Continued Shipboard Testing of B20

Final Report

Richard D. Ricketts — Research Associate/Marine Superintendent
Large Lakes Observatory
University of Minnesota Duluth

December 18th, 2009

University of Minnesota Duluth
Large Lakes Observatory
109 Research Laboratory Building
2205 E. 5th Street
Duluth, MN 55812

Research funded in part by the Great Lakes Maritime Research Institute.
This study was supported by the U.S. Maritime Administration
Grant # DTMA1-G-06-005

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Executive Summary

In 2008, the University of Minnesota Duluth research vessel Blue Heron took part in a study of the use of biodiesel in a marine setting. The study, initiated by Dr. Dan Pope of UMD's Department of Mechanical and Industrial Engineering, compared fuel consumption, atmospheric emissions, ship operations and maintenance issues when using 100% conventional diesel versus B20, a fuel mixture consisting of 80% conventional diesel and 20% biodiesel. During 2009 we continued to test the use of B20 on board the Blue Heron in order to see if the trends in fuel consumption and emissions persisted and to determine if any operational or maintenance issues appeared after extended use of biodiesel.

The Blue Heron is the largest University owned research vessel on the Great Lakes. The vessel is owned by the University of Minnesota and operated by the Large Lakes Observatory at UMD. During the 2009 cruise season the ship was on the water for sixty-nine days working mostly with scientists specializing in the physical sciences such as biology, chemistry, geology and physics. The ship also has several educational cruises each year and has worked with scientists from other fields, such as engineering (this project) and physiology (motion-sickness studies).

The vessel is an 86' former Grand Banks fishing trawler purchased by the University in 1997 after it was made available as a result of the U.S. federal government fisheries buyback program. The ship is outfitted with three diesel powered systems: the main engine, a Caterpillar 3508TA 750HP, and two generator sets (a Caterpillar 3304 65KW and a Caterpillar C4.4 76KW). For the 2008 and 2009 projects a data acquisition system, fuel logging systems, and flue gas analyzer were installed in the engine room and bosun's locker. This equipment measured and recorded fuel consumption, engine RPM, exhaust temperature, exhaust pressure and emissions of CO, NO_X, CO_2, and O_2. In addition, fuel logs were kept which noted time and amount of refueling as well as engine hours of service for fuel filters and when the filters were replaced.

During 2009 the Blue Heron refueled with B20 seven times between January and September. Each refueling consisted of between approximately 1,500 and 2,500 gallons of biodiesel. Our refueling process has not been simplified since the 2008 season and still consists of the fuel being mixed at the refinery in a large tanker truck, transferred to a smaller tanker truck for ease of access to the Blue Heron at the pier and then a final transfer to the Blue Heron. This process has the potential of introducing contaminants into the fuel.

As Pope noted in his 2008 report, the USEPA has collected results from the literature on dynamometer tests conducted with on road diesel engines using B20. These laboratory tests indicate that using B20 in on road diesel engines decreases the emissions of unburned hydrocarbons (HC), particulate matter (PM), and carbon monoxide (CO) while increasing the emission of oxides of nitrogen (NO_X) compared to the use of standard diesel. In addition, the USEPA study indicates no change in emission of carbon dioxide (CO_2) and predicts a slight drop in fuel economy. As Pope noted, it is difficult to compare the dynamometer analyses to field analyses. Engine load, approximated in this report by engine speed (revolutions-per-minute or RPM), will vary due to external variables such as sea state, water currents and wind speed. We make no attempt to control for these variables in this report. Data are average over periods of constant engine speed which vary from ten minutes to several hours.

Data were collected from mid-May to mid-September 2009. Fuel filter life-spans were noted for the entire period. Engine speed and fuel consumption data were collected from mid-June to mid-September. Exhaust temperature data were collected throughout August to mid-September while emissions data (NO_X, CO_2, CO, and oxygen O_2) were collected intermittently (due to equipment failure) throughout August to mid-September. The data for fuel consumption, exhaust temperature and emissions were analyzed as a function of engine speed (RPM). Engine speeds vary from low (RPM in the 400s) while on station and not moving, to medium speeds (RPM in the 500s to 900s) while doing survey work, to high speeds (RPM in the 1200s to 1400s) during transits.

