have large droplet diameters which reduces their ability to atomize, or disperse into finer particles (Hoekman & Robbins, 2012), which counteracts this effect. Reduced atomization of fuel particles decreases combustion efficiency which leads to an increase in HC and PM (Agarwal et al., 2015; Lapuerta et al., 2008a). In our analysis, we observe a negative and significant relationship between viscosity and HC and PM emissions, while we observe a positive and significant relationship between viscosity and the biodiesel NOx effect (Figure 2). Our analysis therefore suggests that the increase in air-fuel mixing from advance injection timing due to viscosity has a more important effect than droplet size on the completeness of combustion.

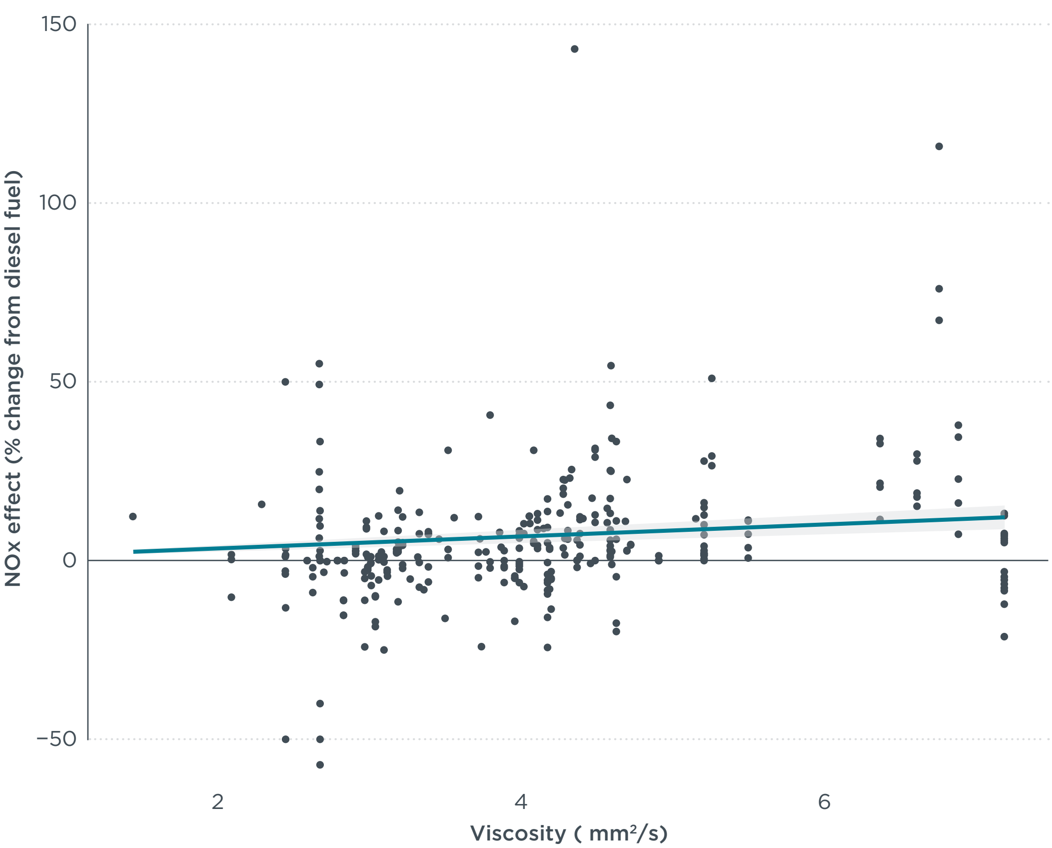

Figure 2. NOx effect by biodiesel viscosity.

Density also has an effect on emissions formation. Agarwal et al. (2015) find that density affects fuel injection duration, the total mass of fuel injected, and the degree of fuel atomization. Density also affects volumetric fuel efficiency, or the efficiency of the combustion cylinder to compress gas. The relationship between fuel density and NOx formation is complex; Lee et al. (1998) suggest that changes in volumetric efficiency, flow rate, and spray characteristics from low density fuels contribute to reduced NOx. Particulate matter emissions may also decrease at low density while HC and CO emissions increase due to changes to the air-fuel mixing process.

We observe a positive relationship between fuel density and NOx formation in our analysis, as shown in Figure 3. The relationship between density and HC and PM emissions is insignificant while the relationship between density and CO emissions is significant and positive.

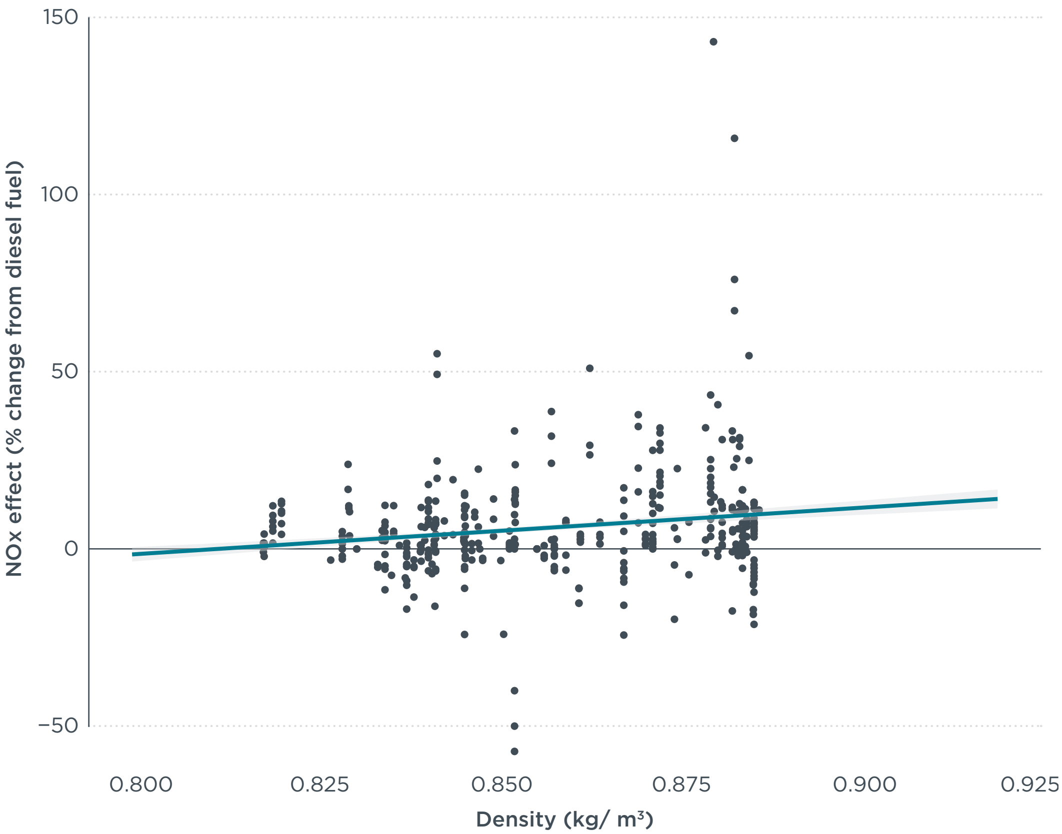

Figure 3. NOx effect by biodiesel density.

Several other studies find that the degree of unsaturation of a fatty acid, measured by the number of carbon double bonds, corresponds with the physical properties of biodiesel including density, viscosity, and CN (Dharma et al., 2016; Hoekman et al., 2012; Wang et al., 2016). Unsaturated fatty acids are associated with low viscosity and high density. As detailed above, these properties correspond with a reduced and increased NOx effect, respectively. Unsaturated fatty acids also tend to have lower CNs, which increases ignition delay and NOx formation. Corroborating this trend, Yanowitz and McCormick (2009) find that a biodiesel's degree of saturation is inversely correlated with NOx emissions in a study on biodiesel emissions from HDVs in North America.

We calculate the NOx effect of common U.S. feedstocks regressed on blend level to range between -12.5% and 13.4% for 100% biodiesel (B100) (Figure 4). We find that the biodiesel NOx effect is largest for rapeseed or (canola oil) while it is lowest for studies conducted with animal fat feedstocks.

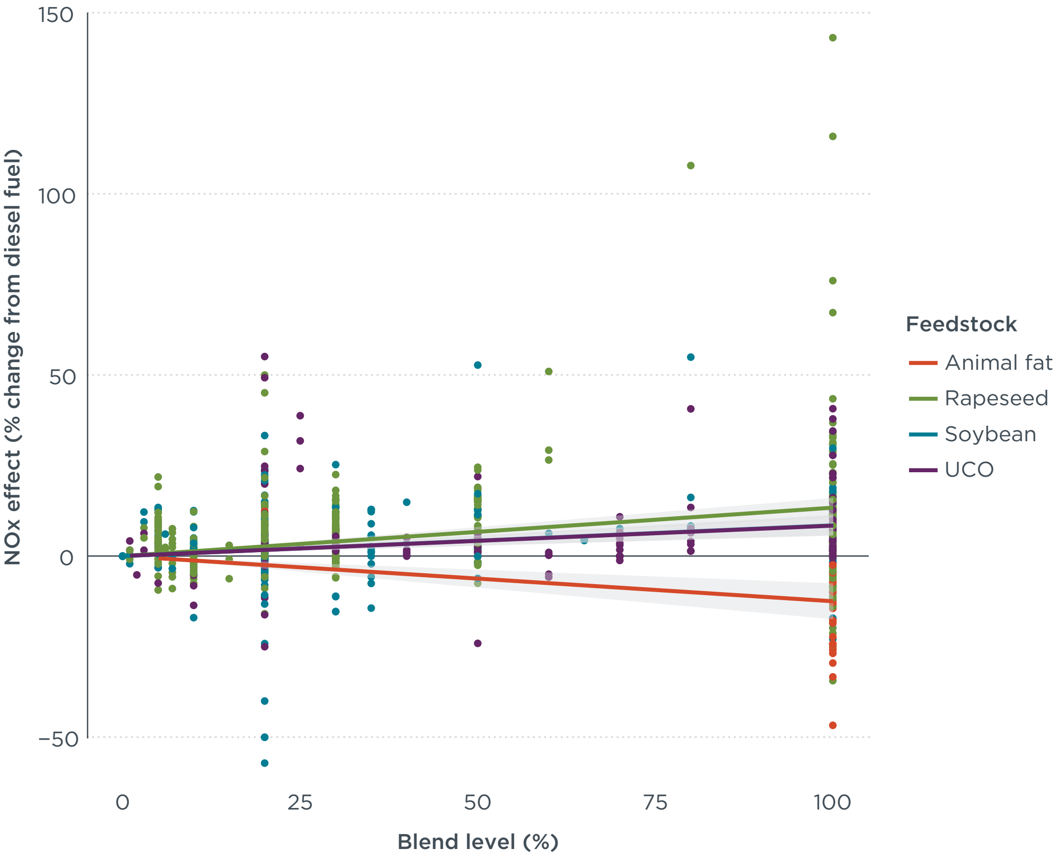

Figure 4. NOx effect by biodiesel feedstock.

