

Measurement of Emissions from a Passenger Truck Fueled with Biodiesel from Different Feedstocks

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ABSTRACT

Biodiesel has generated increased interest recently as an alternative to petroleum-derived diesel. Due to its high oxygen content, biodiesel typically burns more completely than petroleum diesel, and thus has lower emissions of hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM). However, biodiesel may increase or decrease nitrogen oxide (NO_x) and carbon dioxide (CO₂) emissions, depending on biodiesel feedstock, engine type, and test cycle. The purpose of this study was to compare emissions from 20% blends of biodiesel made from 4 feedstocks (soybean oil, canola oil, waste cooking oil, and animal fat) with emissions from ultra low sulfur diesel (ULSD). Emissions of NO_x and CO₂ were made under real-world driving conditions using a Horiba On-Board Measurement System OBS-1300 on a highway route and arterial route; emissions of NO_x, CO₂, HC, CO, and PM were measured in a controlled setting using a chassis dynamometer with Urban Dynamometer Drive Schedule. Dynamometer test results showed statistically significant lower emissions of HC, CO, and PM from all B20 blends compared to ULSD. For CO₂, both on-road testing (arterial, highway, and idling) and dynamometer testing showed no statistically significant difference in emissions among the B20 blends and ULSD. For NO_x, dynamometer testing showed only B20 from soybean oil to have statistically significant higher emissions. This is generally consistent with the on-road testing, which showed no statistically significant difference in NO_x emissions between ULSD and the B20 blends.

Keywords: Alternative Fuel; Biodiesel; Diesel; Emissions; On-Road Testing; Portable Emission Measurement System (PEMS); Dynamometer

1. Introduction

As global population increases and developing countries industrialize, energy demand around the world is increasing markedly. World energy consumption is expected to increase by 50% by 2020 [1]. According to the Energy Information Administration's (EIA's) International Energy Outlook, world demand for crude oil is expected to grow from 84 million barrels/day in 2005 to over 114 million barrels/day in 2030 [2].

Biodiesel has generated increased interest in the US and elsewhere recently as an alternative to petroleum-derived diesel. Because it can be produced from domestic natural sources such as soybeans, canola, and recycled cooking oil, biodiesel can help reduce dependence on petroleum fuel from foreign sources, and thus foster en-

ergy independence [3]. Due to its high oxygen content, biodiesel typically burns more completely than petroleum diesel, and thus has lower emissions of hydrocarbons (HC), carbon monoxide (CO), and particulate matter. Since biodiesel is essentially free of sulfur, SO₂ emissions are negligible. However, a B20 blend of biodiesel may increase or decrease nitrogen oxide (NO_x) emissions (from +12% to -13%) and carbon dioxide (CO₂) emissions (from +1% to -67%), depending on biodiesel feedstock, engine type, and test cycle [3-7].

Biodiesel feedstocks that reduce NO_x would be beneficial to US regions facing problems with ground-level ozone, fine particulates, and/or acid precipitation. From the viewpoint of climate change, all regions should avoid biodiesel from feedstocks that increase CO₂ emissions. Therefore, determining which biodiesel feedstocks in-

crease and decrease NO_x and CO_2 emissions is important.

Various studies have compared NO_x emissions from biodiesel from one feedstock with those from petroleum diesel, based on chassis or engine dynamometer testing [7-10]. Several additional studies of NO_x emissions from one biodiesel feedstock have involved on-road or in-use testing [11-14]. Comparing emissions from various feedstocks across studies can be difficult due to different engines and testing protocols.

Various studies [5,6,8,15-20] have compared NO_x emissions from multiple biodiesel feedstocks using the same engine and testing protocol with either engine or chassis dyno testing. None involved on-road testing. None of the studies looked at NO_x emissions from biodiesel from animal fat, which is potentially important as a waste product source that would not compete with food crops.

For a given engine type, the amount of CO_2 produced should correlate with the fuel carbon content, which would vary with feedstock. Various studies have compared CO_2 emissions from biodiesel from one feedstock with those from petroleum diesel, based on chassis or engine dyno testing [7-9,21,22]. Several additional studies of CO_2 emissions from one biodiesel feedstock have involved on-road testing [12,14]. As for NO_x , comparing CO_2 emissions from various feedstocks across studies can be difficult due to different engines and testing protocols.

A few studies [8,17,18,23] have compared CO_2 emissions from biodiesel from multiple feedstocks using the same engine and testing protocol, using chassis or dyno testing. None involved on-road testing. None of the studies looked at CO_2 emissions from biodiesel from animal fat.

The study described in this paper aimed to go beyond previous studies of NO_x and CO_2 emissions from multiple biodiesel feedstocks, in terms of test conditions and feedstocks, by: 1) involving more test states/cycles/conditions (on-road arterial, on-road highway, steady-state idling, and chassis dynamometer testing), and 2) by including feedstocks previously untested (canola for NO_x and animal fat for NO_x and CO_2).