When comparing the 2009 data to data collected in 2008 we note:

- During 2008, B20 and standard diesel exhibit similar fuel consumption rates. The drop in fuel economy predicted by the USEPA analysis is small enough that its existence may be hidden by the noise in the data. The 2009 B20 interestingly enough indicates generally lower fuel consumption at low to medium engine speeds when compared to the 2008 B20 data and fuel consumption rates similar to the 2008 B20 data at high engine speeds.
- Some of the B20 2008 and 2009 data indicate higher fuel consumption rates than standard diesel at high engine speeds. Clogging in the fuel filters while using B20 may cause higher readings from the fuel logging system.
- NO_X, CO_2, CO, and O_2 emissions were similar between the B20 and standard diesel and between the B20 data collected in 2008 and 2009.
- NO_X values for B20 in 2009 at medium engine speeds (600 to 800 RPM) were slightly higher than the NO_X values for B20 in 2008 or the standard diesel. These data were collected while the ship was undertaking mid-water trawling for a fisheries stock assessment study. This type of work may place an extra load on the main engine.
- CO_2 values for the B20 data from 2009 is slightly lower than the data collected in 2008, possibly indicative of the lower fuel consumption.
- As Pope noted in his 2008 report unburned hydrocarbons (HC) were too low for our equipment to measure during the constant engine speed conditions we have outlined here. The CO concentrations are also low and therefore difficult for the emissions probe to accurately measure. The emissions probe’s lack of accuracy at such low CO concentrations probably contributes to the high level of scatter seen in the CO data.

In addition to fuel consumption and emissions, we also looked at operational and maintenance issues associated with the continued use of B20. We still note no material incompatibility issues (e.g. weeping or failing hosing, o-rings, etc.) since initiating the use of B20 on July 21st 2008. Biodiesel gels at a higher temperature than diesel. We did not have any operational issues in the spring of 2009 after the fuel was stored for six months over winter in our fuel tanks. Fuel filter usage is still high. Pope noted a significant decrease in operational lifetime of the primary fuel filter when using B20 during the 2008 season. This decreased primary fuel filter lifespan continued during 2009. We suspect that prefiltering the fuel before use will limit this problem and are planning on putting in place a prefiltering program before the 2010 season.

1. Introduction

The current project is a continuation of a project initiated in 2008 to test the use of biodiesel in a maritime setting. There are few published reports of the use of biodiesel in marine settings, although the USEPA has compiled data regarding the impact of biodiesel use in heavy-duty highway engines [1]. These data indicate that there is an over 65% drop in unburned hydrocarbon emissions, an over 45% drop in particulate matter and carbon monoxide emissions and a 10% increase in oxides of nitrogen emissions when comparing conventional diesel to 100% biodiesel. A 20% biodiesel/80% conventional diesel blend does not have the material compatibility issues seen with higher biodiesel blends [2] but does garner changes in emissions as seen with higher biodiesel blends and pure biodiesel. Using a 20% biodiesel blend drops unburned hydrocarbon emissions by 20% and particulate matter and carbon monoxide emissions by 10% while oxides of nitrogen emissions increase by 2% when compared to conventional diesel use. In addition, the USEPA study indicates no change in emission of carbon dioxide (CO_2) and predicts a slight drop in fuel economy [1].

Understanding the impact of the use of biodiesel on ships will have immediate benefits. On May 12th, 2008, the governor of Minnesota signed into law SF3683 [3]. Section 51 of the law mandated that diesel sold in the state of Minnesota had to have an increasing percentage of biodiesel. Since 2005 diesel sold in Minnesota has had to be 2% biodiesel (B2) of agricultural origin. The new statute mandated a 5% biodiesel blend (B5) by May 2009, 10% biodiesel blend (B10) by May 2012, and 20% biodiesel blend (B20) by May 2015. After May 2012 the higher biodiesel blends (B10 in 2012 and B20 in 2015) will only be required during summer months (April to October) unless the Minnesota commissioners of agriculture, commerce, and pollution control determine that technical issues associated with using biodiesel in cold weather have been addressed. The legislation does include options for delaying the mandate if there are insufficient supplies of biodiesel or insufficient facilities for blending but it would appear that at sometime in the near future diesel sold in the state of Minnesota will be B20 biodiesel. Similar measures have been taken up by the Wisconsin legislature [4]. In addition, new USEPA regulations may limit emissions from marine engines and mandate the use of low sulfur fuel in the Great Lakes [5].

Some work has been done on the use of biodiesel in marine settings. The National Oceanic and Atmospheric Administration's (NOAA) Great Lakes Environmental Research Laboratory (GLERL) has converted three research vessels ranging from 40 to 80 feet in length to operate using B100 [6]. The Great Lakes Maritime Academy has also converted three of its vessels ranging from 41 to 56 feet in length to operate using B100 [7]. In addition, studies utilizing blends from B20 to B100 in vessels were carried out on the Washington State Ferry System [8] and on a consortium of tour boat operators in Montréal [9].

The current project is a continuation of shipboard testing of B20, following up on the project initiated by Pope and Ricketts in 2008 [10]. During 2009 we continued to test the use of B20 on board the University of Minnesota's research vessel, the Blue Heron, in order to see if the trends in fuel consumption and emissions persisted from 2008 into 2009 and to determine if any operational or maintenance issues appeared after extended use of biodiesel.