Relative to other biodiesel feedstocks listed in in Table 1, animal fats have a low bulk modulus, average CN, high density, and low viscosity. Low bulk modulus and viscosity are expected to reduce NOx, while high density is expected to increase NOx formation. Animal fats are also highly saturated, which is expected to diminish the biodiesel NOx effect. However, the negative trend that we find between animal fat biodiesel blend level and the NOx effect is unexpected. The regression analysis for animal fats may be skewed due to a relatively small number of datapoints. Inaccurate product labeling may also lead to inconsistency in results. Of all the biodiesel feedstocks, rapeseed and soybean demonstrate the highest biodiesel NOx effects, as both biodiesels have a high degree of unsaturation and high bulk modulus which are expected to increase the ignition delay period and associated NOx.

We also observe clear differences in PM emissions by feedstock, as shown in Figure 5. In general, the higher oxygen content of biodiesel improves soot oxidation, resulting in lower PM than conventional diesel (Reijnders et al., 2016; Wang et al., 2016). These findings are supported by Gaïl et al. (2007), which observes that the yield of acetylene, a precursor for PM formation, is proportional to a compound's number of double bonds. Supporting this theory, we find that biodiesel produced from animal fats is associated with the largest PM reduction compared to conventional diesel (-76%) while biodiesel from rapeseed feedstocks results in the lowest PM reduction (-19%).

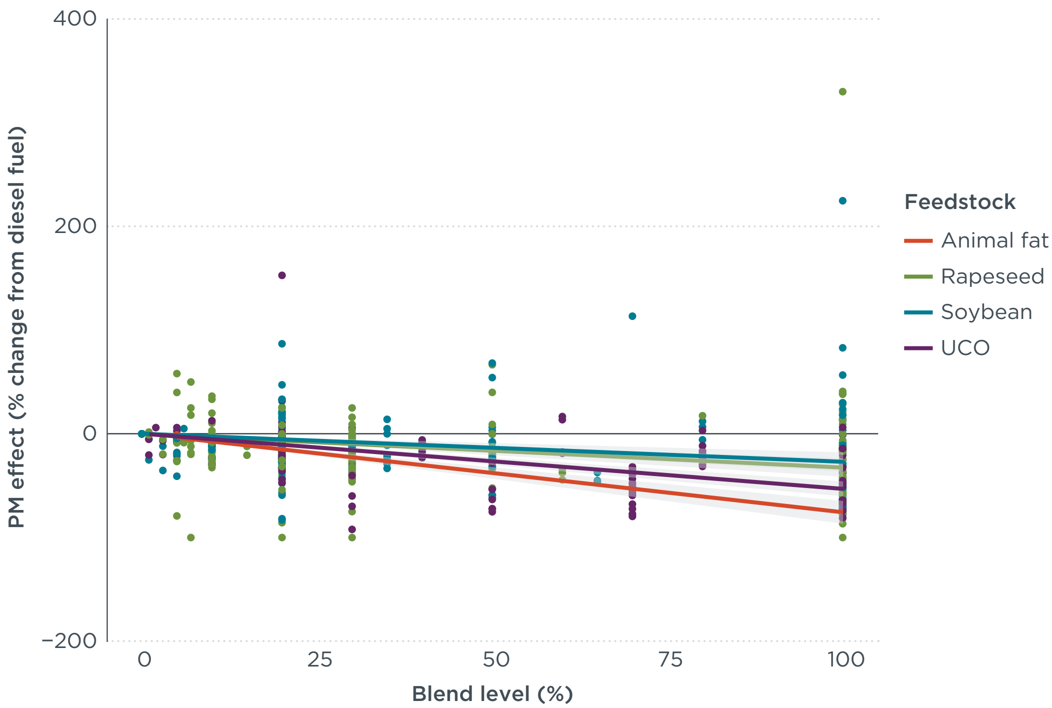

Figure 5. PM effect by biodiesel feedstock.

In summary, ignition delay appears to be the dominant mechanism for determining the NOx effect. Fuels with high viscosity, low compressibility, and low CN extend the ignition delay period leading to premixed combustion and high pressure and temperature increases inside the combustion chamber. While low viscosity may reduce HC and CO formation due to improved spray atomization, this effect does not appear to be dominant. The literature also suggests that low viscosity, low density, and increased feedstock saturation reduce PM formation.

Soybean oil is the most predominant feedstock in the United States, accounting for 68% of domestic feedstock production in 2019 (U.S. EIA, 2020). Because soy biodiesel is fairly unsaturated, NOx and PM emissions are expected to be at the high end of the range of biodiesel feedstocks.

EMISSION TEST CYCLES

Emissions formation is also influenced by driving conditions such as speed and load. In the United States, test cycles are used for engine certification by running vehicles on a chassis dynamometer and measuring the emissions output. The U.S. EPA Federal Test Procedure (FTP) simulates urban and freeway driving conditions by altering engine load and speed. However, laboratory conditions often significantly underpredict on-road emissions release. A study by Bernard et al. (2019) found that actual on-road emissions may be up to 20 times of those recorded as a result of defeat devices and engine design limitations.

Air pollution from vehicles is especially high in urban areas, and this effect is not entirely due to population density. A study by Posada et al. (2020) found that NOx emissions increase nearly four-fold during urban driving conditions compared to emissions averaged over a variety of driving conditions. Heavy-duty vehicles, which consume mostly diesel in the United States, spend roughly an equivalent share of time under urban and freeway driving conditions (Posada et al., 2020), so the high NOx emissions from their use in urban environments make up a significant share of total NOx nationwide.

Urban driving is characterized by low speeds and high engine loads because of the frequent stops and starts, while freeway driving is characterized by high speed and lower loads due to less frequent stops and starts. Engine load, also known as torque, is affected by numerous factors including vehicle mass, wind resistance, friction between the tire and roadway, roadway grade, and the use of accessories such as air conditioning (Kean et al., 2003). Engine load is also affected by acceleration. Ng et al. (2012) finds that NOx formation is positively correlated with engine speed for both conventional diesel and biodiesel blends in an exhaust emissions study. The authors also find that NOx formation is positively correlated with engine load for both fuel types.

We run a regression on the biodiesel NOx effect by biodiesel blend level for different groupings of engine loads used in emissions tests, shown in Figure 6. "Low" engine load represents 0%, or idling conditions, through 40% capacity; "medium" load represents 40% to 70% capacity; and "high" engine load represents 70% to full load conditions. We find that studies testing the biodiesel NOx effect under high-load conditions record a higher biodiesel NOx effect than tests under medium and low loads. Our results thus suggest that blending biodiesel in conventional diesel fuel exacerbates the increase in NOx that diesel vehicles experience under high-load conditions.

We also run a regression on the biodiesel PM effect under the same load conditions (Figure 6). Particulate matter data follows an opposite trend compared to NOx, with low loads producing a positive biodiesel PM effect and high loads producing the lowest PM effect across biodiesel blends.