2. Methodology

2.1. Biodiesel Feedstocks, Blends, and Fuel Properties

Biodiesel from soybean oil, canola oil, waste cooking oil, and animal fat was tested. Soybean and canola oil were selected to represent biodiesel made from vegetable oil. Soybean oil is the primary feedstock in the US because the U.S. is the largest producer of soybean oil. Biodiesel made from non-food crops is called "second generation" biodiesel, and is increasingly emphasized so that it does

not compete with food as an end-use of crops. Waste cooking oil and animal fat biodiesel were included as examples of second generation biodiesel feedstocks. B20 (biodiesel blended with 20% with ultra low sulfur diesel, or ULSD) was tested, because such blends can be used in existing engines without modification [16]. ULSD was tested as a baseline fuel.

Biodiesel from soybean, canola, and waste cooking oil were produced at the Mechanical and Aerospace Engineering Laboratory at UT Arlington. Details of the transesterification method can be found in Pala-En (2012) [24]. Animal fat biodiesel was from Houston Biodiesel. Iowa Central Fuel Testing Laboratory measured physical/chemical properties of ULSD (ASTM D 975) and B20 blends (ASTM D 7467). C, H, O, N content was measured by Intertek QTI.

2.2. Test Vehicle

The test vehicle was a 1994 diesel Chevy C/K 2500 3/4 ton pickup truck, with an extended cab and long bed, which is owned by the UT Arlington research group. Information about the vehicle is given in **Table 1**.

2.3. On-Road Testing Equipment

Emissions were measured as the vehicle travelled on-road using a Horiba On-Board emission measurement System OBS-1300. NO_x and CO_2 concentrations were measured second-by-second, along with vehicle velocity and exhaust temperature, pressure, and flow rate. The OBS-1300 system consists of a MEXA-720 NO_x analyzer, a MEXA-1170 HNDIR analyzer, 2 12 V deep cycle batteries and power supply unit to convert DC to AC, a data logger PC and other accessories. The MEXA-720 NO_x analyzer is a non-sampling type zirconium sensor that measures NO_x concentrations, with accuracy ± 3.3 ppm. The NO_x sensor probe is attached to the tail pipe. The HNDIR analyzer, used to measure CO_2 , has a heated tube attached to the tail pipe, which takes in the sample for analysis. According to the manufacturer, accuracy for the CO_2 emission measurements was $\pm 0.3\%$. A GPS unit is provided log vehicle position as a function of time. Differences in vehicle position with time were used to calculate vehicle velocity; differences in vehicle velocity

Table 1. Specifications of test vehicle.

Parameter	Value
Engine	155 hp, 6.5 L Detroit Diesel V-8
Fuel Tank capacity	34 gallons
Transmission	4 speed automatic
Weight, lb	4387

with time were used to calculate vehicle acceleration. Routine instrument calibrations and warm up were carried out each day before the start of each session of data collection. The sensor was also calibrated weekly as required by the protocol. Maintenance and diagnostic procedures were conducted as required.

2.4. On-Road Testing Procedure

For each biodiesel blend, 1.5 hours of highway testing and 1.5 hours of arterial testing were conducted during off-peak weekday hours (9 a.m.-4 p.m.). Off-peak hours were used so that traffic flow patterns would be more similar among runs. As shown in **Figure 1**, the arterial test route was 6.5 miles, centered on UT Arlington, and the highway test route was 50 miles, centered on the City of Arlington. In addition, 15 minutes of idling data were collected for each fuel. The driver was the same for all testing, to eliminate variability associated with different driving habits. The truck was warmed up prior to data collection to avoid cold-start conditions.

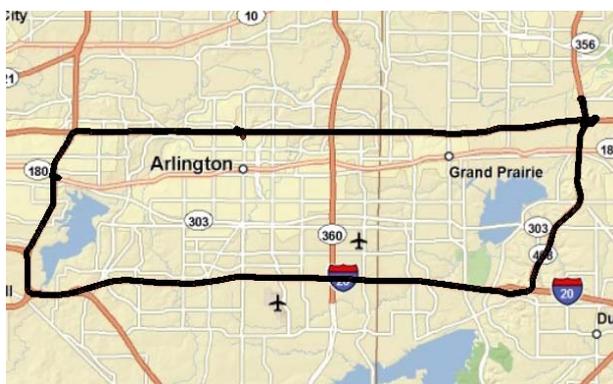


Figure 1. Routes for on-road testing (arterial route at top, highway route at bottom).

The order of testing of each fuel and route was randomly chosen to reduce systematic error and bias conditions. Each B20 blend and route was tested with 2 replications, in the order shown in **Table 2**. The fuel tank was drained between runs.

2.5. Dynamometer Testing Procedure

Chassis dynamometer testing was conducted at the University of Houston’s Texas Diesel Testing and Research Center using a 500 HP AC chassis dynamometer (Burke Porter, model 6356 - 6419). The Urban Dynamometer Drive Schedule (UDDS), shown in **Figure 2**, was selected as it simulates a combination of low speed and idling as well as high speed and high acceleration driving. The driving cycle test consisted of:

- 1) Vehicle fuel system purge with the fuel to be tested;
- 2) Vehicle warm-up;
- 3) Set of three repeated runs, with a 20-minute soaking period between runs.