1.1 Previous Work

Both NOAA's Great Lakes Environmental Research Laboratory and the Great Lakes Maritime Academy have converted three vessels to operate using B100 [6,7]. These six vessels range in size from 40 to 80 feet and generally operate only from spring until fall. Fuel lines were replaced with Teflon hoses in the Great Lakes Maritime Academy's small boats [7]. Emission data and other information about the change over to B100 are unavailable.

The BioMer project involved twelve tour boats that operate on the Saint Lawrence River in the vicinity of Montréal [9]. The vessels ranged in size from 22 to 210 feet in length and were operated primarily with B100 but also B5, B10 and B20. Measurements of emissions from the vessels during the test indicate that total particulate matter, fine particulate matter, carbon monoxide, unburned hydrocarbons, polycyclic aromatic hydrocarbons and sulfur dioxide emissions decrease while nitrogen oxide emissions increase when comparing conventional diesel to B5, B10 and B100 biodiesel. Filter clogging was a problem, causing some of the tour boat companies participating in the project to stop the use of biodiesel. The BioMer researchers suspected the filter clogging was due to biodiesel's increased solvent properties leading to cleaning of the fuel system and rapid clogging of filters.

The Washington State Ferry system has completed two projects involving the use of biodiesel on three of their large (>300ft) vessels [8]. They completed a project in 2004 and 2005 using B20 but stopped use of the fuel after continued problems with filter and fuel purifier clogging. They undertook a second, more systematic, attempt at using biofuels in 2008 and 2009. This project used various types (Canola, soy, and recycled restaurant/animal fat) and grades (5%, 10% and 20%) of biodiesel. Beyond cleaning the fuel tanks and installation of monitoring equipment, no modifications were made to the vessels. No differences were found between the different types of biodiesel. Fuel filter and purifier clogging was caused by microbial growth and clogging was inhibited by the use of a biocide. No emissions data were collected.

1.2 Project Description

This project is a continuation of the 2008 GLMRI project 'Shipboard Testing of B20'. During the 2008 project, the University of Minnesota Duluth research vessel, the Blue Heron, was used to study fuel consumption and emissions when using B20 and standard diesel as fuels. The 2009 projects continued to test the use of B20 on board the Blue Heron in order to see if the trends in fuel consumption and emissions persisted and to determine if any operational or maintenance issues appeared after extended use of biodiesel.

The Blue Heron (shown in Figure 1) is the largest University owned research vessel on the Great Lakes. The vessel is an 86' former Grand Banks fishing trawler purchased in 1997, and as such its mechanical systems are configured the same as other commercially operated ships of similar size. GLMRI funds were used to purchase B20 fuel for the vessel. The ship was refueled seven times with B20 during the 2009 season. Monitoring equipment for the project (flow meters and emission probes) was purchased during the 2008 GLMRI project. As during the 2008 project, flow meters were placed in the fuel lines for the main engine and generators and data cables were run forward to the computer work station in the bosun's locker. Emission probes were placed in the ship's exhaust stack to measure exhaust temperature, exhaust pressure and emissions and data cabling was run forward to the bosun's locker computer station. Dr. Ricketts' participation in the project, the ship's personnel's time maintaining and monitoring the equipment and the additional fuel filters used were not charged to GLMRI and is considered matching funds from the University.

Figure 1: The Research Vessel Blue Heron

Data for the vessel's fuel consumption and emissions were gathered during 2009 operations. A data acquisition and computer system was used to record data for future analyses. Fuel filter logs were also maintained and fuel lines were inspected for leaks. Dr. Pope's continued assistance in re-installing and maintaining the emissions probes was invaluable. The emissions probes measured unburned hydrocarbons, carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), oxides of nitrogen (NO_X), exhaust temperature and exhaust pressure. As during the 2008 season, unburned hydrocarbon emissions did not register during steady-state operation of the main engine and as such are not included in the discussion of results.

Data were collected from mid-May to mid-September 2009. Fuel filter life-spans were noted for the entire period. Engine speed and fuel consumption data were collected from mid-June to mid-September. Exhaust temperature data were collected throughout August to mid-September while emissions data (NO_X, CO_2, CO, and oxygen O_2) were collected intermittently (due to equipment failure) throughout August to mid-September. The data for fuel consumption, exhaust temperature and emissions were analyzed as a function of engine speed (RPM). Engine speeds vary from low (RPM in the 400s) while on station and not moving, to medium speeds (RPM in the 500s to 900s) while doing survey work, to high speeds (RPM in the 1200s to 1400s) during transits. Portions of the results presented in this report were incorporated in a presentation given at the GLMRI University Affiliates Meeting held in Duluth, MN on September 24th, 2009.