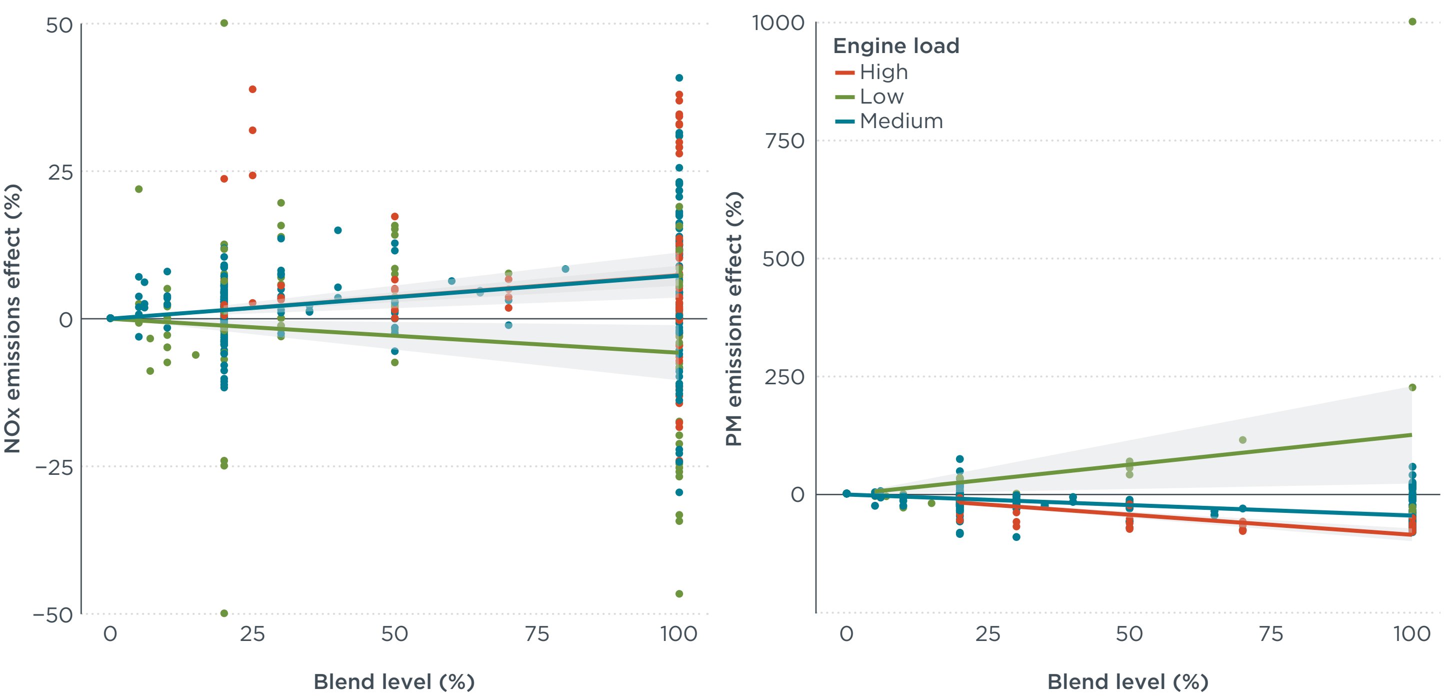

Figure 6. Panel A (left): Biodiesel NOx effect by engine load. Panel B (right): Biodiesel PM effect by engine load.

Engine horsepower is a parameter that reflects the product of load and speed. Although load data is useful to compare across engine types, it is unable to capture differences in exhaust emissions across vehicle weight classes and speed profiles. We group data by engine horsepower and observe that the biodiesel NOx effect is largest at high horsepower and smallest at low horsepower (Figure 7). Since horsepower readings are variable across test cycles, we draw from steady-state experiments for this regression. Data in the lowest horsepower range (0-50) is insignificant.

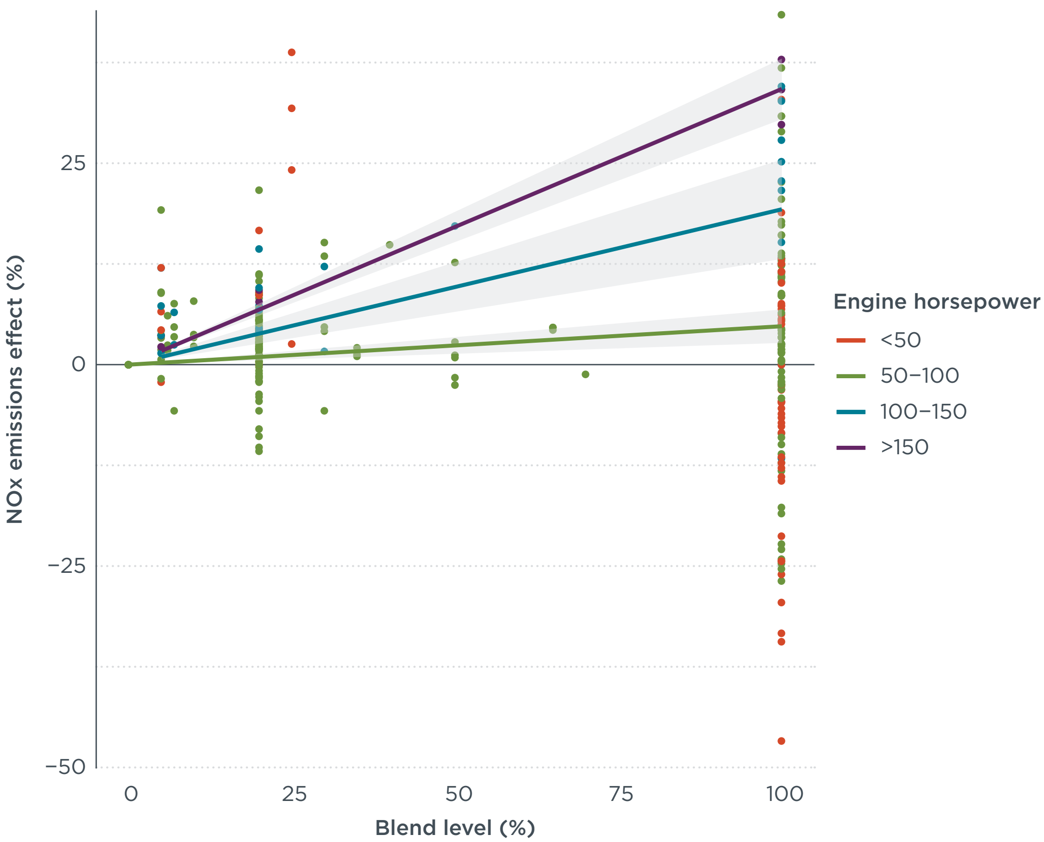

Figure 7. Biodiesel NOx effect by engine horsepower.

Horsepower is a significant explanatory variable when running a regression for the biodiesel NOx effect. This indicates that horsepower, and by extension, driving conditions more generally, highly influences biodiesel NOx formation. In the real world, we would expect biodiesel to exacerbate NOx emissions to the greatest extent when high acceleration is combined with high speed. However, this combination does not embody any one type of driving condition. Sze et al. (2007) measure average horsepower (hp) across various certification test cycles using a heavy-duty highway engine representative of on-road HDVs in the United States between 2002 and 2006. The authors find that average hp readings vary significantly by cycle type. The lowest readings are for cycles representative of urban-driving conditions while the highest readings are for cycles representative of highway driving. For example, the average horsepower for the FTP is measured to be 51.8 hp, while the average reading for the HWY cycle, a high-speed cruise cycle developed by the Coordinating Research Council, is 107.4 hp. Based on these findings, we would expect the biodiesel NOx effect to be worse under highway conditions.

We also analyze the biodiesel emissions effects of HC and CO and find that the reductions in these pollutants with biodiesel blending is greatest at high horsepower. Ng et al. (2012) investigate the effects of engine load on biodiesel emissions and, like our analysis, find that increases in load is associated with higher NOx for both diesel and biodiesel. These authors attribute the NOx increase to a decrease in volumetric efficiency and the additional heating of intake air. The study conversely finds that high loads mitigate the formation of other pollutants, including CO, HC, and PM, for both diesel and biodiesel blends. Low loads generate lean combustion conditions, defined as burning fuel in the presence of excess air. Although lean burning is often desirable for more complete combustion, the literature points to several drawbacks. Sakai et al. (2020) find that during overly lean conditions, a "quenching layer" may form near the cylinder wall, inhibiting the ability of unburned HCs to react. Similarly, Ng finds that overly lean conditions at low engine loads contributes to increased CO, an intermediate combustion compound.

Wang et al. (2016) found that biodiesel reduces PM more effectively at higher engine loads. Under high-load conditions, more fuel is injected into the cylinder creating a fuel-rich combustion environment. Fuel-rich environments generate more PM; however, the high oxygen content of biodiesel counteracts this effect. Supporting this finding, Zhu et al. (2010b) conclude that the high oxygen content of biodiesel mitigates PM formation at medium and high loads.

Ng. et al. also map the relationship between diesel and biodiesel emissions formation and engine speeds. At high speeds, the "absolute time available for complete combustion is reduced," leading to an increase in CO, HC, and PM formation (Ng et al., 2012). Engine speed is associated with a rise in in-cylinder temperatures, found to peak at intermediate speeds. At high engine speeds, NOx begins to decrease, corresponding with the on-road study findings of Posada et al (2020).

Considering that highway conditions are characterized by high speed and high load, we expect to find the greatest benefits of biodiesel blending on HC, CO, and PM emissions under highway conditions and the smallest benefits under urban conditions. For NOx, we expect the biodiesel emissions effect to be greatest under highway conditions.

EMISSION CONTROL TECHNOLOGIES

The mid-2000s were a turning point for U.S. diesel fuels and vehicles. In 2006, EPA introduced the Onroad (Highway) Diesel Fuel Standards rule which required the phase-in of ultra-low sulfur diesel (ULSD) fuel. Since 2004, the agency has introduced HDV emissions standards that set more stringent limits on NOx, HC, and PM. While earlier standards were met by high-pressure combustion techniques, newer standards have required the use of emission control technologies (Posada et al., 2016). Throughout this period, the vehicle manufacturing industry also underwent a broad shift from mechanical unit injectors to high-pressure common-rail fuel injection systems. In the following sections, we investigate the impact each of these changes has had on the biodiesel NOx effect.

First, we examine the effect that emission control technologies implemented to meet the latest HDV standard has had on NOx emissions from biodiesel blends. The latest emission standards for HDVs in the United States were fully implemented in 2010 and require the use of new technologies to meet emissions limits and deliver public health benefits. These include diesel particulate filters (DPFs), diesel oxidization catalysts (DOCs), closed-loop SCR systems, and ammonia slip catalysts.

Since it is difficult to isolate the effects of aftertreatment technologies when filtering data by emissions standard, we group data by use of control technology including DPFs, DOCs, and exhaust gas recirculation (EGR). There was not enough data to test for the effects of SCR, a primary method to reduce NOx in modern diesel engines.

