24 Month Demonstration Project Utilizing B20 in 2011 Ford F250 Super Duty Pickup Trucks

Donald A. Heck

Iowa Central Fuel Testing Laboratory

One Triton Circle, Fort Dodge, Iowa

Introduction

Biodiesel is a renewable fuel made from the transesterification of plant and/or animal triglycerides with methanol or other short-chain alcohols to form methyl or alkyl esters. Biodiesel used as a neat fuel or blended with petroleum diesel is a renewable source of energy that helps to reduce foreign oil consumption, reduce greenhouse gas emissions, and can help fleet users comply with several mandates for the use of renewable fuels. Lifecycle analysis indicates that biodiesel use produces a real reduction in petroleum usage and carbon dioxide emissions (Sheehan *et. al*, 1998), albeit at a slightly reduced fuel economy due to the lower energy content of biodiesel (Graboski and McCormick, 1998). Guidelines set forth by the Energy Independence and Security Act of 2007 illustrate the requirements for renewable fuels usage, with the 2013 volume requirements calling for the use of 1.28 billion gallons of biomass-based diesel nation-wide (Energy Independence and Security Act 2007, EPA-420-F-13-042). With these requirements in place, nearly every state has some requirement and/or incentive for the use of biofuels. Although many in the automotive industry welcome the use of renewable fuels, information documenting the success of using biofuels will increase confidence in using biofuels.

Several studies have documented the use of biodiesel under a variety of settings. Bickel and Strebig (2000) describe the use of B20 in a small fleet of 1997 Ford LT9000 road maintenance vehicles. The study was conducted for two years and found no differences in fuel economy or engine wear. Fraer (2005) describes the use of B20 in a small fleet of United States Postal Service cargo vans and tractor trailers. Overall engine wear and maintenance costs were reported to be similar; however, the B20 vehicles were noted to experience more fuel filter plugging, injector nozzle replacements, and added accumulation of engine sludge on top of the cylinder heads. Specific data on fuel economy was not recorded, but was not felt to be different between the B20 and diesel groups.

Several studies detail the use of 5% to 20% biodiesel in public transit busses (BIOBUS 2003; Proc *et. al*, 2006; Barnitt *et. al*, 2008). Fuel economy and overall maintenance costs for the units running biodiesel blends were reported to be similar to the diesel units in these studies. Notable differences attributed to the units running biodiesel blends included increased fuel filter plugging which, while not increasing overall maintenance costs, did produce disruptions in customer service. Also common with the use of biodiesel was a reduction in soot loading in the lube oil.

More recently, two studies have been conducted looking at the use of 20% biodiesel in Class-8 on-highway tractor trailers. McKinley and Lumkes (2009) conducted a 12-month evaluation comparing 10 tractor trailers running on B20 with 10 tractor trailers running on ULSD as controls. Fuel economy was reported to be similar for both groups. Specific maintenance and repair data were not collected for this study; however, it was noted that the B20 group experienced more fuel filter plugging than the ULSD group. Wear metals analysis revealed a 6-fold increase in the lead content in the B20 group; this increase was largely attributed to two B20 units. Because the control and B20 units had already been in service prior to the start of the study, it was not clear if the excessive lead contamination in these two units was due to normal engine wear or a pre-existing condition.

Heck *et. al* (2010) conducted a 26-month study comparing 10 tractor trailers running on B20 with 10 tractor trailers running on ULSD as controls. One significant advantage to this study was the fact that all units introduced into the study were delivered new from the manufacturer, thus eliminating the concern for pre-existing conditions in the units. The B20 group experienced a small (1.4%), but statistically significant decrease in fuel economy. Overall maintenance costs for the two groups were comparable; however, the B20 group experienced a 20% increase in fuel-related expenses, largely attributed to increased fuel filter replacements and slightly shortened maintenance intervals. No significant differences were noted in engine oil performance; a limited tear-down of some of the engines did not reveal any significant differences between the two groups.

This demonstration project provides quantitative information for the use of B20 in 2011 Ford F250 Super Duty pickup trucks. The study utilized three units, with two units running B20 (one soy-based and one tallow-based), and one unit running #2 ULSD as a control. The demonstration period ran 24 months from July 2011 through June 2013 and captured data from a combined 76,000 miles logged from all three units. Information was collected regarding fuel economy, fuel quality, engine and lube oil performance, and maintenance issues. All three units ran successfully for the duration of the demonstration period with no major differences in fuel economy or performance observed among the three units.

Vehicle and Driver Selection

The study consisted of a control unit running on 100% ULSD, and two B20 units, with one unit running on 20% soy biodiesel (Soy B20) and the other unit running with 20% tallow biodiesel (Tallow B20). All units were factory delivered 2011 Ford F250 Super Duty two-wheel drive extended cab pickups. Each unit was equipped with an automatic transmission and a 6.7 liter Power Stroke diesel engine designed to be compatible with up to 20% biodiesel. In addition, all units were configured with retail gas station pump testing equipment, adding approximately 1200 pounds of extra weight to each unit. Drivers for each unit were employed by the State of Iowa Department of Agriculture and Land Stewardship, Bureau of Weights and Measures. All three units ran routes within the state of Iowa, with the ULSD unit running primarily in the Mason City area (northern Iowa), the Tallow B20 unit running primarily in the Carroll area (central Iowa), and the Soy B20 unit running primarily in the Des Moines area (central and southern Iowa).

Vehicle Fueling

The decision to use 20% biodiesel blends with either soy- or tallow-based biodiesel was driven by several factors. Most original equipment manufacturers (OEMs) already accept the use of up to 5%

biodiesel blends in their equipment, and many have stated that blends up to 20% (or more in some cases) are acceptable (NBB 2006). Recognizing the increased usage of B20, the National Biodiesel Board and other groups formed the B20 Fleet Evaluation Team (B20 FET) to develop fact-based technical guidelines for B20 use (NBB 2005), and for 2008, ASTM introduced the new D7467 standard that provides guidance for fuel quality in biodiesel blends from 6% to 20%. More recently, Ford and General Motors introduced B20-compatible turbo diesel engines for their heavy duty trucks for the 2011 model year, and several other diesel engine manufacturers have approved the use of biodiesel in their equipment. Given that the Ford Power Stroke B20 engine was designed to be compatible with B20, we felt that this blend level would allow for meaningful comparison with ULSD without being too difficult to implement during the cold Midwestern winters.

Fueling for the ULSD unit occurred at a retail fuel station known to sell straight #2 ULSD with no biodiesel (B0). This station was supplied by the Magellan terminal in Clear Lake, Iowa. Fuel for the Soy B20 unit was supplied by a Des Moines-based distributor who made two, 500-gallon deliveries per year. The B20 blend was prepared with soy biodiesel provided by the Cargill, Iowa Falls production facility with #2 ULSD provided by the Magellan terminal in Des Moines. Blending was done by splash-blending when the fuel was loaded onto the delivery truck, and the finished product was delivered to a 500-gallon storage tank located along the Soy B20 route with convenient access for the driver. The Tallow B20 blend was prepared with tallow biodiesel provided by the Western Iowa Energy production facility in Wall Lake, Iowa with #2 ULSD provided by the Magellan/Growmark terminal in Fort Dodge, Iowa, with two deliveries per year. Blending was also done by splash-blending when the fuel was loaded onto the delivery truck, and the finished product was delivered to a 500-gallon storage tank located along the Tallow B20 route with convenient access for the driver. Both biodiesel units were fitted with an external 50-gallon tank so that the driver could re-fuel when out of range of the storage tank, if necessary, thus maintaining consistent use of the B20 blends.

Minor adjustments in fuel composition were made for winter driving. The ULSD unit continued to run straight #2 ULSD but with the addition of a cold flow improvement additive. For the fall/winter 500-gallon fuel deliveries, both biodiesel units used an altered ULSD mix with a final composition of 60% #2 ULSD, 20% #1 ULSD, and 20% biodiesel. In addition, double the amount of cold flow improvement additive was used.

Data Collection and Analysis

Data collection for the study began the first week of July 2011 and continued for 24 months through June 2013. Significant periods where data collection was not successful occurred in August/September for the ULSD unit (4 weeks), March 2012 for the Soy B20 unit (3 weeks), and July/August 2012 for the Tallow B20 unit (3 weeks). All data capture relied exclusively upon the data loggers and not on the individual driver's records. Real-time data was collected for each unit using a data logger from Control-Tec, LLC, Allen Park, MI. The data loggers were mounted on the driver's side rear floor with Verizon cellular modems mounted on top of the loggers. An external antenna was mounted to the roof of each unit for transmitting data by GPS satellite. To capture data, the data recorders were plugged into the vehicle's OBD-II port; data downloads were then submitted to Control-Tec upon turning off the vehicle's ignition and made available via Control-Tec's website. Channels collected for this study included (but were not limited to) speed, fuel consumption, ambient temperature, engine load, exhaust pressure, fuel pressure, and distance travelled. In addition, temperature sending units were installed in the fuel tanks of each unit for monitoring ambient fuel temperatures inside the fuel tank. This was performed by removing the bed of the truck so that the sending unit of the fuel tank could be accessed and thermocouples installed. Beginning the second week of September, 2011, data for DPF regeneration times and intervals were captured as well.