2. Methods

Our methodology is the same as that used in the 2008 study [10]. We have three diesel powered systems on board the R/V Blue Heron: the main engine (a CAT 3508 TA), a CAT 3304 TA generator set and a CAT C4.4 generator set. Fuel logging systems manufactured by FloScan Instrument Company, Inc., and purchased in 2008, were used to monitor fuel consumption. The system on each engine consists of a forward flow meter, a return flow meter and a fuel flow gauge. Output from each of the fuel logging system was input to our data acquisition system.

The fuel loggers were connected to a DataTaker® DT80 data logger with output from the data logger (fuel consumption, main engine speed and exhaust pressure and temperature) displayed in the Bosun's locker on three gauges and a computer monitor. A Testo 350-XL flue gas analyzer was used to monitor emissions (HC, CO, O_2, CO_2, NO_x) and was also connected to the bosun's locker computer. Main engine speed, exhaust temperature, and exhaust pressure where recorded every 2 seconds, fuel consumption was recorded every 5 seconds, and the emissions data where recorded every 30 seconds. Data from the data logger and flue gas analyzer were saved in Excel® formatted files. Additional details about the data acquisition set up can be found in the 2008 report [10].

Refueling with B20 occurred seven times in 2009: on January 26th, May 28th, June 11th, July 29th, August 11th, August 28th, and September 26th. Refueling amounts ranged from 1500 to 2500 gallons and the Blue Heron took on 15,837 gallons of fuel during 2009. Our refueling process has not been simplified since the 2008 season and still consists of the fuel being mixed at the refinery in a large tanker truck, transferred to a smaller tanker truck for ease of access to the Blue Heron at the pier and then a final transfer to the Blue Heron. This process has the potential of introducing contaminants into the fuel.

3. Results

As Pope noted in our 2008 report [10] it is difficult to compare the dynamometer analyses of heavy-duty highway engines discussed in the 2002 USEPA analyses of biodiesel fuel usage [1] with field analyses. Engine load, approximated in this report by engine speed (revolutions-per-minute or RPM), will vary due to external variables such as sea state, water currents and wind speed. We make no attempt to control for these variables in this report. Data are averaged over periods of constant engine speed which vary from ten minutes to several hours. As noted in the Introduction, the USEPA analyses indicate a significant drop in carbon monoxide emissions and a slight increase in oxides of nitrogen emissions with no change in carbon dioxide emissions when using B20 compared to non-biodiesel fuel.

3.1 Fuel Consumption

Figure 2 shows the main engine fuel consumption in gallons per hour (GPH) as a function of main engine speed in RPMs for the 2008 data (both standard diesel and B20) as well as the 2009 B20 data. Engine speeds vary from low (RPM in the 400s) while on station and not moving, to medium speeds (RPM in the 500s to 900s) while doing survey work, to high speeds (RPM in the 1200s to 1400s) during transits. During 2008, B20 and standard diesel exhibit similar fuel consumption rates. The drop in fuel economy predicted by the USEPA analysis [1] is small enough that its existence may be hidden by the noise in the data. The 2009 B20 interestingly enough indicates generally lower fuel consumption at low to medium engine speeds when compared to the 2008 B20 data and fuel consumption rates similar to the 2008 B20 data at high engine speeds. The lower fuel consumption seen in the 2009 B20 data at low and medium engine speeds could be an indication of better engine performance due to biodiesel's increased lubricity, as hypothesized by the Canadian BioMer project [9] or could be an artifact of a limited