We find a significant difference between vehicles equipped with EGR systems and without, with the former producing a higher biodiesel NOx effect across various blend levels (Figure 8). This may be because EGRs do not provide as much of a benefit for NOx reduction with biodiesel due to its high oxygen content (Ye & Boehman, 2010; Yoon et al., 2009). The use of EGRs are also associated with extended ignition delay (Ladommatos et al., 1998). Thus, the difference between diesel and biodiesel NOx emissions is widened in vehicles equipped with EGR.

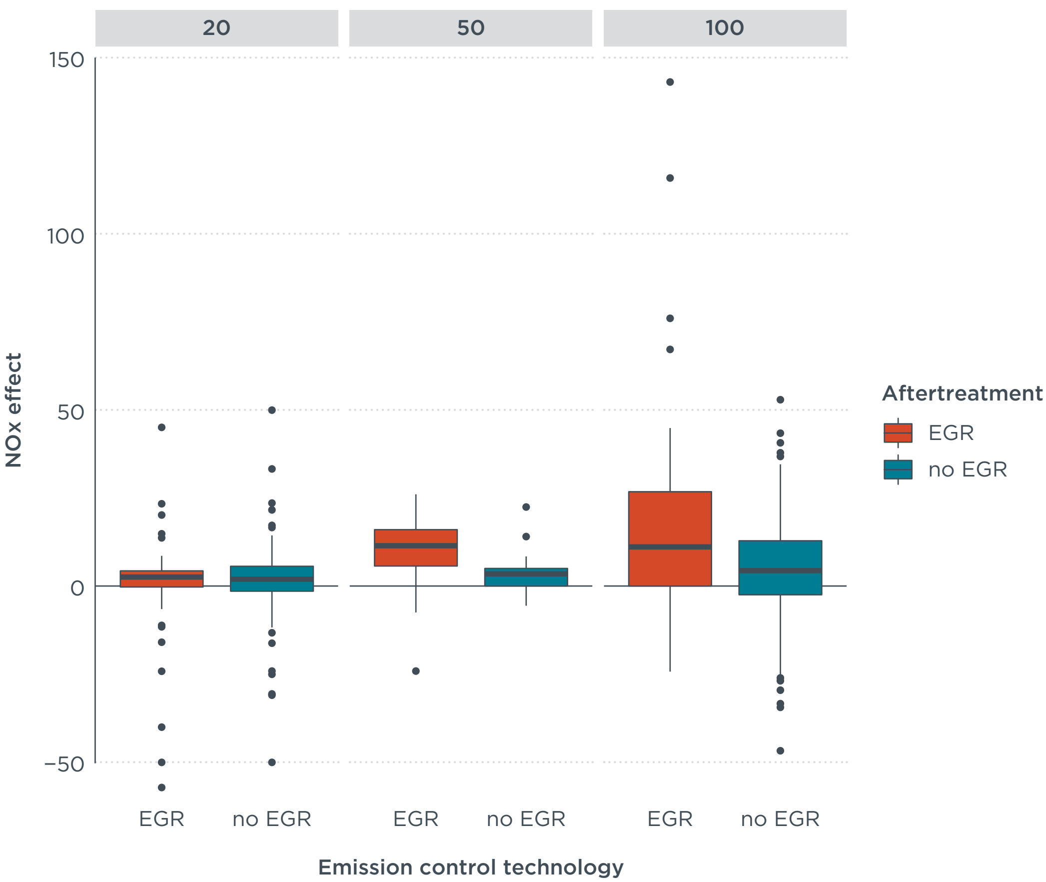

Figure 8. Biodiesel NOx effect with and without EGR.

For DPFs, Cordiner et al. (2016) observe an improvement in the regeneration rate, or the process for removing accumulated PM, when biodiesel is used. Authors attribute this improvement to biodiesel's high oxygen content which enhances soot oxidation. However, the findings are contradicted by a study by Buono et al. (2012) which records a lower DPF regeneration rate with biodiesel. Czerwinski et al. (2013) also report that biodiesel may alter the regeneration behavior of DPFs due to changes in the nanostructure of PM formation. These changes appear to be associated with a reduction in the temperature required to achieve regeneration, although it is not clear why.

Regressing the biodiesel emissions effect on blend level, we do not find a significant difference in PM emissions among vehicles equipped with and without DPFs. However, we do find that DPFs increase the biodiesel NOx effect (Figure 9). This may be confounded by a correlation between DPF and SCR systems, phased in under the 2007 and 2010 HDV emission standards, respectively. Unlike DPFs, the performance of SCR for NOx mitigation was found to degrade with biodiesel in a study on the effects of biodiesel impurities on emission control technologies (A. Williams, 2011). We do not have enough datapoints on SCR systems to test for this effect in our dataset.

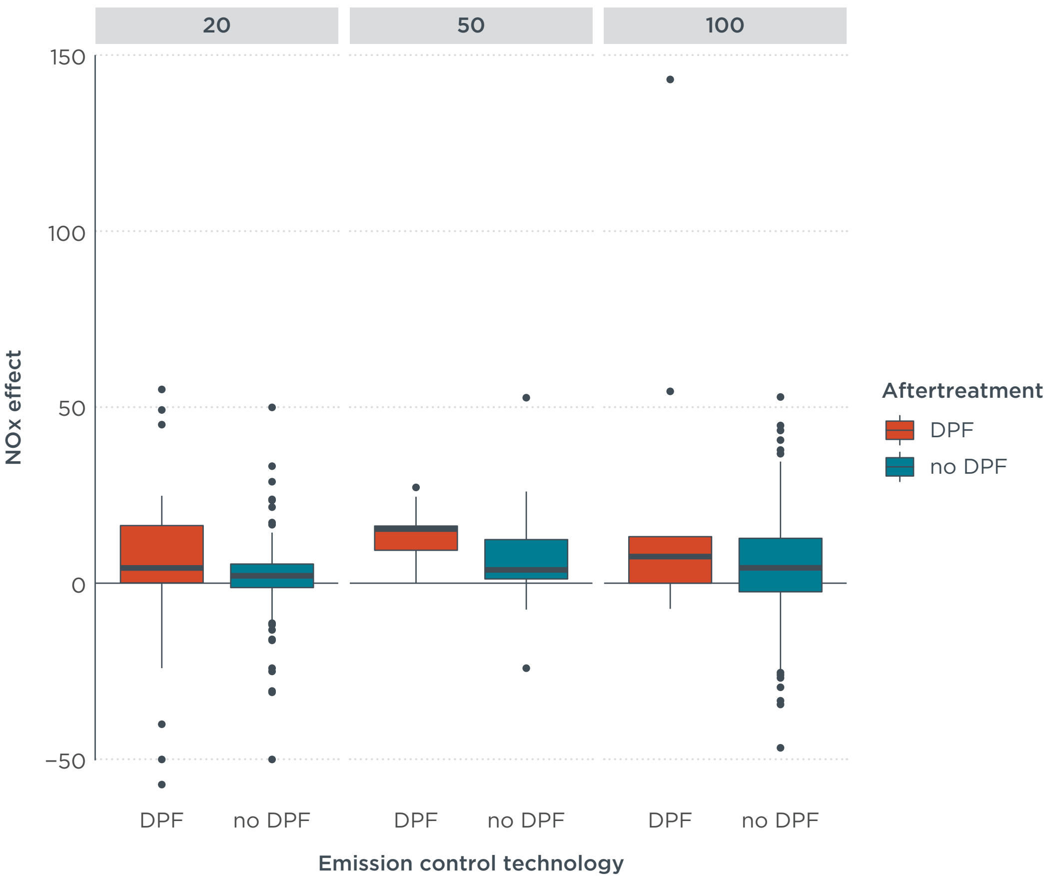

Figure 9. Biodiesel NOx effect with and without DPFs.

We also find that the biodiesel NOx effect is higher in vehicles equipped with DOCs (Figure 10). This means that although both DPFs and DOCs mitigate emissions overall, they also increase the degree to which biodiesel increases NOx compared to conventional diesel.

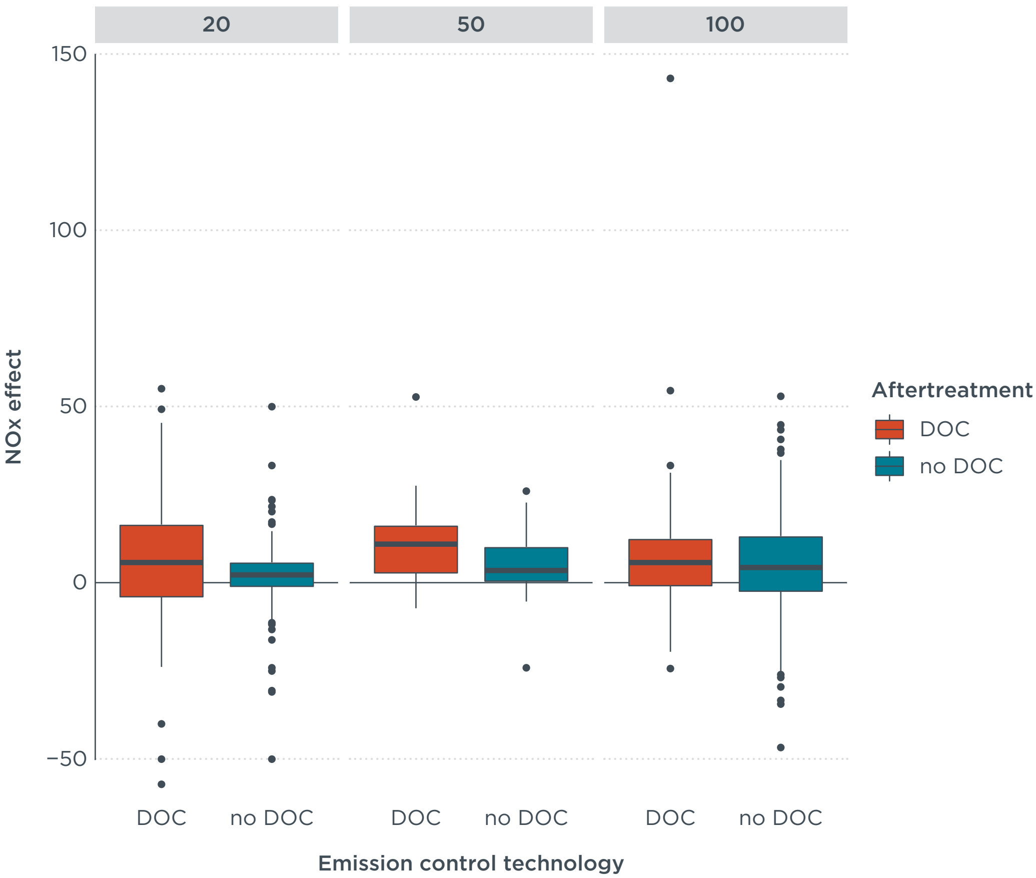

Figure 10. Biodiesel NOx effect with and without DOCs.