Both ULSD and B20 fuel samples were collected periodically for fuel analysis including biodiesel content, oxidation stability, water and sediment, total acid number, and cloud point. One sample from each of the B20 fuels was sent out for cetane testing. Used engine oil samples were collected for analysis including wear metals, soot, viscosity, total acid number, total base number and fuel dilution. Although fouled fuel filters were not an issue during the study period, one fuel filter from each unit was analyzed. Scheduled and unscheduled maintenance records were documented for comparison.

Fuel Economy

Successful data capture for the ULSD unit occurred for 34,212 miles out of approximately 69,800 miles driven by the end of the study period. Successful data capture for the soy B20 unit included 14,501 miles out of approximately 33,500 miles travelled, and included 28,076 miles out of approximately 51,800 miles travelled for the tallow B20 unit (Table 1a). The driving cycle for all three units included both in-town and highway driving; however, the degree of each type of driving could not be controlled for. Because a difference in drive cycles can significantly impact fuel economy measurements, only trips of greater than 10 Km were captured for analysis in order to minimize any bias in the drive cycles. The majority of trips captured were less than 100 Km in length; however, due to the intermittent nature of data transfer via cell towers, some of the individually recorded trips may in fact represent components of a single, longer trip. Fuel consumption was broken down for the baseline and test only periods as well (Tables 1b and 1c).

Table 1a. Record of miles captured and fuel consumption for entire study. Captured miles include all trips greater than 10 Km that were successfully recorded by the data loggers for the entire trip.

Fuel Consumption for Entire Study	ULSD	Soy	Tallow
Total Miles Captured	34,212	14,501	28,076
Gallons Consumed Excluding Idle Time	1784	733	1433
Gallons Consumed Including Idle Time	1837	765	1551

Table 1b. Record of miles captured and fuel consumption for baseline period only. Captured miles include all trips greater than 10 Km during the 9-week baseline period where all units ran straight #2 ULSD (B0).

Fuel Consumption for Baseline Period	ULSD	Soy	Tallow
Total Miles Captured	4028	1295	2567
Gallons Consumed Excluding Idle Time	205	64.6	128
Gallons Consumed Including Idle Time	209	68.0	135

Table 1c. Record of miles captured and fuel consumption for test period only. Captured miles include all trips greater than 10 Km during the entire trip excluding the 9-week baseline period.

Fuel Consumption for Test Only Period	ULSD	Soy	Tallow
Total Miles Captured	30,184	13,205	25,508
Gallons Consumed Excluding Idle Time	1579	668	1305
Gallons Consumed Including Idle Time	1628	697	1416

A comparison of fuel economy (both including and excluding idle time) was made for all 3 units. Idle time can be influenced by operator habits, hence the rationale for calculating fuel economy excluding idle time. Fuel economy was also determined with idle times included to assess how fuel economy was affected by operator habits. Drive time was defined as any movement greater than one meter per second. Other engine parameters (exhaust pressure, engine load, etc.) were calculated using data captured from actual driving time only. For statistical calculations, fuel economy was calculated on a weekly basis and then averaged for the appropriate period of the study (baseline period, test period or entire study).

Excluding idle time, average fuel economy for the ULSD unit for the entire study was 19.18 ± 1.02 mpg (Table 2a). Both B20 units exhibited slightly better fuel economy for the entire study with 19.79 ± 1.06 mpg (Soy B20 unit) and 19.59 ± 1.03 mpg (Tallow B20 unit); although fuel economy for all three units was lower during the test period when compared with the initial baseline period. Differences in fuel economy among all three units during the baseline period were not significantly different ($p > 0.15$ in all comparisons). Likewise, differences in fuel economy during the test portion of the study were not significant when using a two-tailed, student's *t*-test; however, the reduced fuel economy in the ULSD unit was significantly different from the B20 units when using a two-tailed, paired *t*-test ($p = 0.0001$ for comparison of ULSD and Soy B20, and $p = 0.0005$ for comparison of ULSD and Tallow B20).

When including idle time, fuel economy for the ULSD unit dropped to 18.63 for the entire study which represents a 2.8 % reduction in fuel economy (Table 2b). Fuel economy for the Soy B20 unit was reduced by 4.2 % (18.95 mpg) and for the Tallow B20 unit was reduced by 7.6 % (18.10 mpg). The Tallow B20 had the highest idle rate of all three units with an average of 9.34 hours of idle time for every 1000 miles travelled, and represents a three-fold increase in idle time when compared with the ULSD unit with only 3.05 hours idle time per 1000 miles travelled. As expected, longer idle times resulted in greater reductions in fuel economy.

Table 2a. Fuel economy excluding idle time. Data represent fuel economy for driving time only, for successfully captured data from trips greater than 10 Km.

Fuel Economy Excluding Idle Time	ULSD		Soy B20		Tallow B20	
	Economy (MPG)	*n*	Economy (MPG)	*n*	Economy (MPG)	*n*
Baseline Period	19.65 ± 0.42	8	20.04 ± 0.69	7	20.02 ± 1.72	6
Test Period	19.12 ± 1.04	86	19.77 ± 1.09	78	19.55 ± 0.96	85
Entire Study	19.18 ± 1.02	94	19.79 ± 1.06	85	19.59 ± 1.03	91

Table 2b. Fuel economy including idle time. Data represent fuel economy including idle time, for successfully captured data from trips greater than 10 Km. Idle time is expressed as the number of hours idle time per 1000 miles travelled.

Fuel Economy Including Idle Time	ULSD		Soy B20		Tallow B20	
	MPG	Idle (hr)	MPG	Idle (hr)	MPG	Idle (hr)
Baseline Period	19.31	1.39	19.06	7.99	19.01	6.49
Test Period	18.55	3.27	18.94	4.73	18.01	9.34
Entire Study	18.63	3.05	18.95	5.02	18.10	9.08

The effects of ambient temperature and study duration on fuel economy were analyzed. Fuel economy over the course of the study trended lower for the ULSD and Soy B20 units and remained the same for the Tallow B20 unit (Figure 1). Average weekly temperatures exhibited a seasonal pattern as expected (Figure 2); however, seasonal variations in fuel economy were not noted for any of the units as seen by the scatter of data points in Figure 1. Although seasonal variations in fuel economy were not evident, a correlation did exist between temperature and fuel economy for the Tallow B20 unit (see trend line, Figure 3).

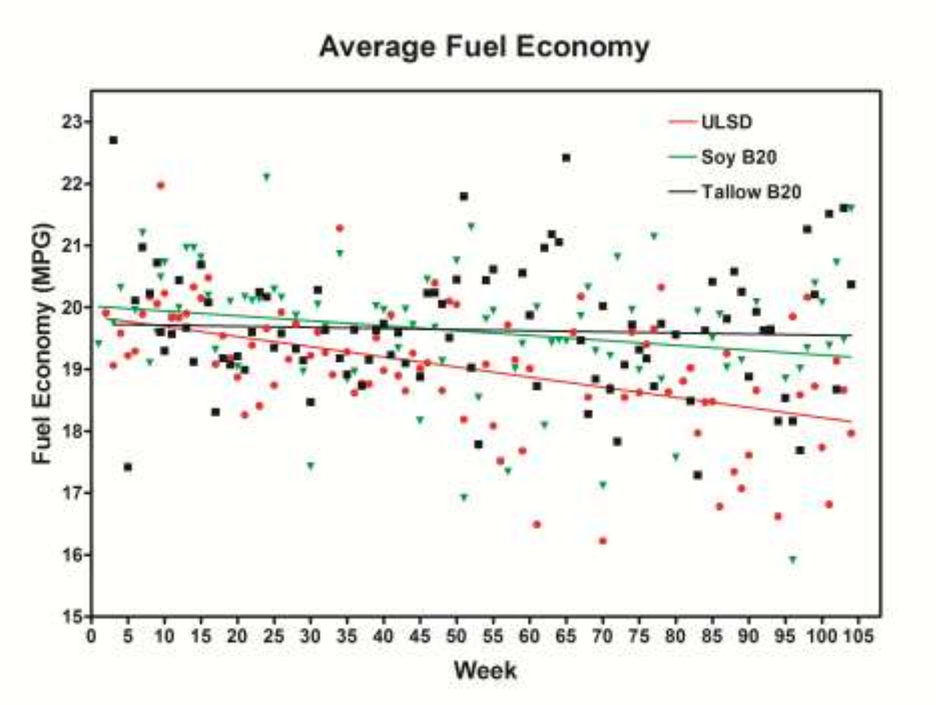

Figure 1. Average fuel economy by week. The average weekly fuel economy was determined for each unit. The study began the first week of July 2011, and is represented as Week 1. Trend lines were plotted for each unit for the entire study period and F tests were performed to determine the effects of fuel choice on fuel economy as the study progressed over time. The trend lines show a statistically significant decline in fuel economy for the ULSD and Soy B20 units as the study progressed (slope significantly different than zero, $p < 0.0001$ for ULSD and $p = 0.0374$ for Soy B20), but not for the Tallow B20 unit (slope not significantly different from zero, $p = 0.6164$).