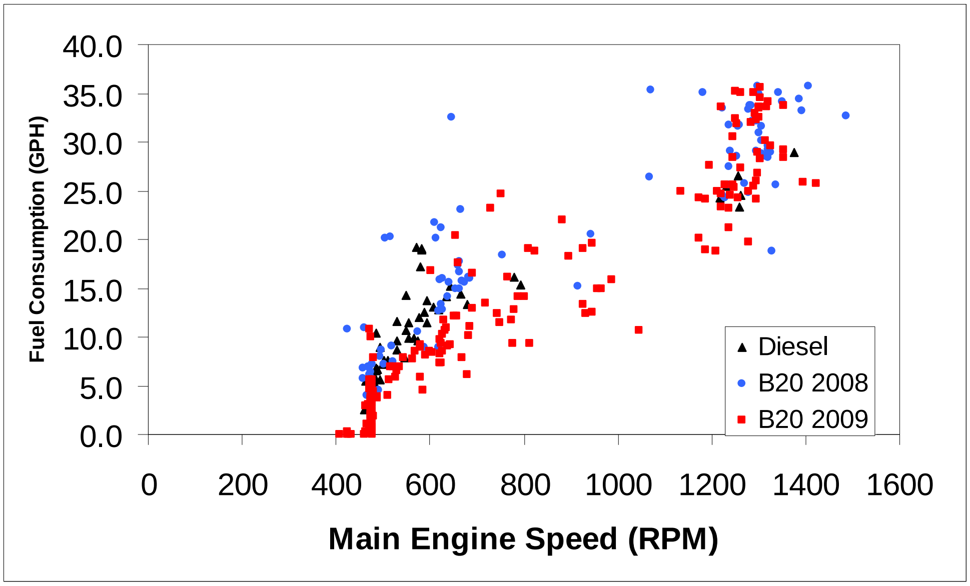


Figure 2: Main engine fuel consumption vs. engine speed

data set. Some of the B20 2008 and 2009 data indicate higher fuel consumption rates than standard diesel at high engine speeds. Clogging in the fuel filters while using B20 may cause higher readings from the fuel logging system.

3.2 Exhaust Temperature

Figure 3 shows the main engine exhaust temperature in degrees Celsius plotted against main engine speed in RPMs for the 2008 data (both standard diesel and B20) as well as the 2009 B20 data. There is little difference between the 2008 and 2009 data. Exhaust temperatures increase linearly from 150°C at 400-500 RPM to 450°C at 1400 RPM. The range of temperatures from 50°C to 150°C at 400 to 500 RPM is expected since some of these data points were collected when the engine was initially turned on and only operating for a short time. The linear increase from 150°C to 450°C is also expected since at higher RPMs one has less excess air and therefore a higher exhaust temperature.

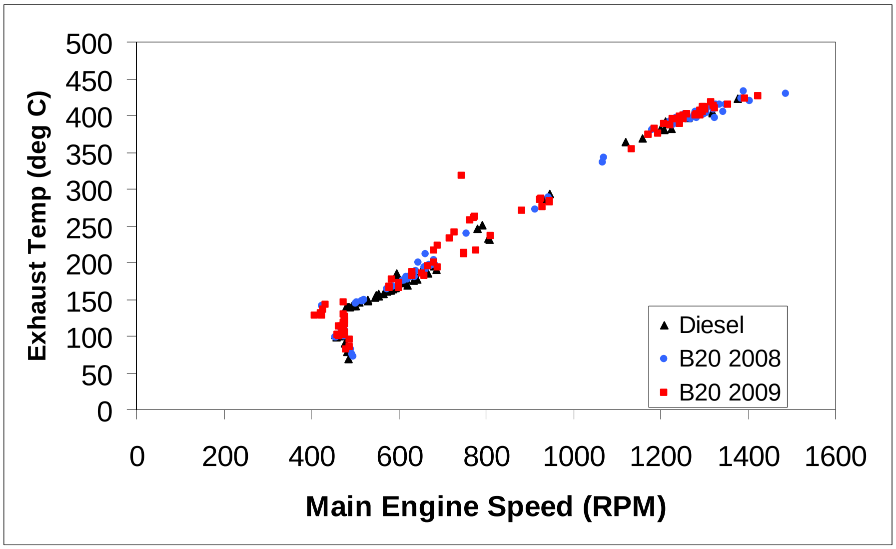


Figure 3: Main engine exhaust temperature vs. engine speed

3.3 Emissions

Percent oxygen (O_2) in the main engine exhaust plotted against main engine speed in RPMs for the 2008 data (both standard diesel and B20) as well as the 2009 B20 data is shown in Figure 4. Percent oxygen decreases with increased engine speed, as expected. At higher engine load (higher RPM), the engine is operating more efficiently and allowing for less excess air (as described for Figure 3) and less excess oxygen. The dip in percent oxygen for some engine speeds in the 600 to 800 RPM range is explained by the same process. These data points were collected while trawling (pulling a large fishing net). The load on the engine was heavier and therefore more oxygen is consumed during operation leaving less oxygen to exit through the exhaust.