Diesel oxidization catalysts assist in the oxidation of HC, CO, and the soluble organic fraction of PM. In addition, DOCs generate NOx to support the operation of other aftertreatment technologies like DPFs (Posada et al., 2016). Cordiner et al. (2016) find that biodiesel increases the NO to NO_2 conversion process in DOCs, although the mechanism for this is not entirely clear. Biodiesel may also contribute to reduced DOC catalyst activity due to ash buildup (A. Williams, 2011)

DIESEL SULFUR QUALITY

The United States has been a global leader in establishing fuel quality standards, first setting a cap on diesel sulfur content beginning in 1994. The original 500 ppm cap was reduced to 15 ppm under EPA's 2006 highway diesel fuel standards rulemaking which remains in effect today. Low-sulfer diesel enables the use of advanced emission control technologies, including DPFs and catalytic converters, which have been estimated to provide tremendous public health benefits. For biodiesel, however, we find that updated sulfur limits mitigate the emissions benefits from biodiesel blending.

We assess the effect of diesel sulfur level on the biodiesel emissions effect in our dataset. We group data by high (>500 ppm), medium (50-500 ppm), and low (<50 ppm) sulfur concentration. We observe a strong relationship between fuel sulfur quality and the biodiesel NOx effect (Figure 11). Here, we only present data for older model vehicles before implementation of the 2007 emission standards to isolate the effects of fuel quality on biodiesel NOx.

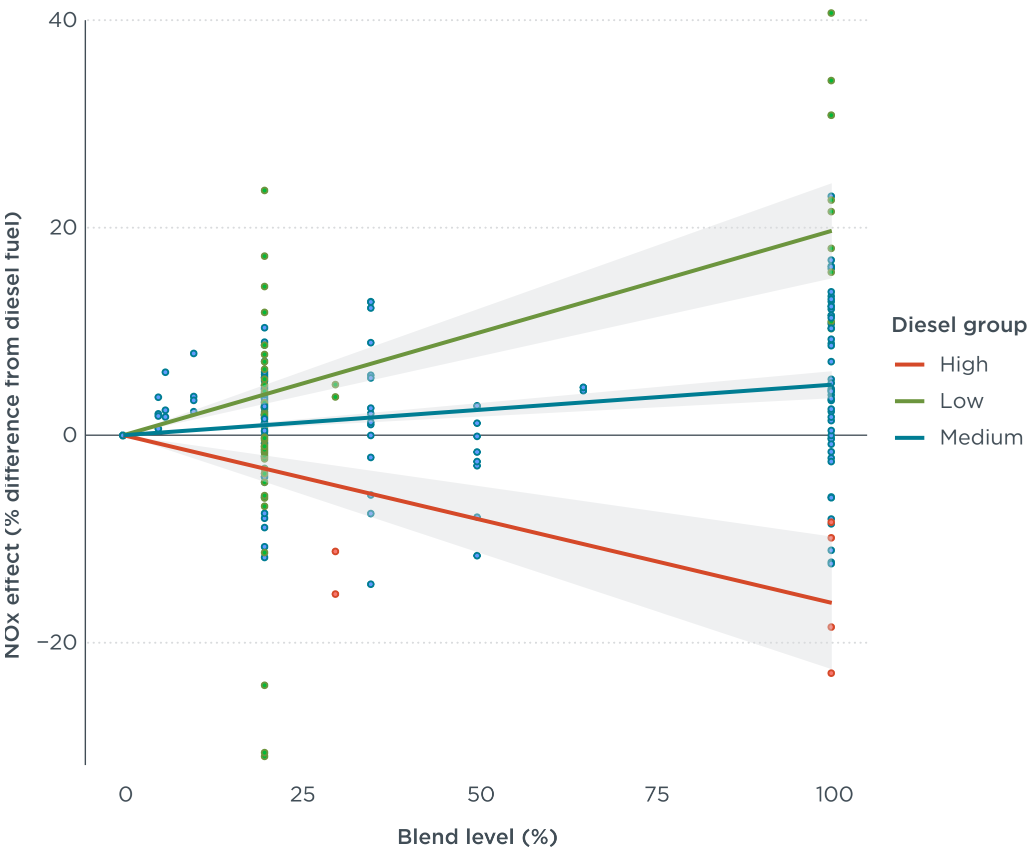

Figure 11. NOx effect grouped by baseline diesel quality. Data is pre-2007 HDV emission standard data.

We find that the biodiesel NOx effect is strongly correlated with fuel quality across the older vehicle model data subset. Combustion of pure biodiesel results in a 16% NOx decrease relative to high-sulfur diesel but an increase of 20% relative to low-sulfur fuel. The relationship between baseline diesel fuel sulfur quality and biodiesel NOx emissions is not well documented in the literature; however, several studies identify changes in fuel property parameters during the desulfurization process which may contribute to the observed effects.

Alam et al. (2004) find that desulfurization increases the cetane number (CN) and lowers the density of diesel fuel. Biodiesel has a higher density than diesel; thus, the difference in density widens when biodiesel is blended into low-sulfur diesel versus blending into higher-sulfur diesel. High CN in fuels is associated with ignition occurring sooner after injection. This reduces time for air-fuel mixing, resulting in a more spread out temperature peak from combustion and lower NOx formation (Lee et al., 1998). Low-sulfur fuels also have low aromatic content. Although the literature has not established a clear relationship between NOx and aromatics, Lee et al. suggest that low-aromatic fuels likely produce lower NOx due to their lower adiabatic flame temperatures. This reflects the temperature of combustion assuming zero heat loss. Across our dataset, combustion of low-sulfur diesel is found to produce lower NOx than that of high-sulfur diesel, likely for these reasons. Biodiesel is thus more polluting, at least in terms of NOx, when blended with cleaner-burning low-sulfur diesel than when blended with high-sulfur diesel.

The literature also finds that the combustion of low-sulfur diesel reduces PM emissions compared to that of high-sulfur diesel (Zhu et al., 2010b). Low-sulfur fuel produces fewer sulfate aerosols, a component of PM, and has lower aromatic content, which reduces the hydrocarbon molecule's tendency for PM formation (Ladommatos et al., 1996). We would expect the biodiesel PM effect to be less significant when blended with low- versus high-sulfur diesel due to these properties. However, we do not observe a significant relationship between biodiesel and PM emissions for both high- and low-sulfur diesel. We also do not observe a significant relationship between biodiesel blending and CO emissions for high- and low-sulfur diesel. For HC, we identify a significant relationship between biodiesel and emissions for medium and high-sulfur diesel datapoints, although this is likely confounded by other parameters.

FUEL INJECTION SYSTEM

We find that an engine's fuel injection system also has a significant impact on the biodiesel NOx effect. Historically, unit injectors were used to deposit fuel into the combustion chamber. These systems have a compact engine design and inject fuels at medium to high pressure. Unit injectors have been phased out in favor of common-rail injection systems because the latter allow more complete combustion and noise control (Perkins, n.d.). The relationship between fuel injection systems and the biodiesel NOx effect has not been widely studied; however, a study by Yanowitz and McCormick (2009) compares the emissions effects of fuel injection systems running on B20 fuel. The authors calculate a 3% increase in the biodiesel NOx effect when running biodiesel through a common-rail versus electronic unit injector system. Hoekman and Robbins (2012) state that although common-rail engines are expected to have better control for fluid properties which advance injection timing, the biodiesel NOx effect persists.

In our regression analysis, we find that common-rail injection systems are associated with a greater biodiesel NOx effect compared to unit injector systems (Figure 12). We assume that unit injectors are electronic rather than mechanically operated since the latter systems were phased out beginning in the late 1980s. Panel A in the figure shows data for all fuel sulfur levels; here we can see there is a more than three-fold difference in the biodiesel NOx effect between unit injection and common-rail systems.