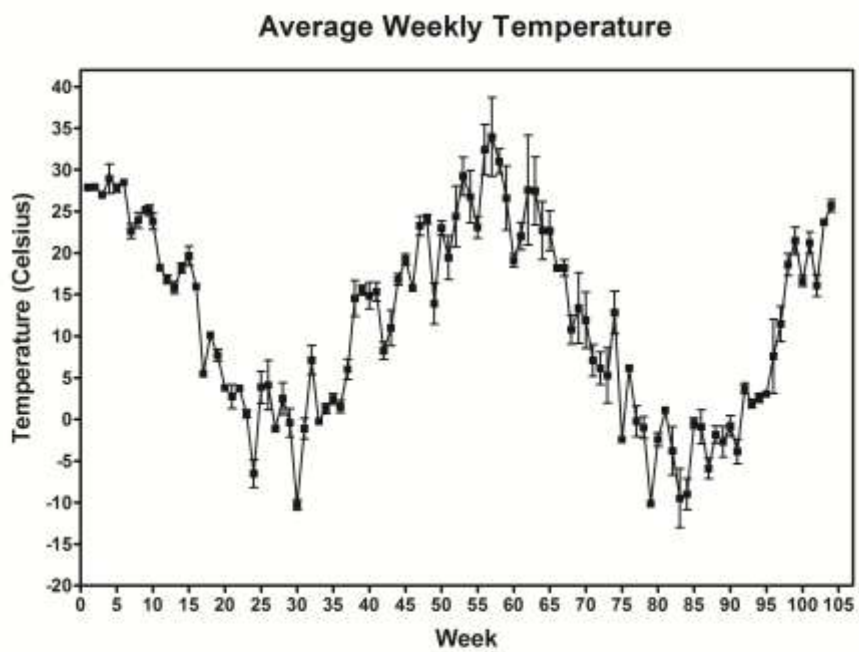

Figure 2. Average weekly ambient temperature. Data represent the combined average weekly ambient temperature recorded for all three units. The study began the first week of July 2011, and is represented as Week 1. Average ambient temperatures experienced by each unit for the entire study, in degrees Celsius, were 10.9 ± 10.6 for the ULSD unit (n = 94), 14.8 ± 11.6 for the Soy B20 unit (n = 85), and 11.0 ± 11.7 for the Tallow B20 unit (n = 91).

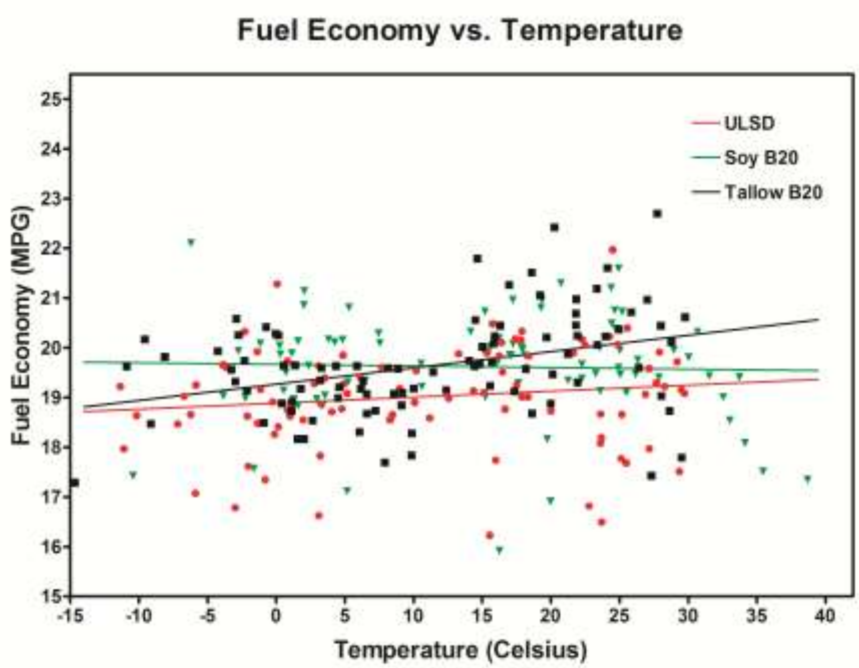

Figure 3. Effect of ambient temperature on average fuel economy. The weekly average fuel economy for each unit was plotted with the average ambient temperature for that week. Trend lines were

plotted for each unit and F tests were performed to determine the effects of temperature on fuel economy. The trend lines show a statistically significant increase in fuel economy for the Tallow B20 unit as the temperature increased (slope significantly different than zero, $p = 0.0006$), but not for the ULSD or Soy B20 units (slope not significantly different from zero, $p = 0.1787$ and 0.7517, respectively).

Fuel Quality

Fuel samples were routinely collected and analyzed for quality. A liter of fuel for the ULSD unit was obtained approximately twice per month from the retail fuel station for laboratory analysis. A liter of fuel from each of the 500-gallon B20 storage tanks was obtained for laboratory analysis from each fresh fuel delivery. Additionally, samples were taken periodically to confirm fuel stability over time. Tests performed included biodiesel content, oxidative stability, water and sediment, total acid number and cloud point. One sample each of the Soy B20 and Tallow B20 fuel mixtures were sent in for cetane analysis.

In general, no quality issues were observed with the fuel samples (Table 3). One ULSD sample failed the water and sediment test with a value of 0.100 % mass (ASTM D2709 limit is 0.05 mass %). This particular fuel sample contained visible water in the sample container; the source of extra water was not determined. Biodiesel content of fuel samples was within expectations for the ULSD and Soy B20 fuels, but averaged only 17% for the Tallow B20 fuel samples which was slightly below the expected value. One ULSD sample had a biodiesel content of 2.2 %. Cloud points were typical for diesel fuel and were slightly higher for the B20 blends as would be expected given the higher cloud point temperature for biodiesel.

Table 3. Fuel quality data. Tests were performed according to the following ASTM and EN methods: ASTM D7371 (biodiesel content), EN 15751 (oxidative stability), ASTM D2709 (water and sediment), ASTM D664 (total acid number), ASTM D2500 (cloud point), and ASTM D613 (cetane).

	ULSD		**Soy B20**		**Tallow B20**	
		n		*n*		*n*
Property						
Biodiesel Content (% vol)	0.12 ± 0.31	55	19.03 ± 0.71	12	17.03 ± 1.85	8
Oxidative Stability (hr)	*see note 1*	55	8.84 ± 3.86	12	7.42 ± 1.80	8
Water & Sediment (% mass)	*see note 2*	55	*see note 3*	12	*see note 4*	8
Total Acid No. (mg KOH/g)	0.01 ± 0.01	55	0.05 ± 0.01	12	0.05 ± 0.01	8
Cloud Point (°Celsius)	-14.4 ± 2.7	55	-11.9 ± 1.7	12	-12.0 ± 2.8	8
Cetane			45.1	1	47.8	1

1) 41 results were greater than 16 hours; 14 test results were between 10 and 16 hours.
2) 53 results were ≤ 0.005 % mass; one result was 0.020 % mass and one result was 0.100 % mass.
3) All results were ≤ 0.005 % mass.
4) 6 results were ≤ 0.005 % mass; one result was 0.008 % mass and one result was 0.010 % mass.

Engine data

Quarterly averages for engine load and exhaust pressure were recorded for each unit (Figures 4 and 5). Engine load is a measure of how hard the engine is working and the exhaust pressure (back pressure) is the resistance the engine needs to overcome in order to expel the waste gasses into the atmosphere. An increase in exhaust pressure will cause the engine to work harder (thus consuming more energy) in order to overcome this resistance (Jaaskelainen, 2007). Engine load for all three units showed seasonal variation with the load values being lowest in the winter months (roughly the third and seventh quarters of the study). Engine load for the Soy B20 unit was lower than the other two units, and this difference was statistically significant when using a paired *t*-test. Exhaust pressure showed mild seasonal variation for all three units. The ULSD unit had the highest average exhaust pressure while the Tallow B20 unit had the lowest average pressure; values for all three units were statistically different from each other. When comparing exhaust pressure as a function of engine load, exhaust pressure increased as engine load increased for all three units, as expected, but with no discernible differences in the distribution of data points among the three units (Figure 6).