The ambient temperature was controlled at 23°C - 25°C. Emissions of NO_x, total hydrocarbons (THC), CO, CO₂ and oxygen (O₂) were analyzed by a five gas analytical bench (Horiba, MEXA 7100). PM was collected and measured using filtration capture and gravimetric method. Fuel consumption data were collected from direct gravimetric measurement, and emission carbon balance inference.

3. Results

3.1. Fuel Properties

Table 3 (at end) compares properties of biodiesel fuel from different feedstocks with ULSD fuel. Viscosity is important due to the potential of high viscosity to adversely affect fuel injection [16]. None of the viscosities

Table 2. On-road testing order.

Test No.	Fuel	Route Type
1	ULSD	Arterial
2	Soybean	Highway
3	WCO	Highway
4	WCO	Arterial
5	Soybean	Arterial
6	Animal Fat	Highway
7	Animal Fat	Arterial
8	Canola	Highway
9	ULSD	Highway
10	Canola	Arterial

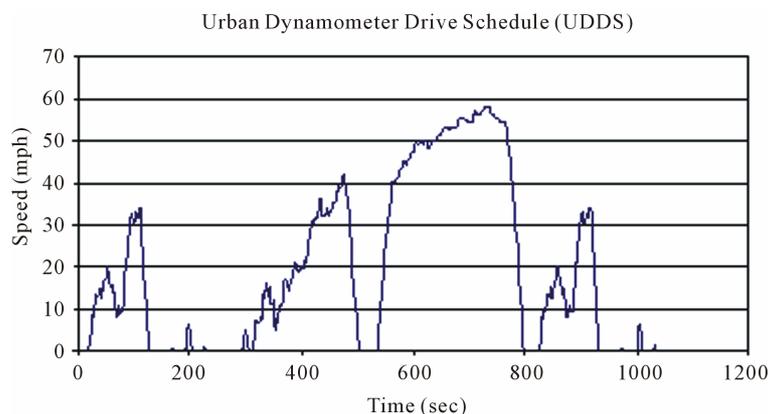


Figure 2. Urban dynamometer drive schedule (UDDS).

Table 3. Fuel properties of ultra low-sulfur diesel and biodiesel blends from 4 feedstocks.

Property	Unit	ASTM limit	ULSD	Soybean B20	Canola B20	WCO B20	AF B20
Acid number	mg KOH/g	0.3 max	N/A	0.12	0.16	0.18	0.06
Viscosity	mm ² /sec	1.9 - 4.1	2.150 ^a	2.458	2.456	3.107	3.072
Flash Point	°C	52, min	63	68	67	65	69
Cloud Point	°C		-21	-15	-17	-8	-7
Sulfur Content	ppm (µg/g)	15, max	2.75	2.28	2.85	6.05	6.65
Distillation Temp	°C	343, max	297.8 ^b	330.0	328.9	337.6	337.3
Ash Content	% mass	0.01, max	0.0000	0.00085	0.00055	0.00046	0.00031
Water & Sediment	% volume	0.05, max	<0.005	<0.005	<0.005	<0.005	<0.005
Copper Corrosion	n/a	No. 3, max	1a	1a	1a	1a	1a
Oxidation Stability	hours	6, min	N/A	3.04	2.37	2.14	13.35
Cetane Number	n/a	47, min	51.6 ^c	55.7	55.7	49.3	48.3
Blend Content	% (V/V)		0.03	22.8	20.33	20.96	21.07
C	%		85.97	83.75	83.64	83.85	84.76
H	%		14.01	13.23	13.44	13.35	12.94
O	%		<0.10	1.32	1.99	1.91	1.37
N	%		0.08	0.05	0.10	<0.05	<0.05

^aASTM limit for diesel is 1.9 - 6.0; ^bASTM limit for diesel is 338, max; ^cASTM limit for diesel is 40, min.

of the B20 blends exceed the ASTM D7467 limit.

Flash point is the lowest temperature at which a substance vaporizes to form an ignitable mixture in air; higher flash points are advantageous from a safety perspective. **Table 3** shows that ULSD has the lowest flash point (63°C), while B20 blends of animal fat, soybean oil, canola, and waste cooking oil have higher flash points (69°C, 68°C, 67°C, and 65°C, respectively).

ASTM protocol requires cloud point testing for biodiesel fuel, but there is not a specific limit. Below the cloud point temperature, wax solidifies in diesel and can

clog fuel filters and injectors in engines. Thus, a lower cloud point is preferable. **Table 3** shows that the biodiesel blends all had higher flash points than ULSD.

Fuels with high sulfur content produce higher sulfur dioxide emissions. To meet requirements for ultra-low sulfur diesel, a fuel's sulfur content must be ≤15 ppm. The sulfur content for all 4 B20 blends was less than 15 ppm, qualifying them as ultra-low sulfur diesel fuels.