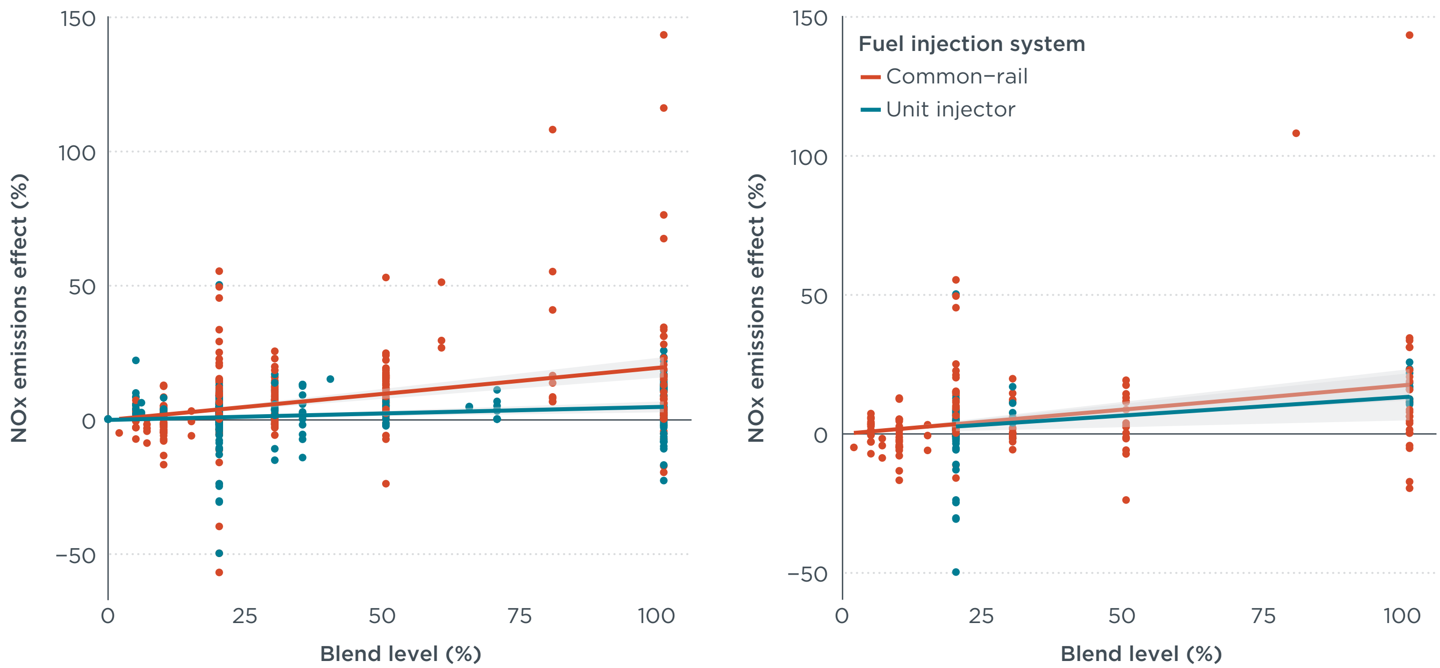

Figure 12. Panel A (left): Biodiesel NOx effect by fuel injection system. Panel B (right): Biodiesel NOx effect by fuel injection system for low sulfur diesel only.

However, we note that the shift from unit injector systems to common-rail systems occurred around the same timeframe as the introduction of ULSD in the United States. Fuel sulfur level may thus be influencing our results. To remove this potentially confounding effect, we also assess the biodiesel NOx effect in common rail versus unit injector systems for studies using only low-sulfur diesel. This result is shown in Figure 12 panel B. We find that the biodiesel NOx effect is 47% higher in common-rail systems compared to unit injector systems. Although the standard error cones in panel B overlap, we find a statistically significant difference between the two trendlines. Thus, we conclude that the biodiesel NOx effect likely is higher in more modern fuel injection systems compared to older ones, independent of the effects of diesel sulfur level.

We also test the biodiesel NOx effect by running a multiple regression analysis on blend level, fuel injection systems, engine horsepower, and diesel sulfur quality. Results for each parameter including the regression coefficient, standard error, and p-value are presented in Table 2. To distinguish between qualitative variables, dummy variables are used for fuel injection systems with common-rail fuel injection systems set equal to 1. Thus, a positive coefficient, β, signifies that common-rail systems generate a higher biodiesel emissions effect relative to unit injectors. This multiple linear regression confirms our previous findings of the significance of these parameters, even after controlling for confounding factors throughout the dataset.

Table 2. Biodiesel NOx effect using multiple linear regression.

Parameter	Coefficient (β)	SE	P-value
Blend level (%)	0.138	0.019	<.001
Fuel injection system	5.890	2.340	0.013
Engine power (hp)	0.035	0.011	0.001
Diesel quality (ppm)	-0.015	0.003	<.001

COMPARISON WITH PREVIOUS META-ANALYSES

On average, we find that biodiesel blending increases emissions for all pollutants relative to previous meta-analyses. For modern conditions, which we define as engines that run on ULSD and common-rail fuel injections systems, we find that biodiesel blending increases emissions for NOx, HC, PM, and CO compared to other meta-analyses (Table 3).

Table 3. Biodiesel exhaust emissions study comparison. Data reported in percent change in emissions between B20 and petroleum diesel fuel.

Pollutant	EPA (2002)	EPA (2010)	Hoekman & Robbins (2012)	ICCT (all data)	ICCT (modern conditions)
NOx	2%	2%	1%	2%	4%
PM	-10%	-16%		-6%	Insignificant
HC	-21%	-14%		-4%	7%
CO	-11%	-13%		Insignificant	10%

As in our study, EPA finds that animal fats produce the lowest biodiesel NOx effect while soybean and rapeseed-based biodiesels produce significantly higher NOx effects. That study also reports that animal fats produce a lower PM effect than soybean and rapeseed-based fuels, corroborating our results. The EPA includes a discussion on the significance of emission test cycles in their study, while Hoekman and Robbins reference the effects of engine speed and load on biodiesel emissions. In our study, we significantly expand significantly on both discussions and investigate the impacts of load, speed, and horsepower on biodiesel emissions.

Both meta-analyses also discuss the effects of baseline diesel sulfur quality. The EPA finds that biodiesel produces higher NOx when blended into “clean” or low-sulfur diesel fuel while Hoekman and Robbins state they only find weak evidence in support of this claim. We find a strong relationship between biodiesel emissions and the baseline sulfur content of diesel fuel, corroborating EPA’s original finding. Hoekman and Robbins discuss the relationship between biodiesel blending and emission control technologies, finding that biodiesel hinders the operation of lean NOx traps and DPFs. We find that biodiesel does not increase PM compared to conventional diesel in vehicles equipped with DPFs. However, biodiesel does increase NOx in vehicles equipped with EGR, DOCs, and DPFs, although the latter effect may be confounded by the presence of SCR systems.

Hoekman and Robbins also posit that modern fuel injection systems should be expected to reduce the biodiesel NOx effect. Conversely, we find that NOx emissions are higher in modern, common-rail systems after controlling for the effects of other possible confounding parameters.

CONCLUSION

This analysis finds that biodiesel blending of common U.S. feedstocks increases NOx emissions while it decreases CO, HC, and PM across the entire dataset. However, much of the data included in our literature review may now be considered outdated because it reflects fuels, injection systems, and emission controls systems that are no longer used in the United States. For modern vehicles and fuels, our findings are considerably different. When only examining data collected with low-sulfur fuel and common rail injection systems, we find that biodiesel increases NOx emissions compared to conventional diesel by 4% for B20 blends. Our analysis finds that the biodiesel PM effect in modern engines is insignificant, while B20 increases CO and HC emissions by 10% and 7%, respectively (Table 3). These findings offer a sharp contrast to the conclusions in earlier studies based on much older test results that biodiesel reduces emissions of PM, CO, and HC. Our analysis demonstrates that the effect of biodiesel blending on exhaust emissions is substantially worse than previously understood. As U.S. regulators work to update annual volume requirements under the Renewable Fuel Standard or pursue new legislation such as a federal national low-carbon fuel standard, it will be important to take into account this updated information on the air quality impacts of increased biodiesel blending.

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APPENDIX A. EMISSIONS FORMATION SUMMARY TABLE

The tables below summarize the relationship between engine operating conditions and fuel property variables and air pollutant formation. Upward arrows represent an increase in the operating condition or fuel property variable.

Table A1. Effects of engine operating conditions on air pollutant formation.

Engine operating conditions		
Variable	**Primary effect**	**Mechanism**
↑ **Ignition delay**	Increase in NO_x Decrease in HC, CO, PM	Ignition delay, or the period between fuel injection and fuel ignition, increases air-fuel mixing inside the combustion chamber. Extended delay improves combustion efficiency but leads to rapid pressure and temperature increases upon combustion
↑ **Injection pressure**	Increase in NO_x Decrease in HC, CO	High pressure conditions improve combustion but advance injection timing and raise temperatures in the cylinder.
↑ **Injection timing**	Decrease in NO_x Increase in HC, CO, PM	Counter to ignition delay, retarded injection timing reduces the air-fuel mixing and the associated high temperatures and pressures in the combustion chamber.

Table A2. Effects of fuel properties on air pollutant formation.

Fuel properties		
Variable	**Primary effect**	**Mechanism**
↑ **Cetane number**	Decrease in NO_x	High cetane numbers correspond with faster ignitability that, in turn, reduces premixed combustion. This limits rapid increases in pressure and temperature.
↑ **Aromatics**	Increase in NO_x	High aromatics are associated with high density and low CN. High aromatics content is also associated with high adiabatic flame temperatures.
↑ **Degree of saturation**	Decrease in NO_x, PM	More saturated (i.e., single bond) fuels like palm and coconut have higher CN so they ignite more easily. Saturated fuels are also correlated with high viscosity and low density.
↑ **Density**	Increase in NO_x, PM	High density fuels are associated with high aromatics and low CN. Dense fuels also have high volumetric efficiency, which raises in-cylinder temperatures.
↑ **Viscosity**	Increase in NO_x, HC, CO	High viscosity may lead to pressure build-up and advanced injection. High pressure conditions also improve air-fuel mixing. However, high viscosity fuels also produce large diameter droplets which hinder vaporization and complete combustion.
↑ **Bulk modulus**	Increase in NO_x Decrease in HC, CO, PM	Bulk modulus is inverse to compressibility such that fuels with high bulk modulus have low compressibility and arrive in the combustion chamber earlier.
↑ **Diesel sulfur content**	Increase in PM	Combustion of high-sulfur fuel produces sulfate aerosols, a component of PM. High-sulfur fuels are also associated with high aromatics and reduced CN.

