Report on Respirable Pollutants Emitted by Heavy Duty Diesel Engines Using Biodiesel and Renewable Diesel

The city of Portland has taken many significant actions throughout the jurisdiction and within its operations to address significant environmental issues, including climate change. In 2007, the city adopted a renewable fuel standard to require blend levels of biogenic fuels in gasoline and most diesel fuel sold within the city. At the time these standards required blending of ethanol at 10 percent by volume in gasoline and by 2010 blending of biodiesel at 10 percent by volume in diesel fuel sold for use in on-road vehicles. Since that time, while ethanol has remained the renewable blend component for gasoline, a different blend stock, commonly called renewable diesel, has come into the marketplace. While renewable fuels tend to be domestically produced rather than imported, the primary policy driver for an RFS is the opportunity to lower emissions from climate forcers like carbon dioxide. While combustion of renewable fuels also emit carbon dioxide, the impact on climate is less because of the contemporary nature of renewable feedstocks as compared to petroleum fuels, which release forms of carbon that had been stored in the earth's crust for millions of years. The perturbation of the carbon cycle that is described as global warming is caused by significant human caused emissions of climate forcers from ancient sources, which then leads to dramatic changes in climate driven phenomena around the world (Masson-Delmotte, et al., 2021).

The climate benefits of renewable fuels like ethanol, biodiesel and renewable diesel are documented in Life Cycle Analyses, e.g., https://www.oregon.gov/deq/ghgp/cfp/Pages/Clean-Fuel-Pathways.aspx and are not a focus of this analysis. Instead, the scope of this report is on research regarding respirable emissions from the use of biodiesel and renewable diesel published since the Portland RFS was adopted. Respirable pollutants of concern include oxides of nitrogen (NOx), hydrocarbons (HC), carbon monoxide (CO) and ultrafine particulate matter (PM). Each of these at sufficient concentrations that can at times be realized in urban settings have direct and indirect adverse impacts on human health. Good policy would dictate that efforts to address climate would not necessarily come at a cost to human health.

BIODIESEL

Biodiesel is currently the most widely used biofuel in diesel engines. It is sourced in the United States from numerous feedstocks including soybean oil, animal fats, used cooking oil and canola oil. The fuel is produced by transesterification of fatty acids (FAME for Fatty Acid Methyl Esters) that is typically blended with petroleum diesel. Biodiesel increases the efficiency of fuel combustion due to higher oxygen content and cetane number. Several studies have shown that biodiesel combustion results in lower emissions of CO, HC, and PM but increases in NOx. EPA concluded in a 2002 report (U.S. EPA, 2002) that on the whole biodiesel combustion does not worsen air quality. EPA reaffirmed that finding in a 2020 rulemaking but this and the earlier conclusion was based on literature published before 2008. These studies were based on older, mechanically controlled engines with little or no exhaust aftertreatment. Engine emission certification standards have become more stringent beginning with the

2007 model year and again for 2010 and newer models. These trucks are fitted with sophisticated emission control systems that can make a difference in reported outcomes.

An extensive meta-analysis (O'Malley & Searle, 2021) of 131 published biodiesel exhaust studies conducted between 1983 and 2018 considered the effects of feedstocks, test cycles, fuel injection systems, engine horsepower and emission control technologies. They found that in late model engines a 20 percent blend of biodiesel with ultra-low sulfur diesel increased HC and CO by 7 percent and 10 percent respectively and did not reduce PM compared to conventional diesel. With the use of common rail fuel injection systems typical in late model vehicles, NOx emissions increased by 4 percent while using B20 blends. As blend levels increased, these trend lines continued. Feedstock made a difference in NOx emissions with the greatest effect for rapeseed or canola oil while lowest for fuels made from animal fat. PM emissions tended to be lower for animal fat-based fuels while higher for rapeseed and soybean originated fuels. Test vehicles fitted with diesel particulate filters (DPF) did show improvement in the regeneration rate, likely due to high oxygen content of biodiesel facilitating the removal of accumulated particulate. They concluded that although both diesel oxidation catalysts and diesel particulate filters mitigate overall emissions, these devices increase the degree to which biodiesel increases NOx relative to ULSD.

A detailed investigation (Hajbabaei, et al., 2012) (Durbin, et al., 2011) of biodiesel impacts on two heavy duty engines, one a 2006 with no aftertreatment and a 2007 with a DPF was reported using CARB diesel as the baseline. CARB diesel differs from federal ULSD primarily with a lower aromatic content with anticipated benefits for reduced NOx and engine smoke. This study included engine dynamometer and chassis dynamometer test procedures, several test protocols, and off-road and heavy highway engines. The data are extensive for each of the experimental parameters and conditions. For purposes of this report, we focus on highway vehicles using the Federal Test Procedure, which is the cycle used for federal certification of compliance with highway vehicle standards.

As mentioned earlier, feedstock and engine model year make a difference in emissions. With the 2006 Cummins engine, emissions of HC, CO, and PM showed consistent and significant reductions with the magnitude increasing with blend levels. Soybean originated biodiesel showed 11 percent, 3 percent, and 25 percent reductions respectively. Animal fat biodiesel resulted in 13 percent, 7 percent, and 19 percent reductions respectively. NOx emissions show increasing emission trends along with blend levels and feedstock as before with B20 soy at 6.6 percent and B20 animal at 1.5 percent. These values parallel those reported by EPA in 2002.

For the 2007 Mercedes Benz engine, the HC, CO, and PM emissions were all well below certification limits due to the DPF. NOx emissions were almost the only pollutant for which statistically significant results were reported. The soy-biodiesel B20 blend showed a 5.9 percent increase while the animal-biodiesel blend was 5 percent higher, again compared to CARB diesel. While these percentages were high for the 2007 engine the magnitude of the emission difference for all the measured pollutants were much smaller as compared to the 2006 engine.