Cetane number measures how easily a fuel ignites under compression; a higher cetane number means easier ignition and a shorter ignition delay time. Molecules with

longer chain lengths or higher degrees of saturation have higher cetane numbers. Molecules with higher degrees of saturation tend to have lower NO_x emissions for several reasons [3]:

- The shorter ignition delay time means less time for the reactants (fuel and oxygen) to preheat, which lowers flame temperature and lowers NO_x emissions according to the Zeldovich mechanism.
- Molecules with higher degrees of saturation have lower adiabatic flame temperatures, due to lack of high-energy double bonds; this produce less NO_x according to the Zeldovich mechanism.
- The double bonds of unsaturated molecules may cause higher levels of certain hydrocarbon radicals in the fuel-rich zone of the diesel spray, which increases formation of prompt NO_x .

Several researchers have thus found that the higher cetane number of biofuels leads to a decrease in NO_x emissions for B20 blends [4,15]. According to **Table 3**, vegetable oil biodiesel B20 (both soybean and canola) has the highest cetane number (55.7). WCO B20 and animal fat B20 have cetane numbers (49.3 and 48.3, respectively) lower than ULSD (51.6).

The oxygen content of biodiesel fuel is typically higher than that for regular petroleum diesel, leading to more complete combustion and lower emissions of CO , HC , and PM . **Table 3** shows that B20 from canola has the highest oxygen content (1.99%); other B20 blends of waste cooking oil, animal fat, and soybean oil have oxygen contents of 1.91, 1.37, and 1.32%, respectively, which are higher than for ULSD (<0.10%).

ULSD has higher carbon and hydrogen contents than the biodiesel blends. Higher carbon content may mean that ULSD will emit greater CO_2 emissions. ULSD has lower nitrogen content than the B20 blends. This is likely not significant in terms of NO_x emissions, since thermal NO_x emissions typically dominate for diesel fuel.

Other properties of the biodiesel fuel blends such as acid number, distillation temperature, ash content, water

and sediment, and copper corrosion do not exceed the ASTM standards. The only biodiesel property which did not meet ASTM standards was oxidation stability, for 3 of the 4 B20 blends. Only animal fat B20 met the ASTM standard.

3.2. On-Road Testing

Example emission traces for on-road measurement of NO_x and CO_2 are shown in **Figures 3** and **4**, respectively. Emission test results for the arterial route, highway route and idling testing are shown in **Tables 4-6**, respectively. **Tables 4** and **5** show averages of duplicate runs, with standard deviations in parentheses. Analysis of Variance (ANOVA) F-tests were conducted to determine whether emission means were statistically different; p-values for the tests are given in **Tables 4-6**. Details of the statistical analysis are provided in Pala-En (2012) [24]; results are summarized below.

To a 95% level of confidence, no difference was detected in mean NO_x emissions for the different fuel types for the arterial route, despite their differences in cetane numbers; similarly, no difference was detected in mean NO_x emissions for the different fuel types for the highway route or for idling. Similarly, to a 95% level of confidence, the 3 F-tests for arterial route, highway route, and for idling detected no difference in mean CO_2 emissions for the different fuel types.

To a 95% level of confidence, emissions from the arterial route were higher than those from the highway route for both NO_x and CO_2 ($p = 0.0011$) for all types of B20 and ULSD, by amounts ranging from 13% - 80%. This may be due to the engine operating more efficiently at highway speeds. The average speed of arterial route was about 25 mph, while the highway route average speed was about 55 mph. In addition, more accelerations typically occur on arterial routes; the acceleration mode has been shown to produce higher emissions than cruise mode [25].

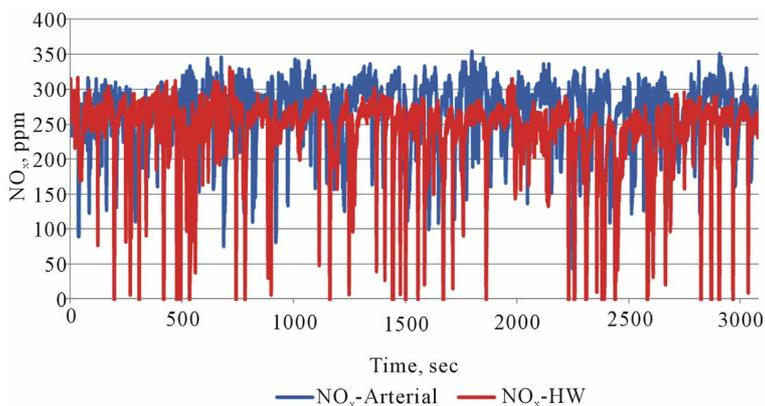


Figure 3. NO_x from on-road testing of soybean B20 for arterial and highway routes.