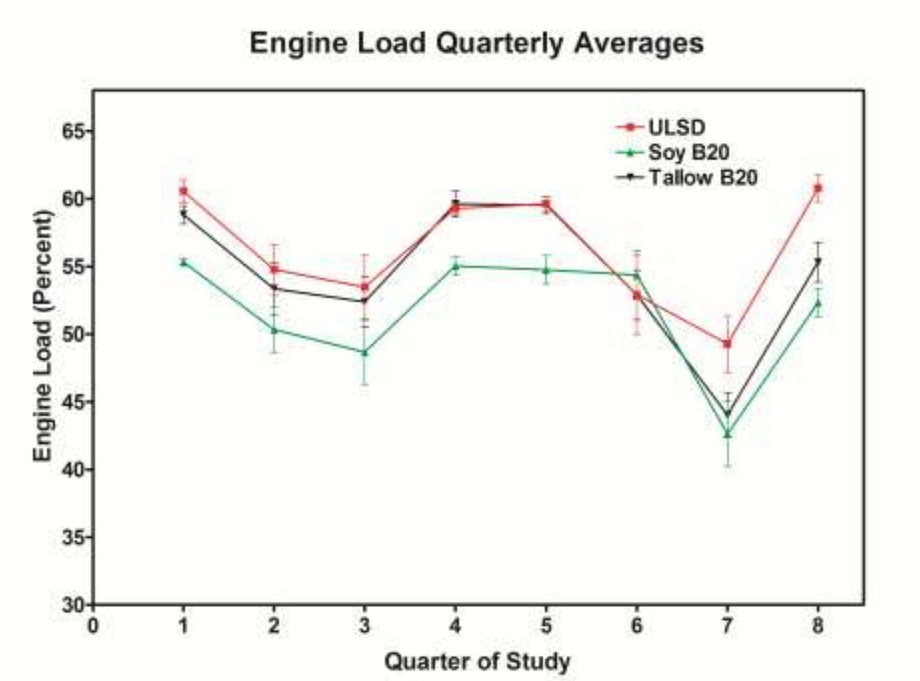

Figure 4. Average engine load by quarter. Quarterly averages for engine load were calculated and plotted for all three units. The first quarter corresponds with the months of July, August and September, 2011. Engine load for the Soy B20 unit was significantly lower than the other two units when using a paired *t*-test ($p < 0.01$ for both comparisons). Average engine loads for the entire study, in percent, were 56.2 ± 7.0 for the ULSD unit ($n = 94$), 52.2 ± 5.8 for the Soy B20 unit ($n = 85$), and 54.4 ± 6.8 for the Tallow B20 unit ($n = 91$).

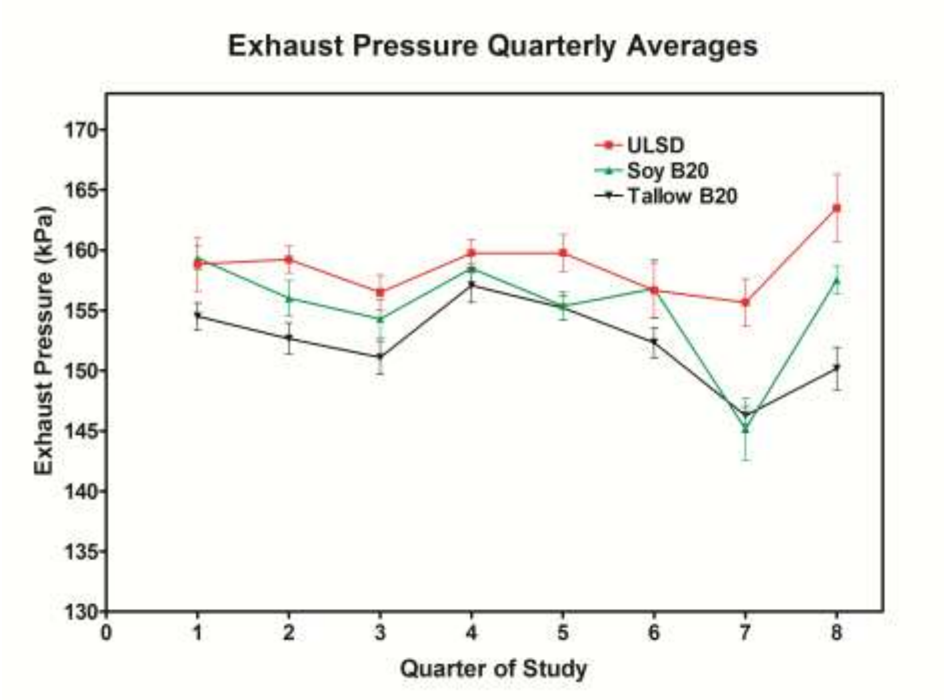

Figure 5. Average exhaust pressure by quarter. Quarterly averages for exhaust pressure were calculated and plotted for all three units. The first quarter corresponds with the months of July, August and September, 2011. Exhaust pressures for all three units were significantly different from each other when using a paired t-test ($p < 0.05$ for all comparisons). Average exhaust pressures for the entire study, in kPa, were 158.6 ± 6.0 for the ULSD unit ($n = 94$), 155.8 ± 5.6 for the Soy B20 unit ($n = 85$), and 152.0 ± 5.2 for the Tallow B20 unit ($n = 91$).

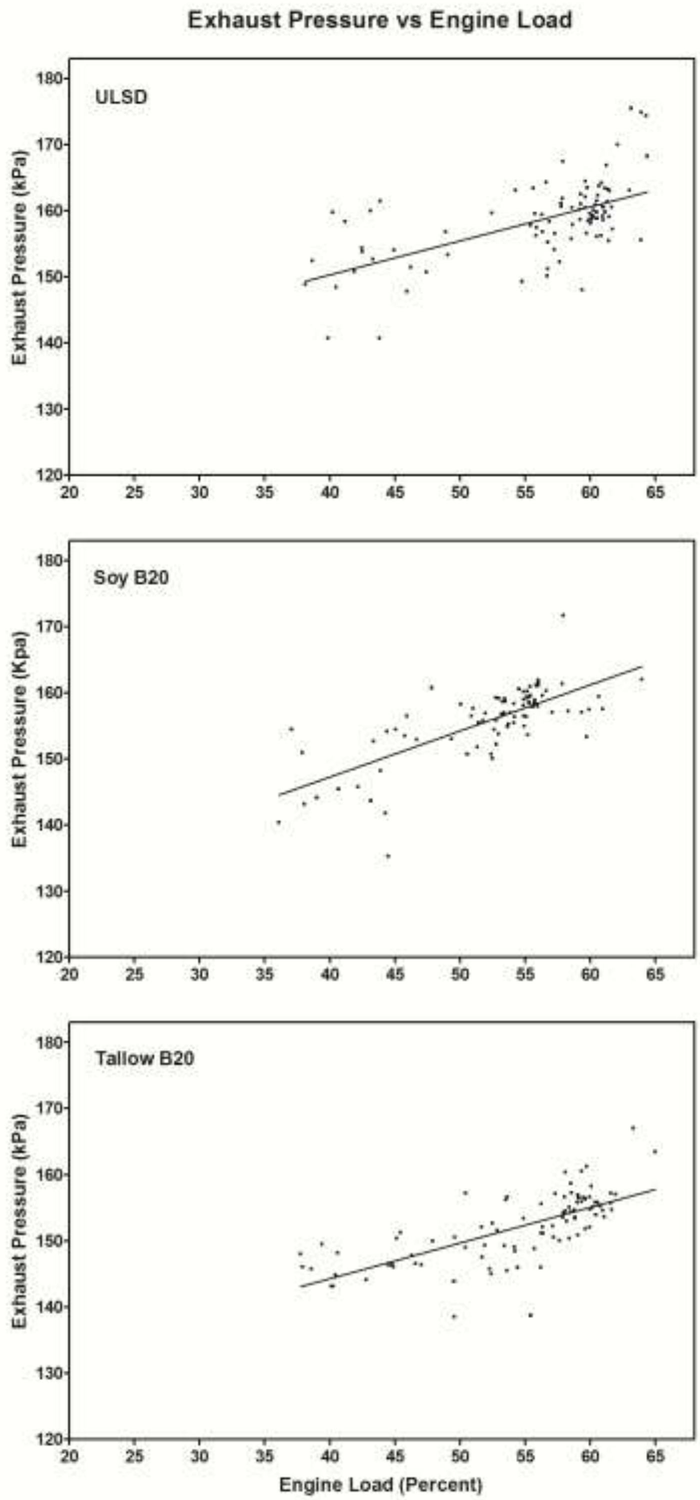

Figure 6. Effects of engine load on exhaust pressure. The weekly averages for exhaust pressure and engine load were calculated for each individual unit and plotted. Trend lines were calculated for each unit and F tests were performed to determine the effects of engine load on exhaust pressure. All three units exhibited a positive correlation with exhaust pressure and engine load (slope significantly different than zero, $p < 0.0001$ for all three units).

The effects of ambient temperature on engine load and exhaust pressure were analyzed (Figures 7 and 8). Both engine load and exhaust pressure increased as the ambient temperature increased. The increase in engine load was relatively sharp between -15 and 5 degrees Celsius for all three units but then leveled off somewhat for the ULSD and Soy B20 units, whereas the Tallow B20 unit continued to show an increase in engine load with temperature (Figure 7). The increase in exhaust pressure was less pronounced in all three units but showed a statistically significant and positive correlation with temperature (Figure 8).

The effects of engine load and exhaust pressure on fuel economy were analyzed. Engine load was not correlated with fuel economy (Figure 9); however, exhaust pressure showed a negative correlation with fuel economy for the ULSD unit alone (Figure 10).