As emission controls on engines have become more sophisticated, it appears that the respirable pollutant benefits of biodiesel tend to be diminished. Although newer, lower emission engines are increasing in number every year, legacy trucks continue to persist, and the respirable emission benefits of biodiesel can be realized in that sector of the fleet. In any case, biodiesel still retains its inherent climate benefits regardless of the engine model year.

RENEWABLE DIESEL

Renewable diesel is considered a second-generation biofuel. Technically known as hydrotreated vegetable oil (HVO), it is made from the same feedstocks as biodiesel but manufactured through various processes such as hydrotreating, gasification and pyrolysis. It meets the ASTM D 975 specification for petroleum diesel making it a drop-in fuel replacement for petroleum diesel. Although HVO is produced from the same feedstocks as FAME, feedstock source has little to no effect on the quality or properties of HVO fuels (Karavalkis, et al., 2016) A number of studies have been completed investigating the respirable emission impacts of renewable diesel compared to baseline diesel fuels (Sugiyama, Goto, Kitano, Mogi, & Honkanen, 2012) (Pirjola, et al., 2019) (Westphal, et al., 2013) showing reduced emissions in respirable pollutants with increasing blend levels. As promising as these reports are, they use baseline fuels, vehicles, and test procedures not typically available or used in the United States. Instead, we focus on the CARB supported work cited earlier (Durbin, et al., 2011) (Hajbabaei, et al., 2012) that included HVO fuel among tested conditions.

In the 2011 study, HVO was tested using the 2006 Cummins engine. Blend levels of R20, R50 and R100 were used. Relative to CARB diesel as the baseline fuel, HC, CO, PM, and NOx emissions were reduced 4 percent, 12 percent, 34 percent, and 9.9 percent respectively at the R100 blend level using the FTP protocol. One study using a direct injection 4-cylinder engine reported a 27 percent reduction in PM but accompanied by a 26 percent increase in NOx (Singh, Subramanian, & Singal, 2015). Even with the NOx increase with HVO, the fuel still outperformed the same engine running on biodiesel.

Test results from other late model engines appears to be more mixed. A European study using EN590 as a base fuel cited in the CALEPA Multimedia Evaluation of Renewable Diesel (Multi Media Working Group, 2015) showed reductions in most regulated emissions in a late model truck fitted with exhaust gas recirculation (EGR), a diesel oxidation catalyst and a particle oxidation catalyst[1] (Murtonen, Aakko-Saksa, Kuronen, Mikkonen, & Lehtoranta, 2009). Notably, PM emission were reduced by 7 percent while NOx showed a slight increase. The researchers speculated that the NOx increase may be due to several factors, e.g., the role of density /EGR, the effect of engine parameters on NOx/PM trade-off curve, low load test cycle and the effect of fuel density and viscosity on fuel injection systems.

More recent work was reported in the United States (Karavalkis, et al., 2016) using two late model engines, a 2014 Cummins ISX15 and a 2010 Cummins ISB6.7. Both vehicles are equipped with diesel

[1] POC is a specialized flow through diesel oxidation catalyst that captures and regenerates solid particles. These devices are not on the verified technology lists managed by EPA or CARB.

oxidation catalysts, diesel particulate filters and selective catalytic reduction exhaust systems. Fuels were blended at 20, 50 and 100 percent levels. Two driving cycles were used, the EPA Urban Dynamometer Driving Schedule (UDDS) and the CARB Heavy Heavy-Duty Diesel Truck (HHDDT) Transient Cycle. Overall, the results showed lower total hydrocarbons and CO emissions for all blends of HVO for the Cummins ISX-15, with these emissions at the detection limits for the Cummins ISB6.7 engine. NOx emission results were mixed. The Cummins ISX-15 showed higher NOx over the UDDS cycle but lower with blend level over the HHDDT Transient cycle, although in either case emissions were lower than the same engine using a B20 blend. The results for the ISB6.7 engine showed reductions with increasing blend levels for the UDDS cycle with a slight but insignificant increase on the HHDDT Transient cycle compared to CARB diesel. Again, in this case, the increases are less than the same engine using B20 fuel. The researchers suggest the measurement variability appears to be associated with changes in engine operation over the three consecutive HHDDT tests and the lack of SCR preconditioning for the Cummins ISB6.7 engine. The researchers cited other studies (Aatola, Larmi, Sarjovaara, & Mikkonen, 2009) (Bhardwaj, Kolbeck, Kkoerfer, & Honkanen, 2013) (Lehto, Elonheimo, Hakkinen, & Sarjovaara, 2012) (Kuromen, Mikkonen, Aakkl, & Murtonen, 2007) (Happonen, Heikkila, Murtonen, Lehto, & Sarjovaara, 2012) that generally show reductions in NOx with HVO relative to petroleum based fuels. These studies were not reviewed for detail here because they were unavailable or required subscription to access.

PM emissions are reported higher for the HVO fuels for the Cummins ISX-15 on both cycles, while PM emissions were much lower for the Cummins ISB6.7 vehicle. Researchers cited several other studies that show consistent reductions in PM emissions from HVO fuels relative to petroleum baselines (Hartikka, Kuronen, & Kiiski, 2012) (Na, Biswas, Robertson, Sahay, & Okamoto, 2015) (Erkkila, Nylund, Hulkkonen, & Tilli, 2011). These studies were not reviewed here for detail here because they were unavailable or required subscription to access. The results from the Murtonen et al 2009 report that showed PM reductions with a late model engine was noted earlier. In any case, the researchers recommend further studies to understand PM formation mechanisms with HVO fuels from current technology vehicles equipped with advanced aftertreatment systems.