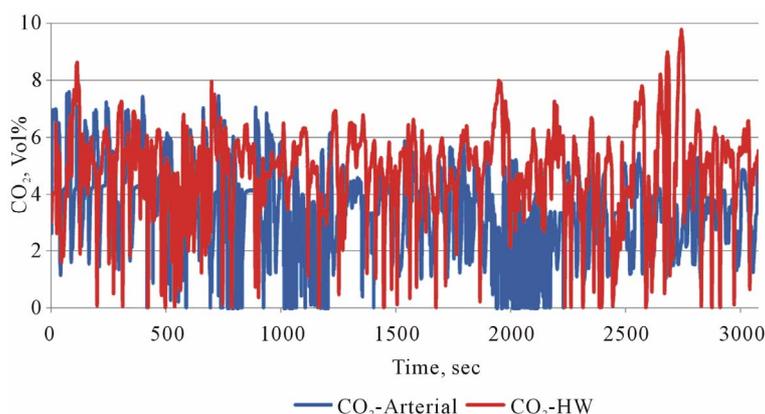


Figure 4. CO₂ from on-road testing of soybean B20 for arterial and highway routes.

Table 4. On-road testing results—arterial route.

Fuel Type	Average Emissions (g/mile)	
	CO ₂	NO _x
ULSD	46.61 (±6.02)	0.240 (±0.030)
Soybean B20	45.76 (±1.21)	0.248 (±0.020)
Canola B20	36.95 (±6.47)	0.233 (±0.014)
Waste Cooking Oil B20	41.90 (±5.46)	0.239 (±0.015)
Animal Fat B20	48.78 (±0.82)	0.227 (±0.002)
p-value	0.1674	0.7748
Conclusion	No difference among means	No difference among means

Table 5. On-road testing results—highway route.

Fuel Type	Average Emissions (g/mile)	
	CO ₂	NO _x
ULSD	35.74 (±0.14)	0.159 (±0.003)
Soybean B20	38.81 (±8.95)	0.138 (±0.040)
Canola B20	32.57 (±5.17)	0.153 (±0.005)
Waste Cooking Oil B20	36.39 (±2.73)	0.172 (±0.009)
Animal Fat B20	32.71 (±0.87)	0.161 (±0.001)
p-value	0.8503	0.6578
Conclusion	No difference among means	No difference among means

3.3. Dynamometer Testing

Example emission traces for NO_x and CO₂ for dynamometer testing are shown in **Figures 5** and **6**, respectively. **Table 7** (at end) shows average dynamometer emissions test results for 3 replications of each fuel. The magnitude of emissions from dynamometer testing is much greater than those from on-road testing. The test

Table 6. Idling test results.

Fuel Type	Average Emissions (g/sec)	
	CO ₂	NO _x
ULSD	0.125 (±0.036)	0.0008 (±0.00001)
Soybean B20	0.086 (±0.097)	0.0004 (±0.00040)
Canola B20	0.153 (±0.017)	0.0012 (±0.00001)
Waste Cooking Oil B20	0.094 (±0.048)	0.0006 (±0.00040)
Animal Fat B20	0.085 (±0.005)	0.0009 (±0.00006)
p-value	0.6429	0.1815
Conclusion	No difference among means	No difference among means

results are not directly comparable, because the vehicle load was different. For dynamometer testing, load was added to the vehicle to achieve 6000 lbs, to meet the minimum requirement of the laboratory equipment.

As for on-road testing, ANOVA tests were conducted to a 95% level of confidence to determine whether emission means were statistically different. Prior to conducting each ANOVA test, checks for constant variance and normal distribution of residuals were conducted; data transformations were executed when necessary. For each of the 5 pollutants (NO_x, CO₂, CO, HC, and PM), as well as fuel economy, the ANOVA test detected differences among mean emissions for the different fuel types; thus, pairwise comparisons of means were conducted for each pollutant and fuel economy using Dunnett's T test and Tukey's method, both to a 95% level of confidence. P-values of the tests are shown in **Table 7**. Details of the statistical analysis are provided in Pala-En (2012); results are summarized below.

Nitrogen Oxides. Both Dunnett's T-test and Tukey's method showed a statistically significant difference in NO_x emissions between soybean B20 and ULSD, but not between the other biodiesel blends and ULSD, or be-

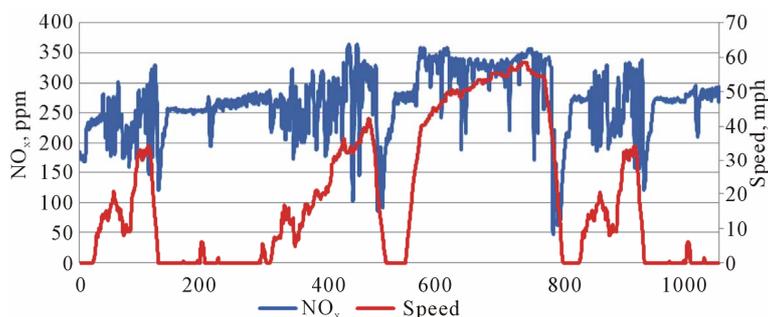


Figure 5. NO_x from UDDS driving cycle for canola B20.