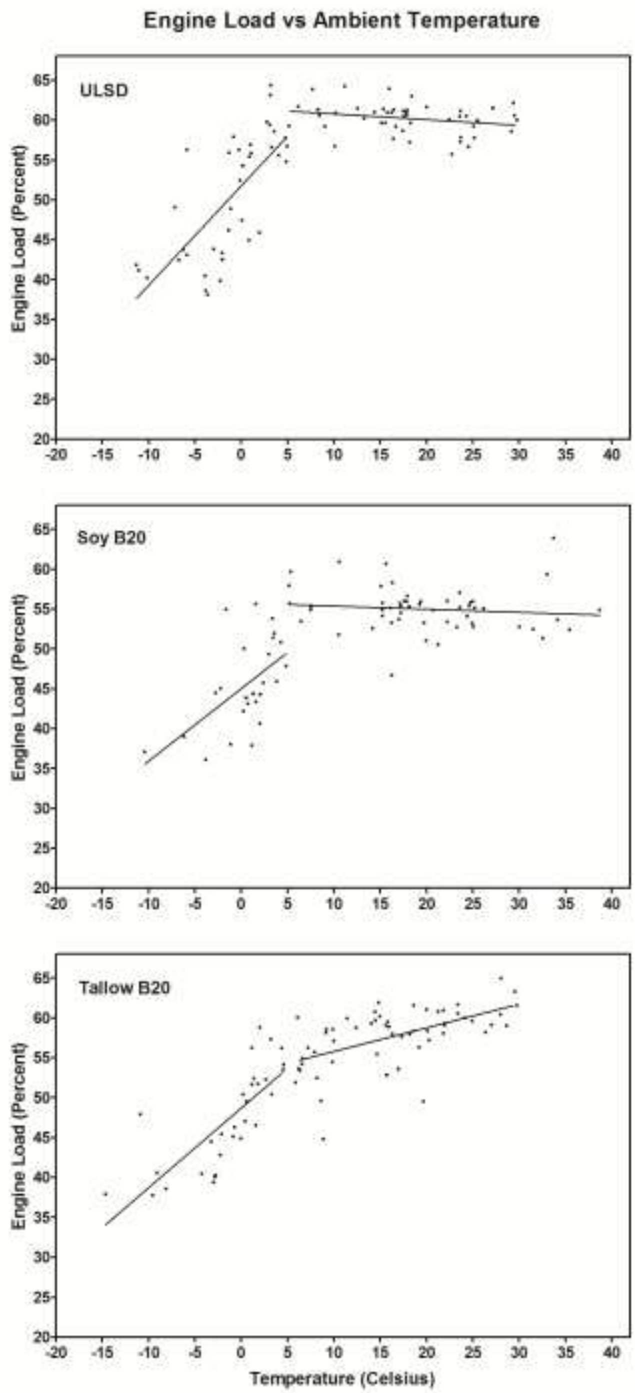

Figure 7. Effects of ambient temperature on engine load. The weekly averages for engine load and ambient temperature were calculated for each individual unit and plotted. Separate trend lines were calculated for each data set with one trend line corresponding to load values between -15 and 5 degrees Celsius and another trend line corresponding to load values for temperatures above 5 degrees Celsius. F tests were then performed to determine whether engine load was dependent on the ambient temperature. All three units exhibited a positive correlation with engine load and ambient temperature between -15 and 5 degrees Celsius (slope significantly different than zero, $p < 0.01$ for all comparisons). Only the Tallow B20 unit exhibited a positive correlation with ambient temperature above 5 degrees ($p < 0.0001$).

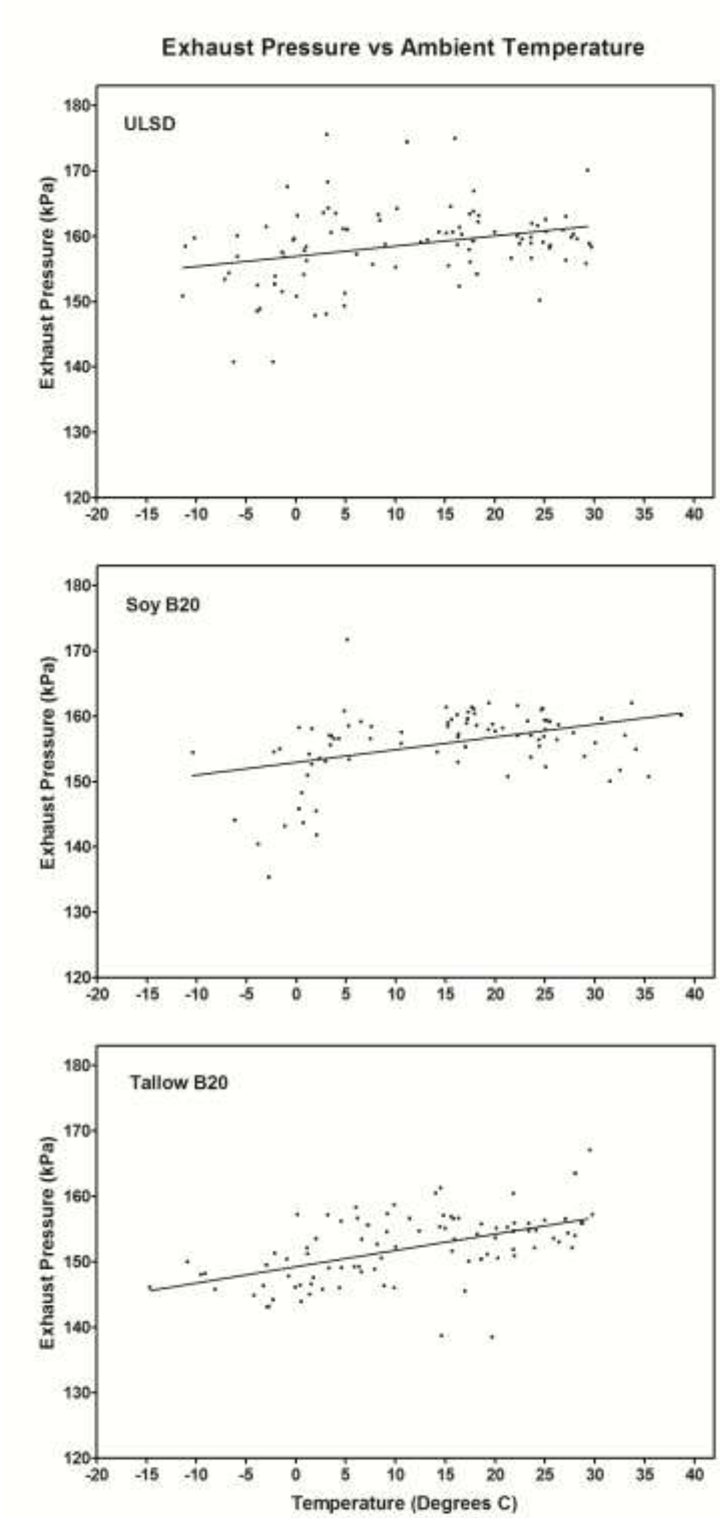

Figure 8. Effects of ambient temperature on exhaust pressure. The weekly averages for exhaust pressure and ambient temperature were calculated for each individual unit and plotted. Trend lines were calculated for each unit and F tests were performed to determine whether engine load was dependent on ambient temperature. All three units exhibited a positive correlation with exhaust pressure and temperature (slope significantly different than zero, $p < 0.01$ for all three units).