Although this is beyond the scope of this query, it is worthwhile to note that the California Environmental Protection Agency completed an extensive multimedia evaluation of HVO fuel (Multi Media Working Group, 2015). This report considered not only respirable emission effects but also water resource impacts and issues, toxicology of exhaust emissions and by products plus soil and hazardous waste impacts from the use and production of renewable diesel. The working group concluded that HVO fuel does not pose a significant adverse impact on public health, or the environment given the state of knowledge and presence of existing programs to manage and control impacts.

SUMMARY

Biodiesel continues to provide benefits with reduced climate forcing impacts along with, and in older mechanically controlled engines reliable emission reductions in pollution that directly and adversely impacts human health. Renewable diesel, based on this review offers similar if not more substantial benefits for climate and human health because of the opportunity presented for higher blend levels to be tolerated in diesel engines.

As the inventory of diesel-powered vehicles with advanced exhaust control increases, the respirable pollutant benefit achieved for biodiesel is not as large as from the older engines. Nonetheless, biodiesel retains utility as a pollution management strategy because it is less capital intensive than aftermarket exhaust controls on an individual basis. Biodiesel still retains its advantages for climate benefits even with lesser respirable pollutant reductions.

Renewable diesel, because it meets the same standards as petroleum diesel, offers the opportunity for higher blend levels than currently possible with biodiesel. This review confirmed respirable pollutant benefits from use in older engines and did highlight that further investigation is warranted to confirm the degree of benefit when this fuel is used in engines with advanced exhaust controls.

In either case, biodiesel or renewable diesel, any uncertainty suggests that the risk of continued use for air quality purposes is small and certainly lower than continued use of petroleum diesel. The one pollutant that represents the most risk is NOx. Due to the nature of the combustion process in diesel engines, there exists the engineering challenge to simultaneously control nitrogen oxides and particulate matter, with the tradeoff typically being to favor one over the other. However, even in those reports where NOx increases with HVO fuel, the increase is less than what is observed in the use of biodiesel, for instance, and sometimes only marginally greater than from the use of petroleum diesel.

Whether increased NOx is a problem depends upon several variables, with the magnitude and sign of the effect are unknown or uncertain. Nitrogen oxides are, themselves, a criteria pollutant under the federal Clean Air Act but only the Los Angeles area has ever violated the federal standard. This area moved back into attainment and secured maintenance status in 1998. The Portland area has never violated NOx criteria pollutant standards. NOx along with volatile organic compounds in the presence of heat energy forms tropospheric ozone, commonly referred to as smog. While many parts of the country have persistent ozone issues, the Portland/Vancouver area has not violated ozone standards since the 1970s. In addition to health impacts, tropospheric ozone is also acknowledged as a climate forcer, alongside other well-known gases like carbon dioxide. For ozone to form though, the necessary atmospheric concentrations and presence of ozone precursors like nitrogen oxides and volatile organic compounds must be in place and in the proper proportions. Too much or not enough of any one of the required elements may hinder ozone formation. Los Angeles and Houston, for instance are NOx limited ozone areas, meaning that further reductions of nitrogen oxides are critical to avoid ozone formation. Portland/Vancouver, on the other hand, is modeled to be VOC-limited for ozone, which means that increases in NOX may lower the risk of ozone creation (Xie & Lamb, 2005). NOx also plays a role in the oxidation of another potent climate forcer, methane, reducing its concentration in the atmosphere (Enhalt & Prather, 2001) so concentrations can have a positive effect on reducing other climate forcers like methane. It may never be a good policy to argue for any amount of combustion byproduct to increase in the atmosphere, but it is not entirely clear that greater levels of nitrogen oxides are necessarily as deleterious in this region as they would eb in other parts of the country.

When considering the question as to whether expanding the use of HVO fuel will result in positive outcomes for respirable pollutants, it is illustrative to consider a life cycle analysis completed for Helsinki Finland (Lakanen, et al., 2020). Metropolitan Helsinki has a population of about 1.5 million as compared to the Portland/Vancouver metro area population of 2.5 million[2]. This handprint analysis considered life cycle and locally emitted emissions in the circumstance that renewable diesel replaced petroleum diesel in the fleet. Reduction potential was quantified considering the actual car fleet, mileage, local temperature and laboratory emission measurements. The results showed overall emissions of $PM_{2.5}$ and NOx reduced by 44 and 11 percent, respectively. $PM_{2.5}$ and NOx emissions from the car fleet alone were reduced 49 percent and 7 percent. Traffic related emissions dominated the results. The researchers note that there was a substantial air pollution benefit for 23 percent of the Helsinki light duty diesel fleet that lacked modern exhaust filtration. They also observe that while the emission reduction benefit is less for more modern cars, HVO decreases the burden on exhaust gas cleaning systems that accounts for their lower emission profile while still reducing overall emissions in the entire car fleet. The results suggest that while the magnitude of the result from using HVO widely in the Portland area would differ, the likelihood is that the effect is still positive for reducing the most harmful pollutants emitted by diesel engines.

References

Aatola, H., Larmi, M., Sarjovaara, T., & Mikkonen, S. (2009). Hydrotreated Vegetable Oil (HVO) as a Renewable Diesel Fuel: Trade-off between NOX, Particulate Emission and Fuel Consumption of a Heavy Duty Engine. *SAE Int. J. Engines, 1*(1), 1251-1262. doi:10.4271/2008-01-2500

Bhardwaj, O., Kolbeck, A., Kkoerfer, T., & Honkanen, M. (2013). Potential of Hydrogenated Vegetable Oil (HVO) in Future High Efficiency Combustion System. *SAE Int. J. Fuels Lubr., 6*(1), 157-169. doi:10.4271/2013-01-1677

Durbin, T., Miller, J., Johnson, K., Hajbabaei, M., Kado, N., Kobayashi, R., . . . Cahill, T. (2011). *CARB Assessment of the Emissions from the Use of Biodiesel as a Motor Vehicle Fuel in California.* Sacramento: California Air Resources Board. Retrieved from http://www.arb.ca.gov/fuels/diesel/altdiesel/

Enhalt, D., & Prather, M. (2001). *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the International Panel on Climate Change.* Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Erkkila, K., Nylund, N., Hulkkonen, T., & Tilli, A. (2011). Emmission performance of paraffinic HVO diesel fuel in heavy duty vehicles. *SAE Technical Paper, 2011-01-1996*. doi:10.4271/2011-01-1996

[2] 26 percent of light duty vehicles in Helsinki are diesel, 0.3 percent are diesel powered in the U.S.