APPENDIX B. FULL STUDY LIST

Table B1. Biodiesel emissions studies included in meta-analysis.

Study	Location	Vehicle type	FAME feedstock(s)	Test cycle(s)	Emission standard	Pollutant(s) measured
Acevedo and Mantilla (2011)	Colombia	HDV Engine	Palm	Steady-state test	—	NO_x, PM (omitted), HC, CO
Adi (2012)	United States	Engine	Cold-flow soybean	Steady-state test	—	NO_x, PM
Alam et al. (2004)	United States	HDV	Soybean	AVL 8-Mode	Tier 2	NO_x, PM, HC, CO
Altun (2011)	Turkey	LDV Engine	UCO, animal fat	Steady-state test	—	NO_x, CO
Arapaki (2007)	Greece	LDV	UCO	NEDC	Euro 3	NO_x, PM, HC, CO
Arbab (2013)	Malaysia	Engine	Palm, Palm/jatropha/coconut blends	Steady-state test	—	NO_x, HC, CO
Armas et al. (2013)	Spain	LDV	Animal fat	EUDC, NEDC	Euro 4	NO_x, HC, CO
Bakeas et al. (June 2011)	Greece, Italy	LDV	Soybean, palm, UCO	Artemis Urban, Road, Motorway, NEDC	Euro 4	NO_x, PM, HC, CO
Behcet (2011)	Turkey	Engine	Fish oil	Steady-state test	—	NO_x, HC, CO
Behcet (2014)	Turkey	Engine	Fish oil, UCO	Steady-state test	—	NO_x, HC, CO
Bielaczyc et al. (2009)	Poland	LDV	Rapeseed	UDC, EUDC	Euro 4	NO_x, PM, HC, CO
Canakci and Van Gerpen (2003)	United Sttes	HDV Engine	UCO, soybean	Steady-state test	—	NO_x, HC, CO
Chang (1996)	United States	HDV Engine	Soybean	Steady-state test	—	NO_x, PM, HC, CO
Chase (2000)	United States	HDV	Rapeseed ethyl ester (REE), vegetable oil	FTP Transient	Tier 1	NO_x, PM, HC, CO
Chin (2012)	United States	HDV	Soybean	Steady-state test	Tier 2	NO_x, PM, CO
Clark (1999)	United States	HDV	Soybean	FTP	Tier 1	NOx, PM, HC, CO
Clark and Lyons (1999)	United States	HDV	Soybean	WVU 5 peak truck cycle	Tier 1	NOx, PM, HC, CO
Czerwinski (2013)	Germany	HDV	Rapeseed	Steady-state test	—	NOx, PM, HC, CO
Di (2009)	China	HDV Engine	UCO	Steady-state test	—	NOx, PM, HC
Durbin (1999)	United States	HDV	FAME	FTP	Tier 1	NOx, HC, CO
Durbin (2002)	United States	HDV	Soybean, UCO	FTP	Tier 1	NOx, PM, HC, CO
Eckerle (2008)	United States	HDV	Soybean	UDDS (6k), HWY55	Tier 2	NOx
Farzenah (2006)	United States	HDV	Soybean, FAME	On-road driving cycles (Urban, Rural)	Tier 1	NOx
Fattah (2014)	Malaysia	Engine	Palm	Steady-state test	—	NOx, HC, CO
Fontaras et al. (2009)	Greece	LDV	Soybean	Artemis Urban, Road; UDC	Euro 2	NOx, PM, HC, CO
Fontaras et al. (2010)	Greece	LDV	Palm, rapeseed, sunflower oil, UCO, soybean	Artemis Urban, Road, Motorway; UDC	Euro 3	NOx, PM, HC
Frank (2004)	United States	HDV	FAME	FTP	Tier 2	NOx, PM, HC, CO
Ge (2017)	Korea	LDV	Rapeseed	Steady-state test	—	NOx, PM, CO
Geng (2019)	United States, China	HDV Engine	UCO	Steady-state test	—	NOx
Graboski (1996)	United States	HDV	Soybean	FTP Transient (Composite)	Tier 1	NOx, PM, HC, CO

Study	Location	Vehicle type	FAME feedstock(s)	Test cycle(s)	Emission standard	Pollutant(s) measured
Graboski (2003)	United States	HDV	Methyl-lard, methyl-soy, methyl-canola, methyl inedible tallow, methyl edible-tallow, methyl-low free fatty acid grease, methyl-high free acid grease, methyl-laurate (C12:0), methyl-palmitate (C16:0), methyl-stearate (C18:0), methyl-oleate (C18:1), methyl-linoleate C18:2), methyllinolenate (C18:3), methyl soy (soyagold), 1:2 M-terate: M-linseed, methyl-hydrogenated soy, ethyl-stearate (C18:0), ethyl-linoleate (C18:2), ethyl-linseed, ethyl-soy, ethyl-hydrogenated soy	FTP Transient	Tier 1	NOx, PM, HC, CO
Guatam (2013)	India	Engine	Jatropha	Steady-state test	—	NOx, HC, CO
Guido (2013)	Italy	LDV Engine	Rapeseed	Open/closed loop operating modes	Euro 5	NOx, PM, HC, CO
Haas (2001)	United States	HDV	Soybean, soapstock	FTP Transient	Tier 1	NOx, PM, HC, CO
Han et al. (2008)	United States	LDV	Soybean, coconut	Ad-hoc operating points/Misc.	—	NOx, PM, HC, CO
Hansen and Jensen (1997)	Denmark	HDV	Rapeseed	5-mode test (subset of ECE R49)	Euro 2	NOx, PM, HC, CO
Hearne (2005)	United States	HDV	FAME	Rowan University Composite School Bus Cycle (RUCSBC)	Tier 1	NOx, PM, HC, CO
Holdren (2006)	United States	HDV	Soybean, UCO	FTP Transient, US06, AVL 8-Mode, In-Use Test	Tier 1, Tier 2	NOx, PM, HC, CO
Jansen et al. (2014)	Greece	LDV	Rapeseed	NEDC, UDC, EUDC	Euro 4	NOx, HC, CO
Kalam and Masjuki (2008)	Malaysia	HDV	Palm	Steady-state test	—	NOx, HC, CO
Karavalakis (2016)	United States	LDV	UCO	UDDS, HHDDT Transient	Tier 2	NOx, PM, HC, CO
Karavalakis et al. (2007)	Greece	LDV	Soybean	Athens Driving Cycle	Euro 2	NOx, PM, HC, CO
Karavalakis et al. (2009)	Greece	LDV	Rapeseed, palm	NEDC, UDC, ADC	Euro 2	NOx, PM, HC, CO
Karavalakis et al. (2011)	Greece	LDV	Palm, soybean, rapeseed blended with sunflower oil and UCO	Artemis (full), NEDC	Euro 4	NOx, PM, HC, CO
Karavalakis et al. (Dec. 2008)	Greece	LDV	Soybean	UDC, NEDC, ADC	Euro 2	NOx, PM, HC, CO
Karavalakis et al. (Nov. 2008)	Greece	HDV	Palm	UDC, NEDC, ADC	Euro 3	NOx, PM, HC, CO
Kawano et al. (2008)	Japan	LDV	Rapeseed	JE05 Mode Test	Euro 5	NOx, PM, HC, CO
Kaya et al. (2018)	Turkey	LDV	FAME (unspecified)	NEDC, WLTC	Euro 5	NOx, HC, CO
Kinoshita (2003)	Japan	Engine	Palm, rapeseed	Steady-state test	—	NOx, HC, CO
Kinoshita (2006)	Japan	Engine	Palm, coconut, rapeseed	Steady-state test	—	NOx, HC, CO
Kinoshita (2011)	Japan	Engine	Palm, rapeseed	Steady-state test	—	NOx
Knothe (2006)	United States	HDV	Methyl soyate (commercial biodiesel), methyl oleate, methyl pamitate, methyl laurate (technical biodiesel)	FTP Transient	Tier 2	NOx, PM, HC, CO
Koszalka (2010)	Poland	HDV	FAME	13-mode ESC test	Tier 2	NOx, HC, CO