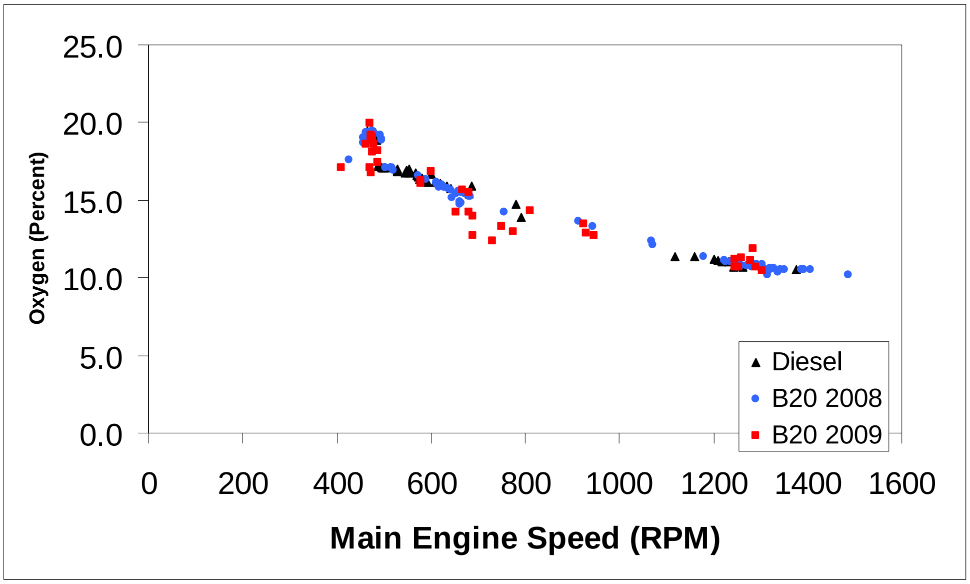


Figure 4: Percent oxygen in main engine exhaust vs. engine speed

Figure 5 shows the parts-per-million (ppm) carbon monoxide (CO) concentration in the main engine exhaust plotted against main engine speed in RPMs for the 2008 data (both standard diesel and B20) as well as the 2009 B20 data. All of the data are similar. As Pope noted in our 2008 GLMRI report [10] the data shows very low CO concentrations that are consistent with the lean operating conditions present in diesel engines and the scatter is most likely due to the accuracy and sensitivity of the emissions monitoring device employed in this study. The USEPA analyses [1] predict a 10% decrease in CO emissions when using B20 compared to standard diesel, a change which our data are not sensitive enough to confirm or deny.