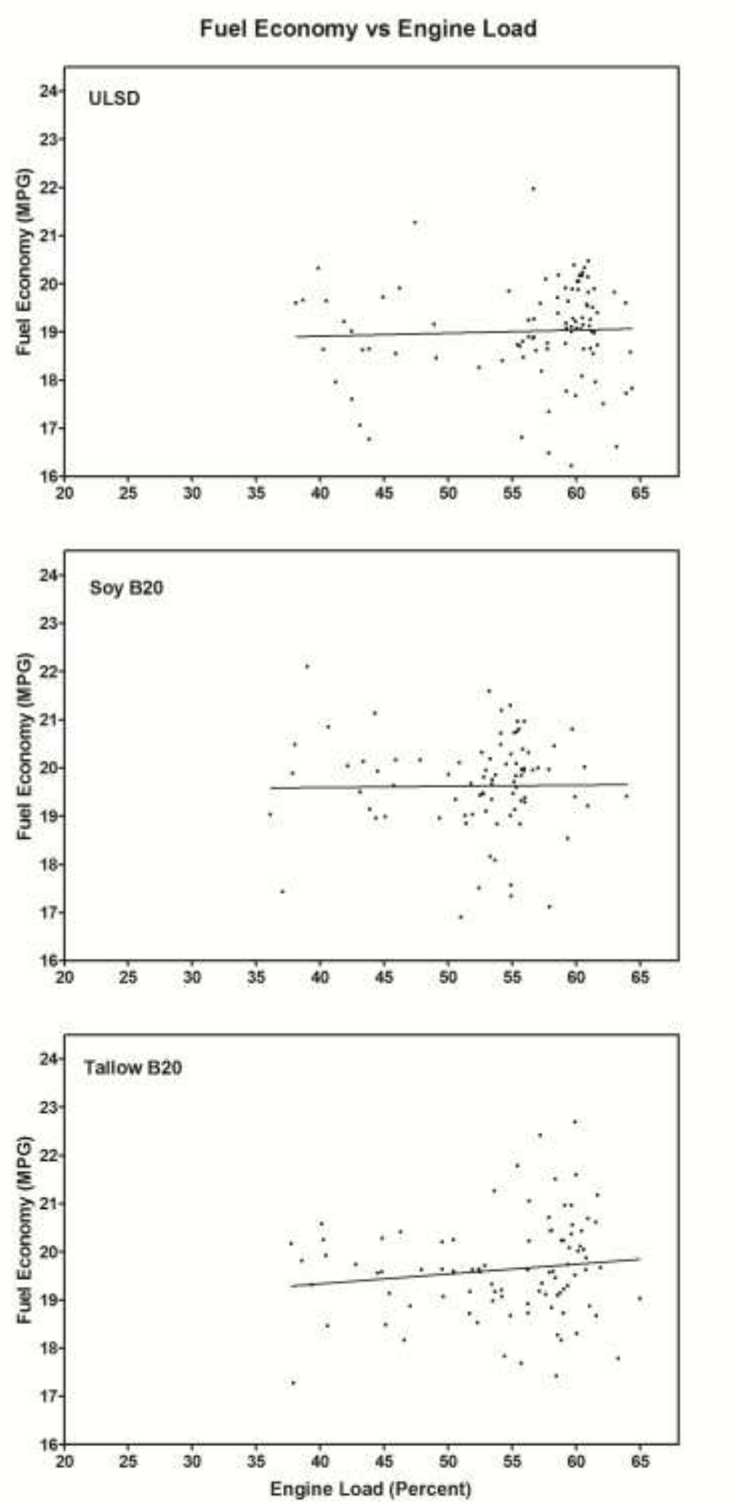

Figure 9. Effects of engine load on fuel economy. The weekly averages for fuel economy and engine load were calculated for each individual unit and plotted. Trend lines were calculated for each unit and F tests were performed to determine whether fuel economy was dependent on engine load. Fuel economy was not correlated with engine load for any of the units (slope not significantly different than zero; $p > 0.05$ for all three units).

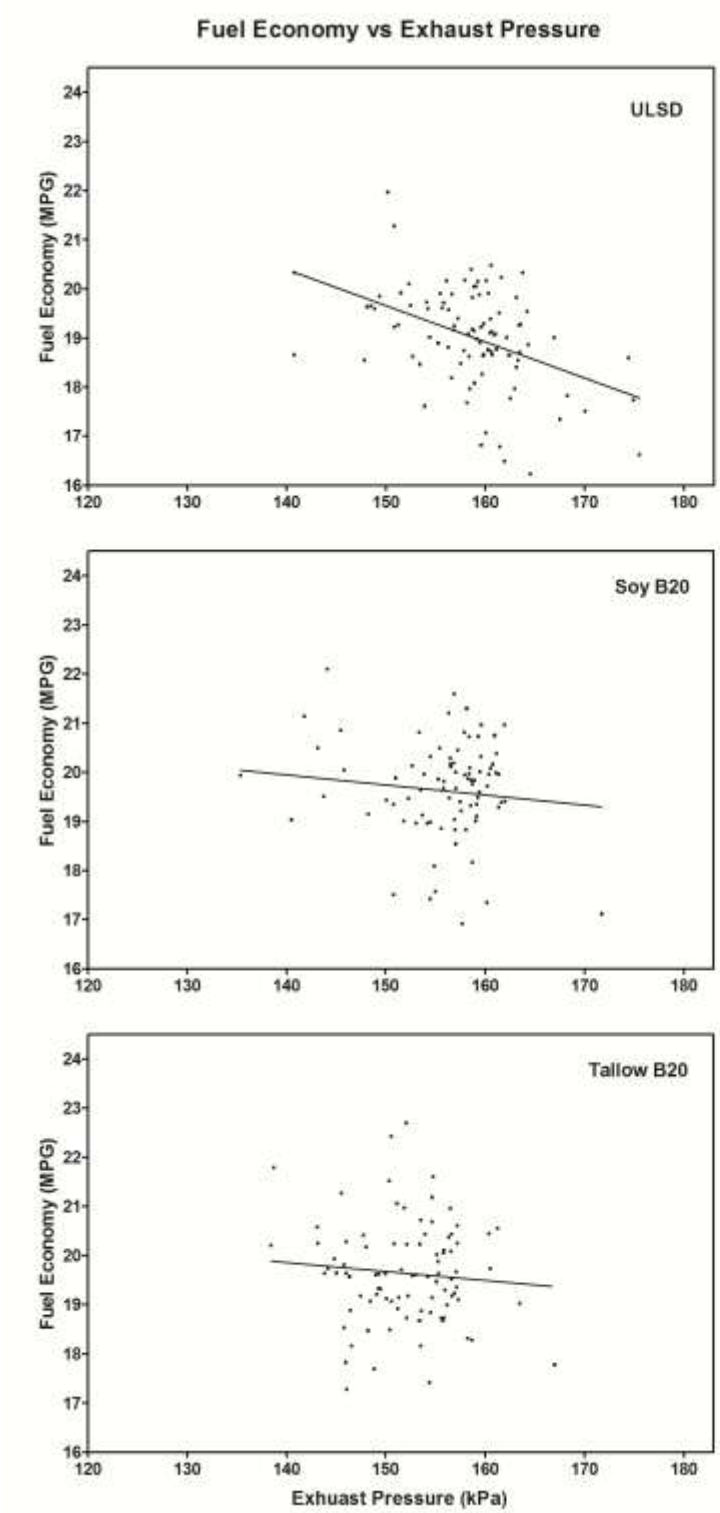

Figure 10. Effects of exhaust pressure on engine economy. The weekly averages for fuel economy and exhaust pressure were calculated for each individual unit and plotted. Trend lines were calculated for each unit and F tests were performed to determine whether fuel economy was dependent on exhaust pressure. Fuel economy for the ULSD unit exhibited a negative correlation with exhaust pressure (slope significantly different than zero, $p < 0.0001$).

All three units were equipped with a diesel particulate filter (DPF) which traps and removes particulate matter from the exhaust. As matter accumulates, exhaust back pressure will increase which will necessitate the removal of the excess matter through a regenerative process. Regeneration is a combustive process where diesel fuel is injected into the exhaust stream to burn off the accumulated matter (EPA-420-F-10-027). The average distance between DPF regenerations was calculated for each of the three units and compared on a quarterly basis (Figure 11). All three units showed seasonal variation, with the warmer months correlating with more frequent regeneration. The ULSD unit exhibited the shortest interval between regenerations overall, and this difference was statistically different than the other two units.

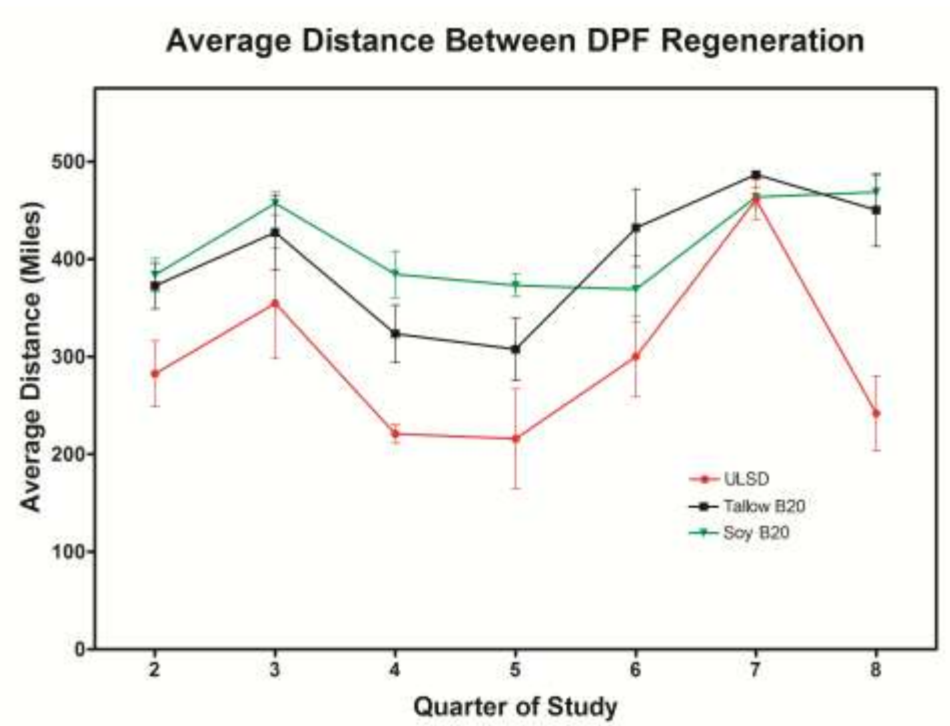

Figure 11. Average distance between DPF regenerations. Quarterly averages for DPF regeneration intervals were calculated and plotted for all three units. The second quarter corresponds with the months of October, November and December, 2011. The average DPF regeneration interval for the ULSD unit was significantly shorter than for the other two units when using a paired *t*-test ($p < 0.0001$ for both comparisons).