Study	Location	Vehicle type	FAME feedstock(s)	Test cycle(s)	Emission standard	Pollutant(s) measured
Kousoulidou et al. (2009)	Greece	LDV	Palm, rapeseed	NEDC; Artemis Urban, Road, Motorway	Euro 3	NOx, PM, HC, CO
Krahl (2005)	Germany	HDV	Rapeseed, rapeseed/soybean/palm oil blends	13-mode ESC test	Euro 3	NOx, PM, HC, CO
Krahl (2008)	Germany	HDV	Rapeseed	13-mode ESC test	Euro 4	NOx, PM, HC, CO
Krahl (2009)	Germany	HDV	Rapeseed	13-mode ESC test	Euro 3	NOx, PM, CO
Lahane (2015)	India	Engine	Karanja	Steady-state test	—	NOx, HC, CO
Lance et al. (2009)	United States, Japan	LDV	Jatropha, coconut, rapeseed	NEDC	Euro 4	NOx, HC, CO
Lapuerta et al. (2008)	Spain	LDV	UCO, sunflower oil	Various SS operating points	Euro 4	NOx, PM
Leevijit (2010)	Thailand	Engine	Palm	Steady-state test	—	NOx, CO
Lesnik (2013)	Slovenia	HDV Engine	Rapeseed	Steady-state test	—	NOx, CO
Li (2007)	Europe	HDV	Rapeseed	23 kW Hot-Start SS	Euro 2	NOx, PM, HC, CO
Lim et al. (2014)	Korea	LDV	Soybean, UCO, jatropha, palm, rapeseed	NEDC	Euro 4	NOx, PM, HC, CO
Liotta and Montalvo (1993)	United States	HDV	Soybean	FTP Transient (Hot Start)	Tier 1	NOx, PM, HC, CO
Lopez (2009)	Spain	HDV	FAME (unspecified)	Transient Cycle	Euro 4	NOx, PM, HC, CO
Lujan (2009)	Spain	LDV	FAME (unspecified)	NEDC	Euro 4	NOx, PM, HC, CO
Macor et al. (2011)	Italy	LDV	Rapeseed	UDC, Artemis Urban	Euro 4	NOx, PM, HC, CO
Marshall (1995)	United States	HDV	Soybean	FTP retarded timing	Tier 1	NOx, PM, HC, CO
Martini et al. (2007)	European Union	LDV	50/50 soybean and sunflower, palm, rapeseed	NEDC, EUDC	Euro 3	NOx, PM, HC, CO
Mazzoleni (2007)	United States	HDV	FAME	On-road Driving Cycle	Tier 1	NOx, PM, HC, CO
McCormick (1997)	United States	HDV	Soybean	FTP Transient (Hot Start)	Tier 1	NOx, PM, HC, CO
McCormick (2003)	US	HDV	UCO, soybean	FTP Transient (Composite)	Tier 1	NOx, PM, HC, CO
McCormick (2005)	United States	HDV	Soybean, UCO, rapeseed, animal fat	FTP Transient	Tier 1	NOx, PM
McCormick (2006)	United States	HDV	Soybean	City-Suburban Heavy Vehicle Cycle (CSHVC), UDDS, RUCSBC, Freeway Cycle	Tier 1, Tier 2	NOx, PM, HC, CO
McGill et al. (2003)	United States	LDV, HDV	Rapeseed	FTP 75, AVL 8-Mode	Tier 1, Euro 2	NOx, PM
Mizushima and Takada (2014)	Japan	HDV	FAME	JE05 “ED12” transient test cycle	Euro 5	NOx, PM
Mofijur (2013)	Malaysia	LDV	Palm, M. oliefera oil	Steady-state test	Euro 2	NOx, HC, CO
Mormino (2009)	Belgium	LDV	Animal fat, palm, rapeseed	Steady-state test	—	NOx, HC
Nabi (2005)	Bangladesh	Engine	Neem oil	Steady-state test	—	NOx, CO
Nathangopal (2018)	India	Engine	Calophyllum inophyllum	Steady-state test	—	NOx, HC, CO
Ng (2011)	Malaysia	LDV	Palm	Steady-state (representative of on-road conditions)	—	NOx, HC, CO

Study	Location	Vehicle type	FAME feedstock(s)	Test cycle(s)	Emission standard	Pollutant(s) measured
Ng (2012)	Malaysia	Engine	Palm, soybean, coconut	7-mode ESC test	Euro 2	NOx, HC, CO
Nikanjam (2009)	United States	HDV	Soybean	UDDS	Tier 2	NOx, HC, CO
Nuszkowki (2008)	United States	HDV	Soybean, animal fat, cottonseed	FTP Transient (Hot Start)	Tier 1	NOx, PM, HC, CO
Olatunji (2010)	United States	HDV	Soybean, animal fat	Steady-state test	Tier 2	NOx, PM, HC, CO
Ozsezen and Canacki (2010)	Turkey	HDV	Palm	Steady-state test	—	NOx, HC, CO
Ozsezen and Canacki (2011)	Turkey	Engine	Palm, rapeseed	Steady-state test	—	NOx, HC, CO
Pala-En (2013)	United States	HDV	Rapeseed, UCO, animal fat, soybean	UDDS, On-road (highway, arterial, idling)	Tier 2	NOx, PM, HC, CO
Payri (2005)	Spain	HDV	UCO	Steady-state test	Euro 3	NOx, PM, HC, CO
Peterson (2000)	United States	HDV	Soybean	FTP Transient (Hot Start)	Tier 1	NOx, PM, HC, CO
Peterson and Reece (1996)	United States	HDV	Rapeseed ethyl ester (REE)	FTP Transient	Tier 1	NOx, PM, HC, CO
Proc (2006)	United States	HDV	FAME	City-Suburban Heavy Vehicle Cycle (CSHVC)	Tier 1	NOx, PM, HC, CO
Prokopowicz et al. (2015)	Poland	LDV	Rapeseed	NEDC, UDC, EUDC	Euro 4	NOx, PM, HC, CO
Purcell (1996)	United States	LDV	Soybean	Heavy Duty Transient (US Bureau of Mines)	Tier 1	NOx, PM, HC, CO
Purcell et al. (1996)	United States	HDV	Soybean	Transient Cycle (US Bureau of Mines)	Euro 1	NOx, PM, HC, CO
Rahman (2013)	Malaysia	Engine	Palm, calophyllum inophyllum	Steady-state test	—	NOx, HC, CO
Rakopoulos (2007)	Greece	HDV	Sunflower oil, cottonseed	Steady-state test	—	NOx, HC, CO
Rantanen (1993)	Finland	HDV	Rapeseed	13-mode ESC test	Tier 1	NOx, PM, HC, CO
Romig and Spataru (1995)	United States	HDV	Rapeseed	FTP Transient (Hot Start)	Tier 1	NOx, PM, HC, CO
Ropkins et al. (2007)	United Kingdom	LDV	Rapeseed	UDC, EUDC, FTP 75	Euro 1	NOx
Rose et al. (2010)	Europe	LDV	Rapeseed	NEDC, UDC, EUDC	Euro 4	NOx, HC, CO
Roy (2016)	Canada	HDV Engine	Rapeseed	Steady-state test	—	NOx, HC, CO
Schumacher (1994)	United States	HDV	Soybean	FTP Transient	Euro 2	NOx, PM, HC, CO
Schumacher (1996)	United States	HDV	Soybean	FTP Transient	Tier 1	NOx, PM, HC, CO
Sedari et al. (1999)	Greece	LDV, Engine	Sunflower oil	On-road idling, Steady-state	Euro 1	NOx
Serrano et al. (2015)	Portugal	LDV	Soybean	NEDC, UDC, EUDC	Euro 5	NOx
Sharp (1994)	United States	HDV	Soybean	FTP Transient (Hot Start)	Tier 1	NOx, PM, HC, CO
Sharp (1996)	United States	HDV	Rapeseed	FTP Transient	Tier 1	NOx, PM, HC, CO
Sharp (2000)	United States	HDV	Soybean	FTP Transient	Tier 1	NOx, PM, HC, CO
Sharp and Knothe (2005)	United States	HDV	Soybean	FTP Transient (Hot Start)	Tier 1	NOx, PM, HC, CO

Study	Location	Vehicle type	FAME feedstock(s)	Test cycle(s)	Emission standard	Pollutant(s) measured
Shen et al. (2018)	China	LDV	Rapeseed	PEMS (Non Highway/Highway Driving)	Euro 3, Euro 4	NOx, PM, HC, CO
Sinha and Kumar (2019)	India	Engine	Jatropha	Steady-state test	—	NOx, HC, CO
Souligny (2004)	Canada	HDV	Animal fat, UCO, vegetable oil	FTP Transient	Tier 1	NOx, PM, HC, CO
Starr (1997)	United States	HDV	Soybean	FTP Transient	Tier 1	NOx, PM, HC, CO
Sze (2007)	United States	HDV	Soybean	HWY, FTP, WHTC, UDDC (6k, 28k)	Tier 2	NOx, PM, HC, CO
Tadano (2015)	Brazil	HDV	Soybean	13-Mode ESC test	Euro 5	NOx
Tatur et al. (2009)	United States	LDV	Soybean	FTP 75, HWFET	Euro 4	NOx, HC, CO
Tian et al. (2013)	China	LDV	Rapeseed	Various	—	NOx, PM, HC
Tompkins (2009)	United States	Engine	Palm	Steady-state test	—	NOx
Tzirakis (2006)	Greece	LDV	UCO	On-road (urban driving)	Euro 4	NOx, CO
Ullman (1983)	United States	HDV	Soybean	1979 13-mode Federal Test Procedure	Tier 1	NOx, PM, HC, CO
Usta (2005)	Turkey	Engine	Tobacco seed oil	Steady-state test	—	NOx, CO
van Niekerk et al. (2019)	United Kingdom	LDV	FAME (unspecified)	WLTC	Euro 4	NOx, CO
Wallington et al. (2016)	United States	LDV	Butyl nonanoate	FTP 75, HWFET, US06	Euro 4	NOx, PM, HC, CO
Wang (2000)	United States	HDV	Soybean	WVU 5 peak truck cycle	Tier 1	NOx, PM, HC, CO
Wirawan et al. (2008)	Indonesia	LDV	Palm	UDC and EUDC	Euro 2	NOx, PM, HC, CO
Wu (2008)	China	HDV Engine	Coconut, rapeseed, soybean, palm, UCO	Steady-state test	Euro 3	NOx, PM, HC, CO
Yasin (2015)	Malaysia, Iran	LDV	Palm	Steady-state test	—	NOx, HC, CO
Yoshida et al. (2008)	Japan	LDV	Rapeseed	NEDC	Euro 5	NOx, PM, HC, CO
Zhu (2010a)	China	HDV Engine	UCO	Steady-state test	Euro 5	NOx, PM, HC, CO
Zhu (2010b)	China	HDV	Palm, rapeseed, UCO	Steady-state test	—	NOx