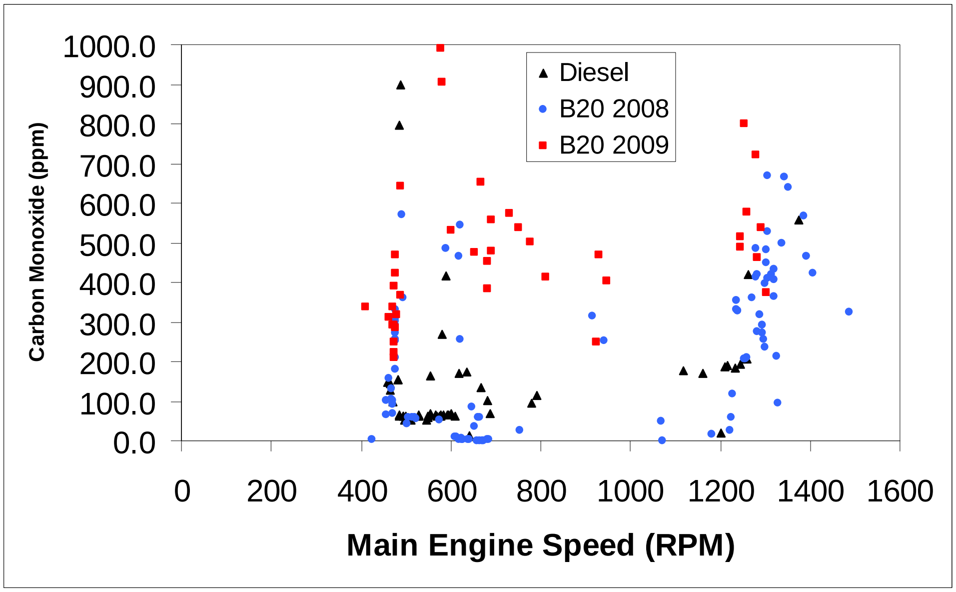


Figure 5: Carbon monoxide (CO) emissions vs. engine speed

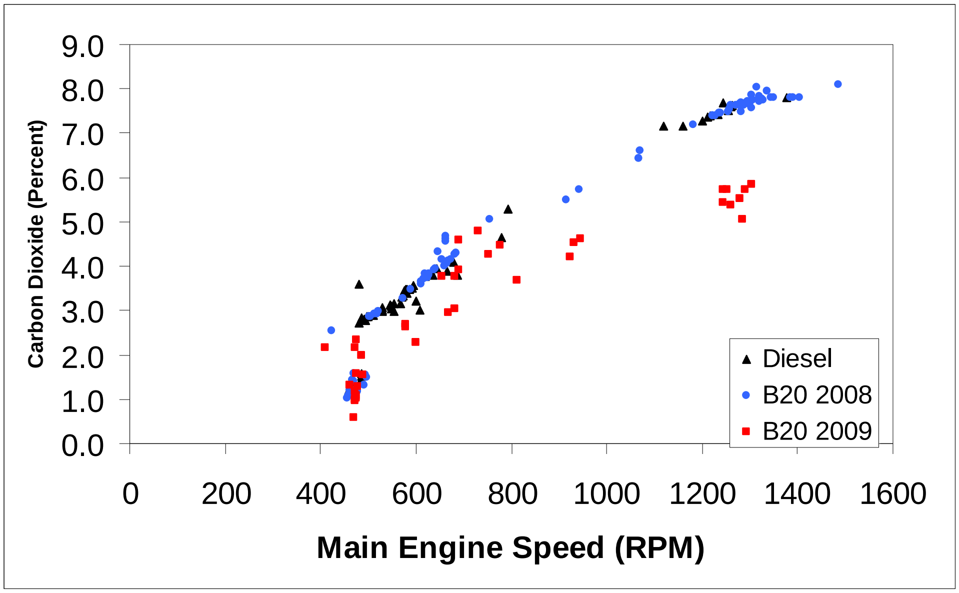


Figure 6: Carbon dioxide (CO2) emissions vs. engine speed

Figure 6 shows the percent carbon dioxide (CO_2) in the main engine exhaust plotted against main engine speed in RPMs for the 2008 data (both standard diesel and B20) as well as the 2009 B20 data. All of the data are similar, especially the 2008 B20 and standard diesel data. The 2009 B20 percent carbon dioxide data are slightly lower than the 2008 data (figure 6), indicative of the lower fuel consumption rate seen during 2009 (figure 3).