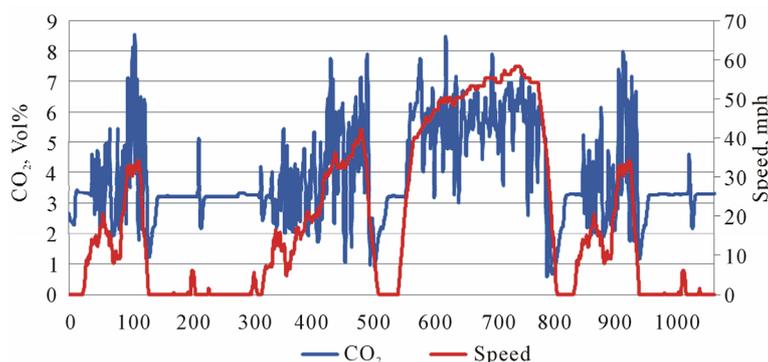


Figure 6. CO₂ from UDDS driving cycle for canola B20.

Table 7. Data from chassis dynamometer tests with urban dynamometer drive schedule.

Fuel Type	Average Emissions Results (g/mile)					Fuel Economy Direct Gravimetric (mile/gal)
	CO ₂	NO _x	CO	HC	PM	
ULSD	697.6 (±2.6)	4.44 (±0.02)	0.845 (±0.02)	0.135 (±0.01)	0.116 (±0.002)	14.00 (±0.06)
Soybean B20	702.2 (±1.9)	4.51 (±0.03)	0.792 (±0.03)	0.115 (±0.01)	0.111 (±0.002)	13.62 (±0.03)
Canola B20	696.0 (±2.9)	4.49 (±0.05)	0.736 (±0.01)	0.107 (±0.00)	0.106 (±0.000)	13.73 (±0.08)
Waste Cooking Oil B20	700.0 (±0.5)	4.49 (±0.02)	0.715 (±0.00)	0.102 (±0.00)	0.111 (±0.002)	13.69 (±0.04)
Animal Fat B20	697.0 (±1.2)	4.45 (±0.01)	0.770 (±0.01)	0.112 (±0.00)	0.110 (±0.002)	13.86 (±0.01)
p-value	0.0217	0.0329	<0.0001	<0.0001*	<0.0001*	<0.0001
Conclusion	CO ₂ emissions for different fuel types are not statistically significant	The only difference that was significant was that for soybean B20	CO emissions from ULSD were statistically different from all type of B20	HC emissions from ULSD were statistically higher than all types of B20	PM emissions from ULSD were statistically higher than all types of B20	Fuel economies from all B20 blends were significantly lower than those from petroleum diesel fuel

*indicates p-value for data after transformation.

tween the other biodiesel blends themselves. These results are surprising in light of the fact that soybean B20 had a higher cetane number than ULSD, and would have thus been expected to produce lower NO_x emissions. With the exception of the higher emissions for soybean B20, these results are consistent with our on-road testing results, which showed no statistically significant difference between NO_x emissions from ULSD and the B20 blends.

Carbon Dioxide. Dunnett's T-test showed that differences in CO₂ emissions between the B20 blends and ULSD were not statistically significant. Tukey's method showed that soybean B20 CO₂ emissions were significantly higher than those for canola B20.

Carbon Monoxide. Dunnett's T test showed CO emissions for all B20 blends to be significantly lower than those for ULSD. These results are surprising, given that only canola B20 had higher oxygen content than ULSD.

Since CO results from incomplete combustion, higher oxygen content typically lowers CO emissions by producing more complete combustion. Tukey's method showed that CO emissions from soybean B20 were significantly higher than canola and WCO B20, and CO emissions from animal fat B20 were significantly higher than WCO B20.

Hydrocarbons (HC). Dunnett's T test showed that HC emissions for all B20 blends are significantly lower than those for ULSD. Again, these results are surprising given the oxygen content results. Tukey's method showed that the HC emissions from soybean and AF B20 were statistically higher than WCO B20.

Particulate Matter. Dunnett's T test showed that PM emissions for all B20 blends are significantly lower than those for ULSD, which is surprising given the oxygen content results. Tukey's method showed that among the 4 types of B20, only PM emissions from canola B20 were significantly lower than those from the other 3 types.

Fuel Economy. Dunnett's T test and Tukey's method showed that fuel economies from all B20 blends were significantly lower than those from petroleum diesel fuel. This is consistent with the results from other studies, which show that fuel economy from biodiesel is typically a few percent lower than that from regular diesel, by amounts ranging from 1% to 2.7%. Among the B20 blends in terms of fuel economy, there were no statistically significant differences.

4. Conclusions

From the 1994 Chevy Silverado test, the following conclusions can be drawn:

- Emissions from the on-road arterial route were higher than those from the highway route at a 95% level of confidence for both CO₂ and NO_x for all types of B20 and ULSD.
- For CO₂, on-road testing (arterial, highway, and idling) and dynamometer testing showed no statistically significant difference in emissions among the B20 blends and ULSD, with the exception of the difference between soybean B20 and canola B20 for dynamometer testing.
- For NO_x, dynamometer testing showed only B20 from soybean oil to have statistically significant higher emissions. This was generally consistent with the on-road testing (arterial, highway, and idling), which showed no statistically significant difference in NO_x emissions between ULSD and the B20 blends.
- According to dynamometer test results:
 - CO emissions for all B20 blends were significantly lower than those for ULSD. CO emissions from soybean B20 were significantly higher than canola and WCO B20, and CO emissions from

animal fat B20 were significantly higher than WCO B20, to a 95% level of confidence.