Maintenance Records and Lube Oil Performance

No fuel-related maintenance issues were recorded for any unit during the course of the study. The Tallow B20 unit reported tire wear issues in November 2011 but the remedy to this situation (if any) was not recorded. The ULSD unit had new tires installed in October 2012. The driver subsequently reported a loss in fuel economy, but this loss was not evident in the fuel economy data. In December 2011, the Soy B20 unit reported an error code indicating low reductant pressure in the selective catalytic reduction (SCR) system, the system responsible for neutralizing nitrogen oxides with urea-based diesel exhaust fluid. The remedy to this situation (if any) was not recorded. The Tallow B20 unit reported an error code indicating a loss in fuel filter pressure in March 2012. The source of the error was determined to be an improperly installed fuel filter from a recent oil change service.

All three units experienced several issues related to the data collection system. Data collection occurred through cellular phone tower transmissions and, given the rural nature of the driving cycles, provided intermittent data due to loss of signal. This was complicated by noise interference generated by the thermocouple devices place in the fuel tanks for monitoring ambient fuel temperatures. In September of 2011, noise-resistant thermocouple plugs were installed in an attempt to reduce this interference. Beginning in December 2011, the Tallow B20 unit began experiencing battery drain, especially after sitting for several days at a time. It was subsequently determined that with the colder weather, the loss in tire pressure was causing the tire pressure monitor to activate the data loggers, causing battery drain after repeated sleep-wake cycles with the data logger. Control-Tec was able to reconfigure the data loggers for all three units to prevent this cycle from occurring.

Engine oil samples and other materials were collected at each 7500 mile service interval for analysis of physical properties and metals content. Some difficulty was experienced collecting oil samples and a few samples were inadvertently thrown out. All units used Motorcraft SAE 5W30 full synthetic motor oil, with Motorcraft 15 micron full-flow oil filters. Fuel filters consisted of a Motorcraft fuel filter kit including a primary and secondary fuel filter. The primary fuel filter was a cartridge style filter located under the bed of the truck and also served as a water separator. The secondary fuel filter was a canister style filter located on top of the engine.

Engine oil analyses were performed on the collected oil samples. Several metals were not present in detectable quantities including nickel, tin, cadmium, vanadium, titanium, molybdenum, antimony, manganese, lithium and barium. The values reported in Table 4 represent the averages for metals that were quantifiable. Iron, chromium, aluminum, copper, lead and silver are indicators of engine wear and appear to trend higher in the Soy B20 unit, although this trend was not statistically significant. The contaminant metals silicon, sodium and potassium trended slightly higher in both of the B20 units, but again this trend was not statistically significant. Several metals are associated with the oil additive package including calcium and magnesium from detergents, and phosphorus and zinc from zinc dialkyldithiophosphate (zddp), an anti-wear agent. All units exhibited similar levels of these metals. All reported concentrations of metals were within expected ranges for normal operation.

Additional data on the physical properties of the engine oil samples are provided in Table 5. Significant soot levels or fuel dilution were not detected in any samples. Kinematic viscosity was similar for all three units and ranged from 11.9 to 12.2 centistokes, and compares with a reported value of 10.8 centistokes for fresh oil (Motorcraft spec sheet). The total acid number (TAN) values were similar for all three units; however, the total base number (TBN) values were lower in both of the B20 units. This difference was statistically significant for the Tallow B20 unit.

Additional materials collected for analysis at each oil change included fuel from the water-in-fuel (WIF) filter assembly, the WIF filter itself, and the fuel filter. Fuel from the WIF assemblies was analyzed by visual inspection. A total of 13 samples were collected and no visible water was found with any of the samples. No analyses were performed on the WIF filters themselves. None of the units experienced fuel filter plugging at any time during the study. Regardless, samples were taken from several fuel filters and analyzed by GC/MS (Figure 12). The chromatograms revealed the expected diesel hydrocarbons with additional biodiesel peaks in the Soy and Tallow B20 samples. No contaminants were detected.

Table 4. Metals profiles for used lubricating oil. Table includes data for metals present in detectable quantities. Oil sample testing was performed by Polaris Laboratories. Values represent the average of 6 replicates (ULSD), 4 replicates (Soy B20) or 5 replicates (Tallow B20).

	ULSD	**Soy B20**	**Tallow B20**
	Concentration (PPM)	Concentration (PPM)	Concentration (PPM)
Wear Metals			
Iron	36.0 ± 17.8	54.0 ± 13.0	37.0 ± 20.0
Chromium	1.3 ± 0.5	1.5 ± 0.6	1.0 ± 0.7
Aluminum	9.0 ± 2.1	12.8 ± 4.3	8.0 ± 3.9
Copper	7.5 ± 11.6	10.0 ± 11.6	7.6 ± 12.5
Lead	0.2 ± 0.4	0.5 ± 1.0	0.2 ± 0.4
Silver	3.0 ± 6.9	4.8 ± 8.2	3.8 ± 8.5
Contaminant Metals			
Silicon	5.8 ± 1.2	6.3 ± 1.3	6.8 ± 1.5
Sodium	5.2 ± 2.0	6.3 ± 2.9	6.6 ± 2.5
Potassium	3.2 ± 1.5	3.5 ± 1.7	3.8 ± 1.8
Additive Metals			
Boron	1.4 ± 1.7	1.0 ± 0.8	0.4 ± 0.5
Magnesium	8.7 ± 4.7	7.8 ± 1.5	6.8 ± 1.8
Calcium	1996 ± 109	1997 ± 28	1963 ± 58
Phosphorus	977 ± 52	986 ± 50	982 ± 56
Zinc	1116 ± 43	1122 ± 37	1116 ± 47

Table 5. Additional properties for used lubricating oil. Oil sample testing was performed by Polaris Laboratories. Values represent the average of 6 replicates (ULSD), 4 replicates (Soy B20) or 5 replicates (Tallow B20).

	ULSD	**Soy B20**	**Tallow B20**
Property			
Fuel dilution (% vol)	< 1.0	< 1.0	< 1.0
Soot (% vol)	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0
Viscosity (centistokes)	12.2 ± 1.0	12.0 ± 1.1	11.9 ± 0.9
Total Acid No. (mg KOH/g)	3.4 ± 0.4	3.7 ± 0.5	3.9 ± 0.7
Total Base No. (mg KOH/g)	6.0 ± 1.8	4.1 ± 0.4	3.8 ± 0.5