Hajbabaei, M., Johnson, K., Okamoto, R., Mitchell, A., Pullman, M., & Durbin, T. (2012). Evaluation of the Impacts of Biodiesel and Second Generation Biofuels on NOx Emissions for CARB Diesel Fuels. *Environmental Science and Technology*, 9163-9173.

Happonen, M., Heikkila, J., Murtonen, T., Lehto, K., & Sarjovaara, T. (2012). Reduction in particulate and NOx emissions by diesel engine parameter adjustments with HVO fuel. *Environmental Science and Technology, 46*, 6198-6204. doi:10.1021/es300447t

Hartikka, T., Kuronen, M., & Kiiski, U. (2012). Technical Performance of HVO (Hydrotreated Vegetable Oil) in Diesel Engines. *SAE Technical Paper, 2012-01-1585*. doi:10.4271/2012-01-1585

Karavalkis, G., Jiang, Y., Yang, J., Durbin, T., Nuottimaki, J., & Lehto, K. (2016). Emissions and Fuel Economy Evaluation from Two Current Technology Heavy-Duty Trucks Operated on HVO and FAME Blends. *SAE Int. J. Fuels Lubr.*, 177-189. doi:10.4271/2016-01-0876

Kuromen, M., Mikkonen, S., Aakkl, P., & Murtonen, T. (2007). Hydrotreated Vegetable Oil as Fuel for Heavy Duty Diesel Engines. *SAE Technical Paper, 2007-01-4031*. doi:10.4271/2007-01-4031

Lakanen, L., Gronman, K., Vaisanen, S., Kasurinen, H., Soininen, A., & Souka, R. (2020). Applying the handprint approach to assess the air pollutant reduction potential of paraffinic renewable diesel fuel in the car fleet of the city of Helsinki. *Journal of Cleaner Production, 290*. doi:10.1016/j.jclepro.2021.125786

Lehto, K., Elonheimo, A., Hakkinen, K., & Sarjovaara, T. (2012). Emission Reduction Using Hydrotreated Vegetable Oil (HVO) With Miller Timing and EGR in Diesel Combustion. *SAE Int. J. Fuels Lubr., 5*(1), 218-224. doi:10.4271/2011-01-1955

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S., Pean, C., Berger, S., . . . Zhou, B. (2021). *Climate Change 2021: The Physial Science Basis, Contriubution of Working Grouop I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge: Cambridge University Press.

Multi Media Working Group. (2015). *Multimedia Evaluaiton of Renewable Diesel.* Sacramento: California Environmental Protection Agency. Retrieved July 29, 2021, from https://ww2.arb.ca.gov/resources/documents/fuels-multimedia-evaluation-renewable-diesel

Murtonen, T., Aakko-Saksa, P., Kuronen, M., Mikkonen, S., & Lehtoranta, K. (2009). Emissions with Heavy-duty Diesel Engines and Vehicles using FAME, HVO and GTFL Fuels with and without DOC+POC Aftertreatment. *SAE Int. J. Fuel Lubr, 2*(2), 147-166.

Na, K., Biswas, S., Robertson, W., Sahay, K., & Okamoto, R. (2015). Impact of biodiesel and renewable diesel on emissions of regulated pollutants and greenhouse gases on a 2000 heavy duty truck. *Atmospheric Environment, 107*, 307-314.

O'Malley, J., & Searle, S. (2021). *Air Quality Impacts of Biodiesel in the United States.* Washington D.C.: The International Council on Clean Transportation.

Pirjola, L., Kuuluvainen, H., Timonen, H., Saarikoski, S., Teinila, K., Salo, L., . . . Ronkko, T. (2019). Potential of renewable fuel to reduce diesel exhaust particle emissions. *Applied Energy*. doi:10.1016/j.apenergy.2019.113636

Singh, D., Subramanian, K., & Singal, S. (2015). Emissions and fuel consumption characteristics of a heavy duty engine fueled with hydroprocessed renewable fuel and biodiesel. *Fuel, 155*, 440-446.

Sugiyama, K., Goto, I., Kitano, K., Mogi, K., & Honkanen, M. (2012, January). Effects of Hydrotreated Vegetable Oil (HVO) as Renewable Diesel Fuel on Combustion and Exhaust Emissions in Diesel Engine. *SAE Intl J. Fuels Lubr. , 5*(1), 205-217.

U.S. EPA. (2002). *A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions.* EPA 420-P-02-001.