- HC emissions for all B20 blends were significantly lower than those for ULSD. The HC emissions from soybean and animal fat B20 were statistically higher than WCO B20.
- PM emissions for all B20 blends are significantly lower than those for ULSD. PM emissions from canola B20 were significantly lower than for the other B20 blends.
- Fuel economies from all B20 blends were significantly lower than those from petroleum diesel fuel, to a 95% level of confidence. Among the B20 blends in terms of fuel economy, there were no statistically significant differences.

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REFERENCES

- [1] S. Fernando, H. Chris and S. Jha, "NO_x Reduction from Biodiesel Fuels," *Energy & Fuels*, Vol. 20, No. 1, 2006, pp. 376-382. [doi:10.1021/ef050202m](https://doi.org/10.1021/ef050202m)
- [2] US Department of Energy, Energy Information Administration, Forecast and Analysis of Energy Data, "International Energy Outlook 2008," Report DOE/EIA-0484, 2008. <http://www.eia.doe.gov/oiaf/ieo/oil.html>
- [3] G. A. Ban-Weiss, J. Y. Chen, B. A. Buchholz and R. W. Dibble, "A Numerical Investigation into the Anomalous Slight NO_x Increase When Burning Biodiesel; A New (Old) Theory," *Fuel Processing Technology*, Vol. 88, No. 7, 2007, pp. 659-667. [doi:10.1016/j.fuproc.2007.01.007](https://doi.org/10.1016/j.fuproc.2007.01.007)
- [4] R. L. McCormick, "NREL Final Report. SR-510-31465," 2003.
- [5] G. Karavalakis, S. Stournas and E. Bakeas, "Light Vehicle Regulated and Unregulated Emissions from Different Biodiesels," *Science of the Total Environment*, Vol. 407, No. 10, 2009, pp. 3338-3346. [doi:10.1016/j.scitotenv.2008.12.063](https://doi.org/10.1016/j.scitotenv.2008.12.063)
- [6] C. L. Peterson, J. S. Taberski, J. C. Thompson and C. L. Chase, "The Effect of Biodiesel Feedstock on Regulated Emissions in Chassis Dynamometer Tests of a Pickup Truck," *Transactions of the American Society of Agricultural Engineers*, Vol. 43, No. 6, 2000, pp. 1371-1381.
- [7] H. Aydina and C. İlkılıç, "Effect of Ethanol Blending with Biodiesel on Engine Performance and Exhaust Emissions in a CI Engine," *Applied Thermal Engineering*, Vol. 30, No. 10, 2010, pp. 1199-1204. [doi:10.1016/j.applthermaleng.2010.01.037](https://doi.org/10.1016/j.applthermaleng.2010.01.037)
- [8] G. Fontaras, G. Karavalakis, M. Kousoulidou, T. Tzam-