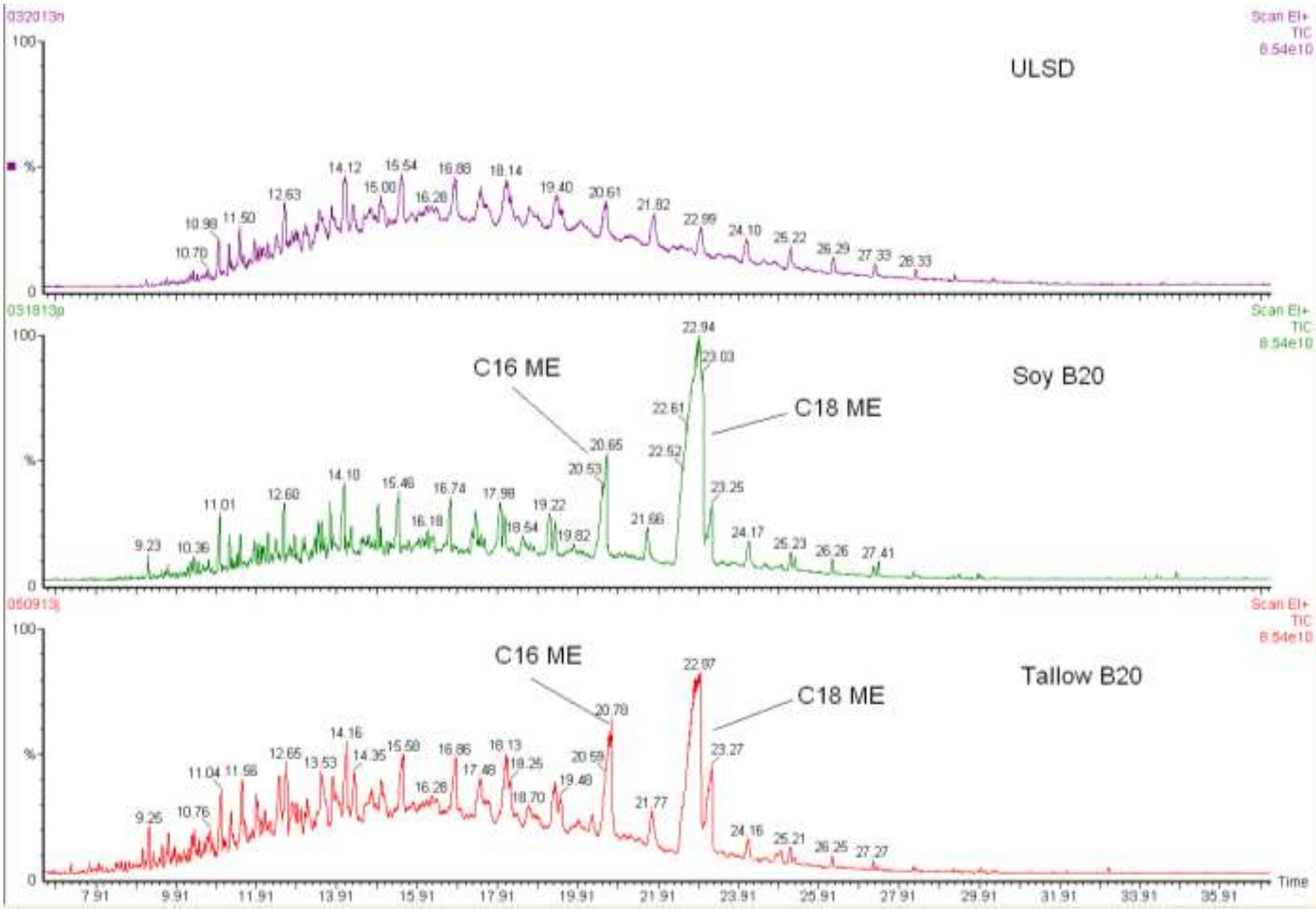

Figure 12. Analysis of fuel filter residue by GC/MS. Samples were derivatized using N-methyl-N-(trimethylsilyl)trifluoroacetamide (MSTFA) and run according to ASTM D 6584 with the oven program modified for the lower temperature limits of the column and mass spectrometer. The 16-carbon and 18-carbon biodiesel molecules are highlighted for the Soy B20 and Tallow B20 filters (C16 ME and C18 ME, respectively).

Summary and Conclusions

A comparison of ULSD with B20 revealed few differences regarding performance and operation. Biodiesel has an overall lower energy content of approximately 8% (Graboski and McCormick 1998) and one would therefore expect a slight loss in fuel economy for the B20 units. This may be a concern when managing fuel expenses for large fleets. Overall fuel economy was comparable among all three units; however, a paired *t*-test revealed that fuel economy for the ULSD unit was statistically different (and lower) than the B20 units. Because only a single ULSD unit was used for the demonstration, it is not possible to determine if this difference was the result of fuel choice or some other variable such as driver habits, driving cycle, or engine variation. As expected, inclusion of idle time reduced fuel economy for all three units, with the Tallow B20 unit experiencing the greatest drop. This difference (7.6 % drop in fuel economy) was greater than any difference in fuel economy among the three units and illustrates the significance of driver habits over fuel choice when concerned with fuel economy.

Several trends were noted regarding engine performance and fuel choice. For all three units, a decrease in ambient temperature correlated with a decrease in engine load. Given this relationship, one might expect that the unit experiencing the highest overall ambient temperature for the study would experience the highest overall engine load. This was not the case as the Soy B20 unit experienced the highest average ambient temperature but exhibited the lowest average engine load whereas the ULSD unit experienced the lowest ambient temperature but had the highest average engine load. Likewise for exhaust pressure, a decrease in ambient temperature correlated with a decrease in exhaust pressure. Again, one might expect that the unit experiencing the highest overall ambient temperature would experience the highest overall exhaust pressure. However, the ULSD exhibited the highest overall exhaust pressure while experiencing the lowest ambient temperatures. These trends suggest that ULSD fuel contributes to higher engine load and exhaust pressure. Given that fuel economy for the ULSD unit was negatively correlated with exhaust pressure, these trends may have contributed to the overall reduced fuel economy in the ULSD unit.

All three units were equipped with DPF filters that undergo active regeneration. The distance interval between regenerations showed seasonal variation, but the ULSD unit exhibited a significant reduction overall in the distance interval between regenerations. This can potentially contribute to reduced fuel economy in two ways. First, the active regeneration process requires the combustion of additional fuel, and second, the time required to regenerate is significantly greater for ULSD than it is for biodiesel blends because of the more reactive nature of biodiesel soot (Williams et. al, 2006). The shortened regeneration intervals, longer regeneration times, and overall increased engine load and exhaust pressure exhibited by the ULSD unit all demonstrate the potential to reduce fuel economy when using ULSD alone, and the advantages that these parameters provide when using biodiesel blends may help to offset the loss of energy content of biodiesel.

All three fuels performed satisfactorily with no fuel-related incidences recorded during the demonstration period, even during the harsh winter months. Engine oil data was comparable among all three units, and none of the units experienced any fuel-related maintenance issues. Fuel economy was comparable among all three units even though the ULSD unit exhibited a statistically significant reduction in economy when compared with the B20 units. Several factors may have contributed to the reduction in fuel economy, but with a single control unit in the demonstration, it is not possible to determine the extent that other factors such as operator habits or engine variability may have had on fuel economy. Overall, this study demonstrates that B20 performance is comparable to ULSD and is a viable alternative to using ULSD alone.

Acknowledgements

This material is based upon work supported by the Department of Energy, the State of Iowa, the Iowa Department of Agriculture and Land Stewardship, Ford Motor Company, Fort Dodge Ford and Iowa Central Community College, under the Department of Energy Award Number DE-FC26-08NT01928.

Dislaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

References

Barnitt, R., R. L. McCormick, and M. Lammert. 2008. St. Louis Metro Biodiesel (B20) Transit Bus Evaluation, 12-Month Final Report. National Renewable Energy Laboratory Technical Report, NREL/TP-540-43486.

Bickel, K. and K. Strebig. 2000. Soy-based diesel fuel study. Final report to the Legislative Commission on Minnesota Resources and Minnesota Soygrowers Association.

BIOBUS: Biodiesel Demonstration and Assessment with the Societe de transport de Montreal (STM), Final Report. 2003. http://www.stcum.qc.ca/English/info/a-biobus-final.pdf

Energy Independence and Security Act of 2007 (Public Law 110-140, H.R. 6). 2007. Washington, D.C., U.S. National Archives. http://purl.access.gpo.gov/GPO/LPS94451

EPA-420-F-10-027. United States Environmental Protection Agency, Office of Transportation and Air Quality. May 2010. http://www.epa.gov/cleandiesel/documents/420f10027.pdf

EPA-420-F-13-042. United States Environmental Protection Agency, Office of Transportation and Air Quality. August 2013. http://www.epa.gov/otaq/fuels/renewablefuels/documents/420f13042.pdf

Fraer, R., H. Dinh, K. Proc, R. L. McCormick, K. Chandler, and B. Buschol. 2005. Operating experience and teardown analysis for engines operated on biodiesel blends (B20). SAE Tech. Paper No. 2005-01-3641. Warrendale, PA.

Graboski, M. S. and R. L. McCormick. 1998. Combustion of fat and vegetable oil derived fuels in diesel engines. *Prog. Energy Combust. Sci.* 24(2): 125-164.

Heck, D. A., Mohammad, A. and Abi-Akar, H. A 2,000,000 Mile Evaluation of the Performance and Operational Impacts of B20 Biodiesel Usage in a Long-Haul Trucking Company. Iowa Central Community College, January 2010. http://www.iowafuellab.com/resources.asp

Jaaskelainen, H. Engine Exhaust Back Pressure. DieselNet Technology Guide. www.DieselNet.com.

McKinley, C. R. and Lumkes, J. H. Jr. 2009. Quantitative evaluation of an on-highway trucking fleet to compare #2 ULSD and B20 fuels and their impact on overall fleet performance. *Applied Eng. In Agric*. 25(3): 335-346.

Motorcraft Spec Sheet. https://www.fcsdchemicalsandlubricants.com/main/additionalinfo/Product%20Data%20Sheet%205W30%20Premium%20Synthetic.pdf

NBB. 2005. Technical recommendations for B20 fleet use based on existing data. Jefferson City, MO.: National Biodiesel Board.

NBB. 2006. OEM Warranty statements and use of biodiesel blends over 5% (B5). Jefferson City, MO.: National Biodiesel Board.

Proc, K., R. Barnitt, R. R. Hayes, M. Ratcliff, R. L. McCormick, L. Ha, and H. Fang. 2006. 100,000-mile evaluation of transit buses operated on biodiesel blends (B20). SAE Tech. Paper No. 2006-01-3253. Warrendale, PA.

Sheehan, J., V. Camobreco, J. Duffield, M. Graboski, and H. Shapouri. 1998. An overview of biodiesel and petroleum diesel life cycles. National Renewable Energy Laboratory Technical Report, NREL/TP-580-24772.

Williams, A., McCormick, R. L., Hayes, R. R., Ireland, J., and Fang, H. L. Effect of Biodiesel Blends on Diesel Particulate Filter Performance. Presented at the Powertrain and Fluid Systems Conference and Exhibition, October 2006, Toronto, Canada.

Version 10/31/13