Westphal, G., Krahl, J., Munack, A., Rosenkranz, N., Schroder, O., Schaak, J., . . . Bunger, J. (2013). Combustion of Hydrotreated Vegetable Oil and Japtropha Methyl Ester in a Heavy Duty Engine: Emissions and Bacterial Mutagenicity. *Environmental Science and Technology*, 6038-6046. doi:10.1021/es400518d

Xie, Y., & Lamb, B. (2005). *Historical and Future Ozone Simulations using the MM5/SMOKE/CMAQ System in the Portland/Vancouver Area.* Department of Civil & Environmental Engineering. Pullman: Washington State University. Retrieved September 7, 2021

Low Emission Diesel (LED) Study: Biodiesel and Renewable Diesel Emissions in Legacy and New Technology Diesel Engines

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Engine Type	SCR Equipped?	DPF Equipped?	HP	Model Year	Manufacturer	Vocation
Off-Road Legacy Engine Tier 3	No	No	115	2009	John Deere	Construction
Off-Road New Technology Diesel Engine (NTDE) Tier 4	Yes	Yes	225	2018	Caterpillar	Industrial Off-Road
On-Road Heavy Duty NTDE	Yes	Yes	450	2019	Cummins	Class 7 or 8 truck

Test Cycle	Engine Application	Description - Dynamometer
Non-Road Transient Cycle (NRTC)	Off-Road	Transient test used for engine certification procedure of off-road diesel engines
D2 ISO 8718 (D2)	Off-Road	Steady state cycle test used for certification of constant speed off-road engines
Federal Test Procedure (FTP)	On-Road	Transient test used for engine certification of heavy-duty on-road engines
Ramped Modal Cycle		
RMC	On-Road	Supplementary emissions test used in federal certification
C1 cycle	Off-Road	Used in certification of variable speed off-road engines

Off-Road Legacy Engine Results (BREAKHORSE POWER)

Nitrogen Oxides

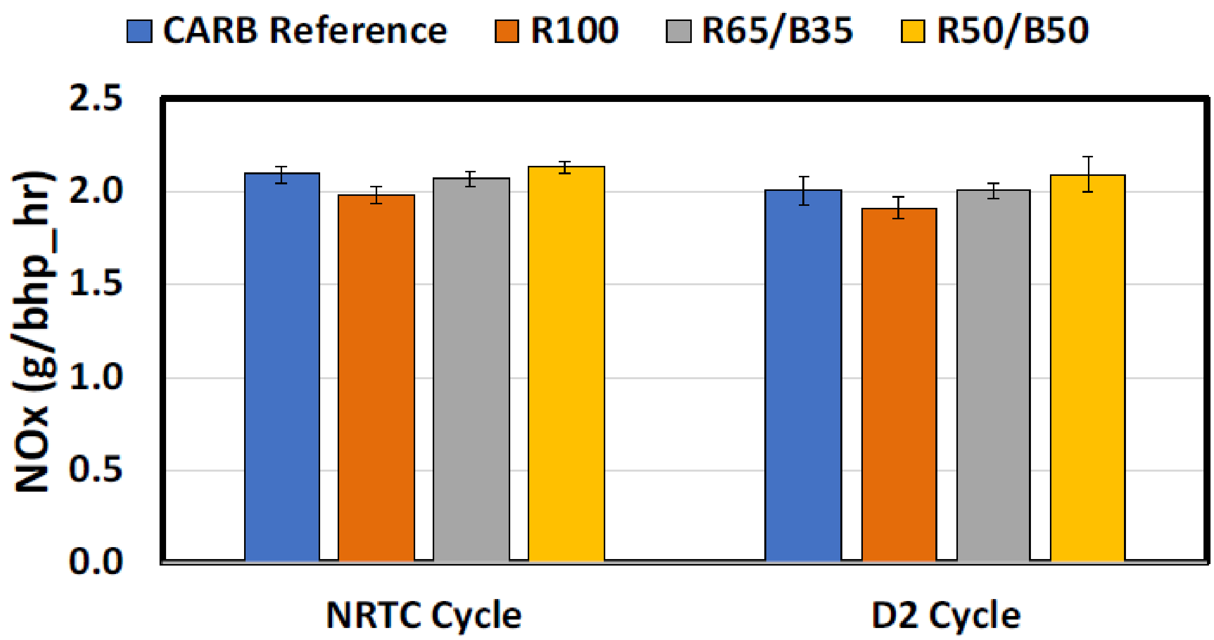

Figure 1 (from Durbin et al) Average NOx Emissions for the Off-Road Legacy Engine

Table 1 NOx Emissions, Percentage Differences, Statistical Comparisons Between Biofuels and CARB Reference Fuel, Off-Road Legacy Engine

Cycle	Fuel Type	Avg. (g/bhp-hr)	% Diff vs. CARB	p-value (t-test)
NRTC	CARB reference fuel	2.09	-	-
	R100	**1.98**	-5.4	**0.00**
	R65/B35	2.07	-1.2	0.18
	R50/B50	**2.13**	1.8	**0.05**
D2	CARB reference fuel	2.01	-	-
	R100	**1.91**	-4.9	**0.00**
	R65/B35	2.01	0.0	0.97
	R50/B50	**2.09**	4.2	**0.02**

Statistically significant results are bolded and their percent differences are shown in red.