- kiozis, L. Ntziachristos, E. Bakeas, S. Stournas and Z. Samaras, "Effects of Biodiesel on Passenger Car Fuel Consumption, Regulated and Non-Regulated Pollutant Emissions over Legislated and Real-World Driving Cycles," *Fuel*, Vol. 88, No. 9, 2009, pp. 1608-1617. [doi:10.1016/j.fuel.2009.02.011](https://doi.org/10.1016/j.fuel.2009.02.011)
- [9] M. Gumus and S. Kasifoglu, "Performance and Emission Evaluation of a Compression Ignition Engine Using a Biodiesel (Apricot Seed Kernel Oil Methyl Ester) and Its Blends with Diesel Fuel," *Biomass and Bioenergy*, Vol. 34, No. 1, 2010, pp. 134-139. [doi:10.1016/j.biombioe.2009.10.010](https://doi.org/10.1016/j.biombioe.2009.10.010)
- [10] K. Ryu, "The Characteristics of Performance and Exhaust Emissions of a Diesel Engine Using a Biodiesel with Antioxidants," *Bioresource Technology*, Vol. 101, No. 1, 2010, pp. S78-S82. [doi:10.1016/j.biortech.2009.05.034](https://doi.org/10.1016/j.biortech.2009.05.034)
- [11] H. C. Frey and K. Kim, "Comparison of Real-World Fuel Use and Emissions for Dump Trucks Fueled with B20 Biodiesel versus Petroleum Diesel," *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1987, 2006, pp. 110-117. [doi:10.3141/1987-12](https://doi.org/10.3141/1987-12)
- [12] K. Ropkins, R. Quinn, J. Beebe, H. Li, B. Daham, J. Tate, M. Bell and A. Gordon, "Real-World Comparison of Probe Vehicle Emissions and Fuel Consumption Using Diesel and 5% Biodiesel (B5) Blend," *Science of the Total Environment*, Vol. 376, No. 1-3, 2007, pp. 267-284. [doi:10.1016/j.scitotenv.2006.11.021](https://doi.org/10.1016/j.scitotenv.2006.11.021)
- [13] H. C. Frey, W. J. Rasdorf, K. Kim, S. H. Pang and P. Lewis, "Comparison of Real-World Emissions of B20 Biodiesel versus Petroleum Diesel for Selected Nonroad Vehicles and Engine Tiers," *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2058, 2008, pp. 33-42. [doi:10.3141/2058-05](https://doi.org/10.3141/2058-05)
- [14] H. C. Frey and K. Kim, "In-Use Measurement of Activity, Fuel Use, and Emissions of Cement Mixer Trucks Operated on Petroleum Diesel and B20 Biodiesel," *Transportation Research—Part D*, Vol. 14, No. 8, 2009, pp. 585-592. [doi:10.1016/j.trd.2009.08.004](https://doi.org/10.1016/j.trd.2009.08.004)
- [15] M. E. Tat, "Investigation of Oxides of Nitrogen Emissions from Biodiesel Fueled Engines," Ph.D. Dissertation, Iowa State University, Ames, 2003.
- [16] C. D. Rakopoulous, K. A. Antonopoulos, D. C. Rakopoulos, D. T. Hountalas and E. G. Giakoumis, "Comparative Performance and Emissions Study of a Direct Injection Diesel Engine Using Blends of Diesel Fuel with Vegetable Oils or Bio-Diesels of Various Origins," *Energy Conservation and Management*, Vol. 47, No. 18-19, 2006, pp. 3272-3287. [doi:10.1016/j.enconman.2006.01.006](https://doi.org/10.1016/j.enconman.2006.01.006)
- [17] R. L. Muncrief, C. W. Rooks, M. Cruz and P. H. Michael, "Combining Biodiesel and Exhaust Gas Recirculation for Reduction in NO_x and Particulate Emissions," *Energy & Fuels*, Vol. 22, No. 2, 2008, pp. 1285-1296. [doi:10.1021/ef700465p](https://doi.org/10.1021/ef700465p)
- [18] G. Karavalakis, S. Stournas and E. Bakeas, "Effects of Diesel/Biodiesel Blends on Regulated and Unregulated Pollutants from a Passenger Vehicle Operated over the European and the Athens Driving Cycles," *Atmospheric Environment*, Vol. 43, No. 10, 2009, pp. 1745-1752. [doi:10.1016/j.atmosenv.2008.12.033](https://doi.org/10.1016/j.atmosenv.2008.12.033)
- [19] F. Wu, J. Wang, W. Chen and S. Shuai, "A Study on Emission Performance of a Diesel Engine Fueled with Five Typical Methyl Ester Biodiesels," *Atmospheric Environment*, Vol. 43, No. 7, 2009, pp. 1481-1485. [doi:10.1016/j.atmosenv.2008.12.007](https://doi.org/10.1016/j.atmosenv.2008.12.007)
- [20] M. Kousoulidou, G. Fontaras, L. Ntziachristos and Z. Samaras, "Biodiesel Blend Effects on Common-Rail Diesel Combustion and Emissions," *Fuel*, Vol. 89, No. 11, 2010, pp. 3442-3449. [doi:10.1016/j.fuel.2010.06.034](https://doi.org/10.1016/j.fuel.2010.06.034)
- [21] Y. Lin, Y. G. Wu and C. Chang, "Combustion Characteristics of Waste-Oil Produced Biodiesel/Diesel Fuel Blends," *Fuel*, Vol. 86, No. 12-13, 2007, pp. 2810-2816. [doi:10.1016/j.fuel.2007.01.012](https://doi.org/10.1016/j.fuel.2007.01.012)
- [22] Z. Utlu and M. S. Koçak, "The Effect of Biodiesel Fuel Obtained from Waste Frying Oil on Direct Injection Diesel Engine Performance and Exhaust Emissions," *Renewable Energy*, Vol. 33, No. 8, 2008, pp. 1936-1941. [doi:10.1016/j.renene.2007.10.006](https://doi.org/10.1016/j.renene.2007.10.006)
- [23] M. Kocak, E. Ileri and Z. Utlu, "Experimental Study of Emission Parameters of Biodiesel Fuel Obtained from Canola, Hazelnut and Waste Cooking Oils," *Energy and Fuels*, Vol. 21, No. 6, 2007, pp. 3622-3626. [doi:10.1021/ef0600558](https://doi.org/10.1021/ef0600558)
- [24] N. Pala En, "On-Road Measurement of NO_x and CO₂ Emissions from Biodiesel Produced from Different Feedstocks," Ph.D. Dissertation, University of Texas at Arlington, Arlington, 2012.
- [25] H. C. Frey, N. M. Roupail, A. Unal and J. D. Colyar, "Measurement of On-Road Tailpipe CO, NO_x and Hydrocarbon Emissions Using a Portable Instrument," *The Annual Meeting of the Air & Waste Management Association*, Orlando, 24-28 June 2001, pp. 1-20.