Particulate Matter

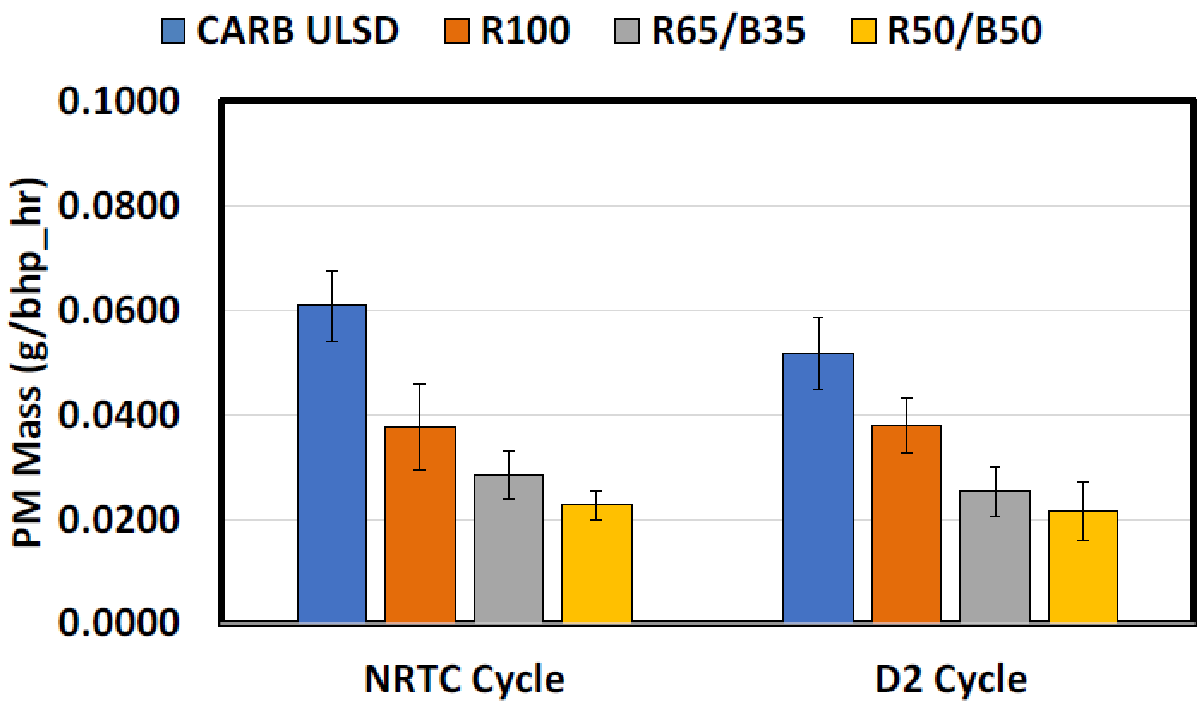

Figure 2 Average PM Emission Results for the Off-Road Legacy Engine. Note: Federal Engine Certification Limit for PM for this engine is 0.17 g/bhp-hr.

Table 2 PM Emissions, Percentage Differences and Statistical Comparisons Between Biofuels and CARB Reference Fuel for Off-Road Legacy Engine

Cycle	Fuel Type	Avg. (g/bhp-hr)	% Diff vs. CARB	p-value (t-test)
NRTC	CARB reference fuel	0.061	-	-
	R100	**0.038**	-38	**0.00**
	R65/B35	**0.028**	-53	**0.00**
	R50/B50	**0.023**	-63	**0.00**
D2	CARB reference fuel	0.052	-	-
	R100	**0.038**	-27	**0.00**
	R65/B35	**0.025**	-51	**0.00**
	R50/B50	**0.022**	-58	**0.00**

Statistically significant results are bolded and their percent differences are shown in red.

Off-Road New Technology Diesel Engine

Nitrogen Oxides

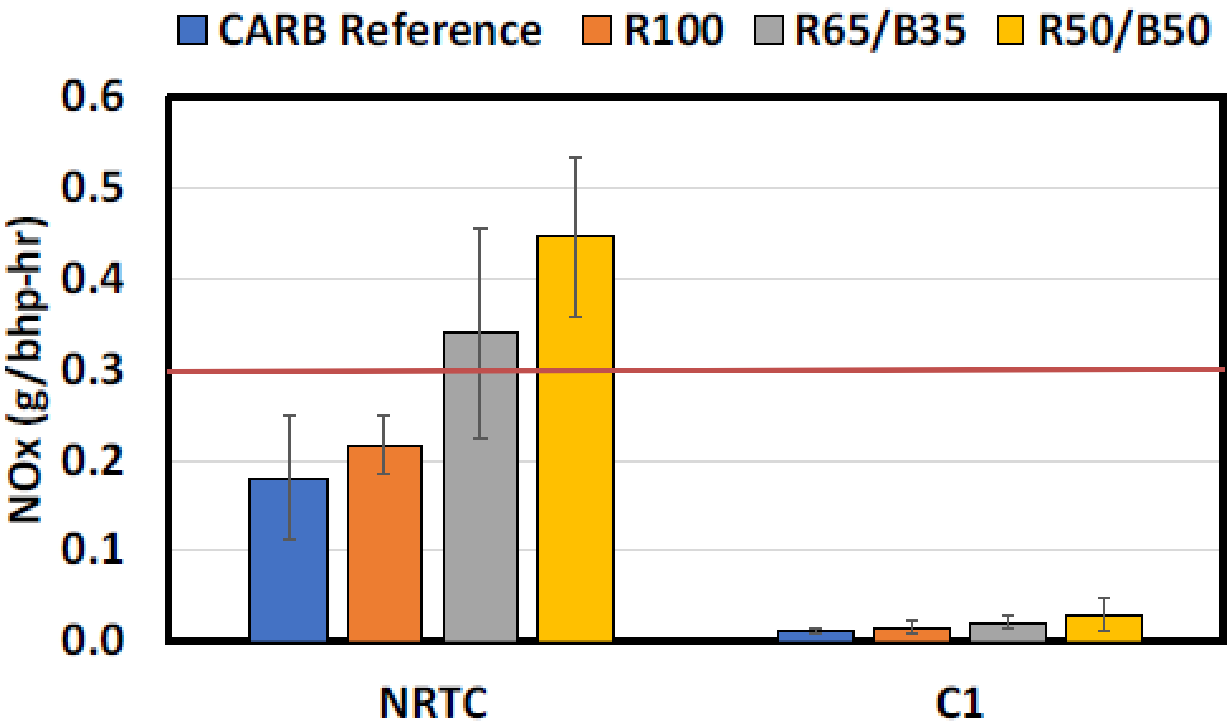

Figure 4 Average NOx Emissions for Off-Road NTDE. Note: Federal Emission Certification Limit for NOx for this engine is 0.30 g/bhp-hr

Table 3 NOx Emissions, Percentage Differences and Statistical Comparisons Between Biofuels and CARB Reference Fuel for Off-Road NTDE

Cycle	Fuel Type	Avg. (g/bhp-hr)	% Diff vs. CARB	p-value (t-test)
NRTC	CARB reference fuel	0.18	-	-
	R100	0.22	20.1	0.11
	R65/B35	**0.34**	88.3	**0.00**
	R50/B50	**0.45**	146.9	**0.00**
C1	CARB reference fuel	0.014	-	-
	R100	0.015	10.5	0.56
	R65/B35	**0.021**	55.1	**0.01**
	R50/B50	**0.030**	119.4	**0.01**

Statistically significant results are bolded and their percent differences are shown in red.

Particulate Matter

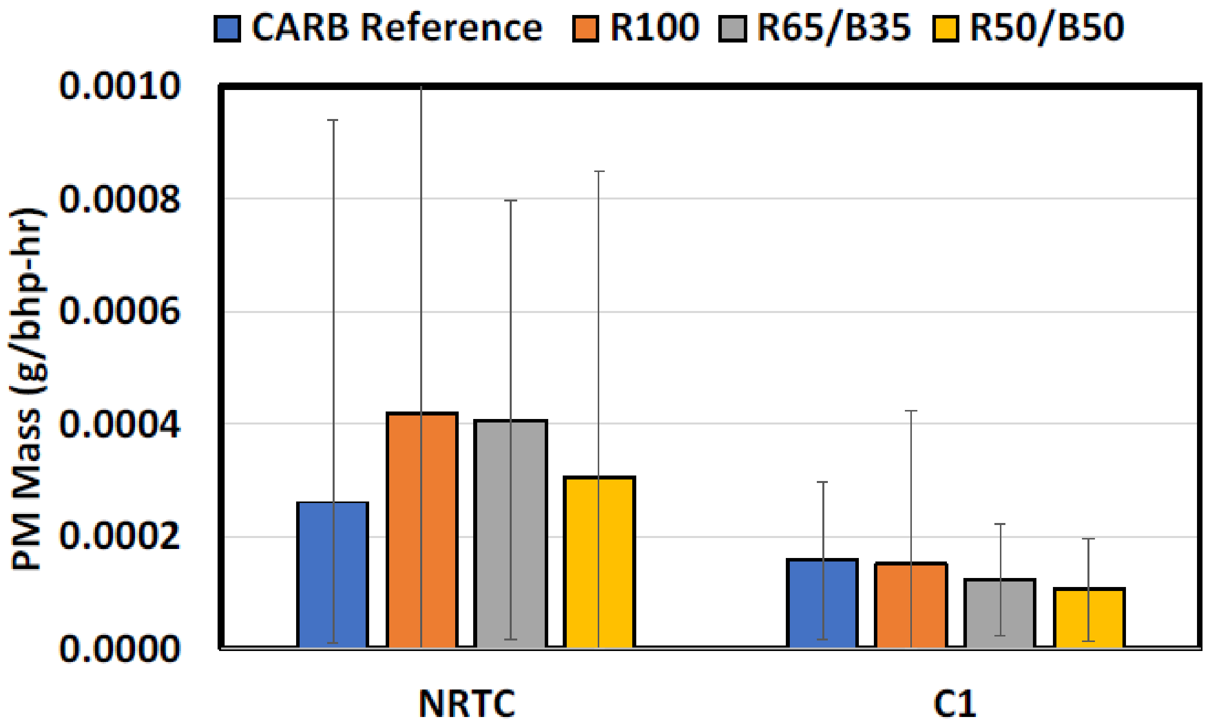

Figure 4 Average PM Emission Results for the Off-Road NTDE. Note Federal Emission Certification Limit for PM for this engine is 0.015 g/bhp-hr

Table 4 PM Emissions, Percentage Differences and Statistical Comparisons Between Biofuels and CARB Reference Fuel for Off-Road NTDE

Cycle	Fuel Type	Avg. (g/bhp-hr)	% Diff vs. CARB	p-value (t-test)
NRTC	CARB reference fuel	0.00026	-	-
	R100	0.00042	60	0.56
	R65/B35	0.00041	56	0.53
	R50/B50	0.00031	17	0.86
C1	CARB reference fuel	0.00016	-	-
	R100	0.00015	-4	0.95
	R65/B35	0.00012	-22	0.54
	R50/B50	0.00011	-33	0.43

Statistically significant results are bolded and their percent differences are shown in red.

On-Road New Technology Diesel Engine

Nitrogen Oxides

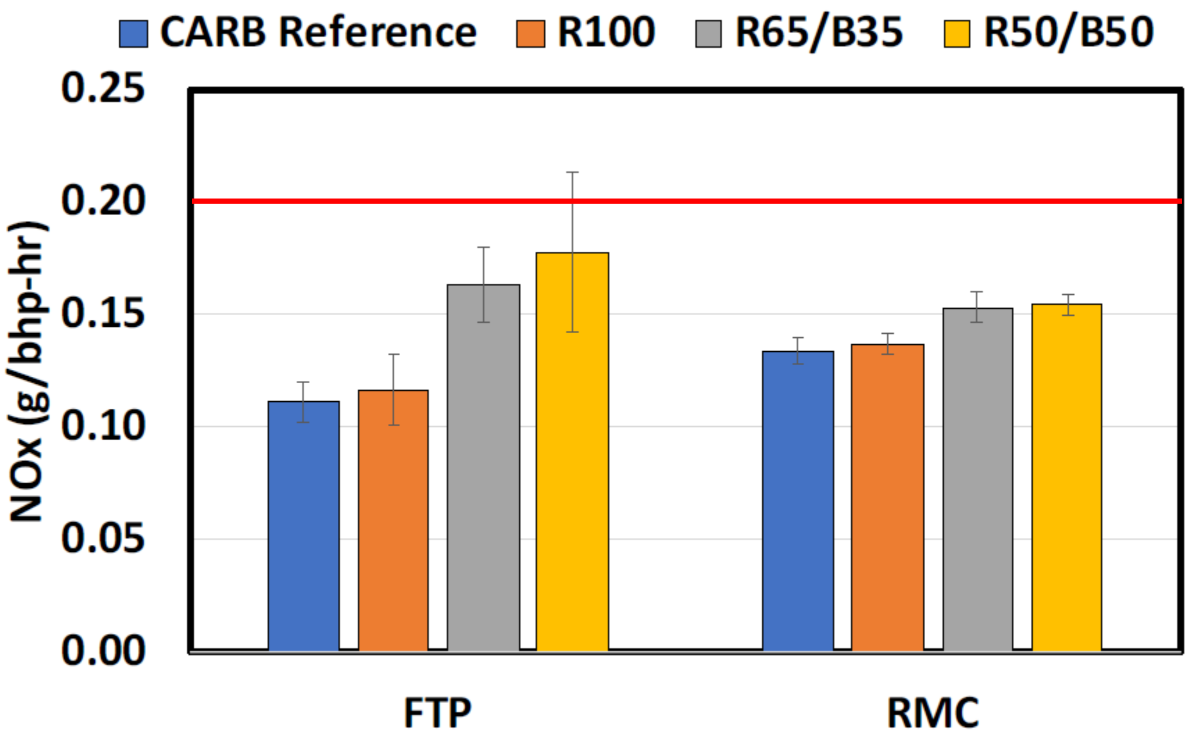

Figure 5 Average NOx Emission Results for On-Road NTDE. Note: Federal Emission Certification Limit for NOx for this engine is 0.2 g/bhp-hr

Table 5 NOx Emissions, Percentage Differences and Statistical Comparisons Between Biofuels and CARB Reference Fuel for the On-Road NTDE

Cycle	Fuel Type	Avg. (g/bhp-hr)	% Diff vs. CARB	p-value (t-test)
FTP	CARB reference fuel	0.11	-	-
	R100	0.12	4.8	0.34
	R65/B35	**0.16**	46.6	**0.00**
	R50/B50	**0.17**	49.5	**0.00**
RMC	CARB reference fuel	0.13	-	-
	R100	0.14	2.3	0.19
	R65/B35	**0.15**	14.2	**0.00**
	R50/B50	**0.15**	15.4	**0.00**

Statistically significant results are bolded and their percent differences are shown in red.

Particulate Matter

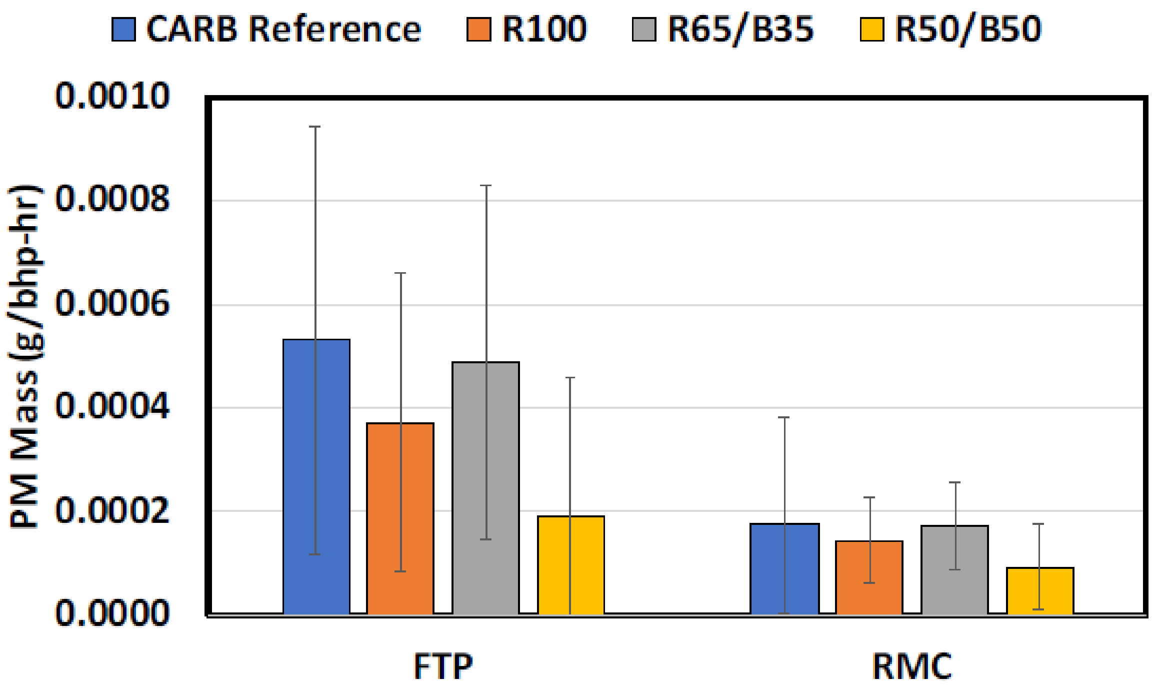

Figure 6 Average PM Emissions for the ON-Road NTDE. Note: Federal Emission Certification Limit for PM for this engine is 0.01 g/bhp-hr

Table 6 PM Emissions, Percentage Differences and Statistical Comparisons Between Biofuels and CARB Reference Fuel for On-Road NTDE

Cycle	Fuel Type	Avg. (g/bhp-hr)	% Diff vs. CARB	p-value (t-test)
FTP	CARB reference fuel	0.00049	-	-
	R100	0.00036	-28	0.38
	R65/B35	0.00052	6	0.86
	R50/B50	0.00018	-64	0.06*
RMC	CARB reference fuel	0.00018	-	-
	R100	0.00015	-18	0.66
	R65/B35	0.00017	-4	0.94
	R50/B50	0.00009	-47	0.26

*Indicates marginally significant result