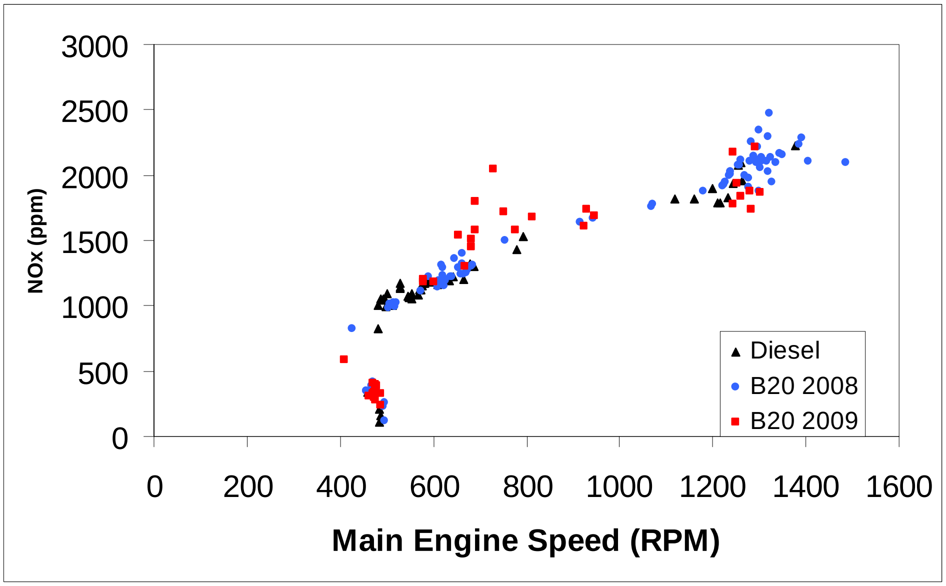


Figure 7: Oxides of nitrogen (NOx) emissions vs. engine speed

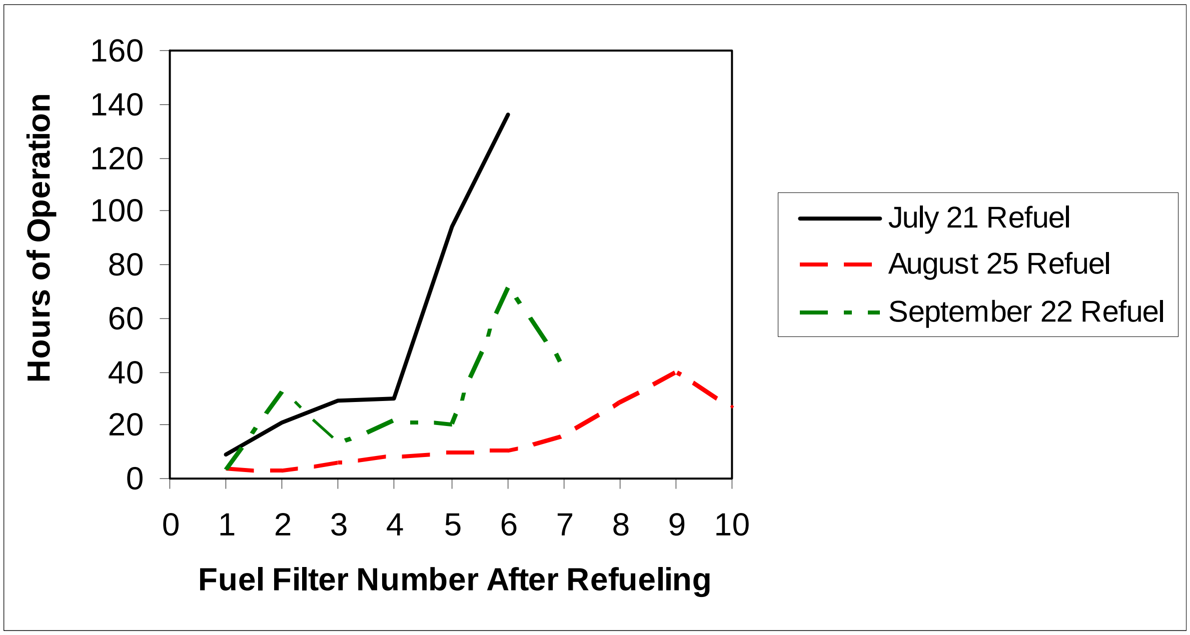
Engine emissions of oxides of nitrogen (NO_x) in parts-per-million (ppm) as a function of engine speed are plotted in Figure 7 for the 2008 data (both standard diesel and B20) as well as the 2009 B20 data. Data from both years are similar. Pope noted a slight increase in NO_x emissions when comparing the 2008 B20 and standard diesel at higher RPMs, and suggested that the increase might be indicative of the increase in NO_x noted in the USEPA analyses [10]. We notice little increase in NO_x at higher RPMs for the 2009 B20 data. The increase in NO_x which the USEPA analyses found was slight (2% for B20 [1]) and may be difficult to measure in field tests. Pope also hypothesized that increase load on the shaft may cause the increased NO_x emissions he noted at higher RPMs. The 2009 data would seem to indicate that this is the likely explanation. The 2009 B20 data exhibit higher NO_x emissions between 600 and 800 RPMs, which are data, as noted above, collected while the Blue Heron was pulling a mid-water trawl net and therefore had a larger engine load. Increased engine load would lead to higher emissions which can be seen in both the NO_x and CO_2 B20 2009 emissions data at engine speeds between 600 and 800 RPMs.

Unburned hydrocarbon emissions were not measured for reasons outlined in the 2008 report [10]: low unburned hydrocarbon emissions levels during steady state operations are below our probe's capabilities. All of the emissions data suffer from limited measurements due to equipment failure as noted in the introduction.

3.4 Operational Issues

We also looked at operational and maintenance issues associated with continued use of B20. We still note no material incompatibility issues (e.g. weeping or failing hosing, o-rings, etc.) since initiating the use of B20 on July 21st 2008. We had B20 in our fuel tanks during our over-winter period (2008-09). Biodiesel gels at a higher temperature than diesel. We did not have any operational issues in the spring of 2009 after the fuel was stored for six months in our fuel tanks. We continue to have a decreased life-span for fuel filters, a problem first noted in Pope's 2008 report [10]. The Blue Heron uses a 2-micron Racor filter as its primary fuel filter and the filter is replaced when the fuel pressure drops to below 50 psi when the engine is at full throttle. When standard diesel was our fuel the first fuel filter used after refueling would be replaced after a few hours with subsequent filters lasting 100 to 200 hours. With B20, the first filter after refueling would last, again, a few hours, with subsequent filters lasting longer but no where near the 100-200 hours seen with standard diesel except on rare occasions (the 2008 and 2009 fuel filter lifetime data are plotted in Figure 8 and the fuel log data is located in Appendix B). Since biodiesel is a solvent, the clogged filters may be due to biodiesel dissolving standard diesel buildup in the fuel system and depositing it in the filters or even dissolving standard diesel buildup in the tanker trucks where the biodiesel is mixed and delivered to the Blue Heron and depositing the buildup in the Blue Heron's fuel filters. The fine (2-micron) fuel filters may also be a problem. Coarser fuel filters may not clog as often. Also note that changes in our operations that were put in place for the project serve to obscure possible causes of the increase in filter usage. When using standard diesel as the fuel, fuel filters were used until fuel pressure dropped to 20-30 psi. When the fuel flow meters were added to our system, we found that if the filters were allowed to constrict fuel pressure to 20-30 psi, we would obtain inaccurate fuel consumption readings. The solution for this problem was to replace the filters more often, i.e. when fuel pressure dropped to 50 psi instead of 20-30 psi. Due to this complication it is difficult to say that we are truly seeing an increase in fuel filter usage due to biodiesel usage.

2008 fuel filter usage:



2009 fuel filter usage:

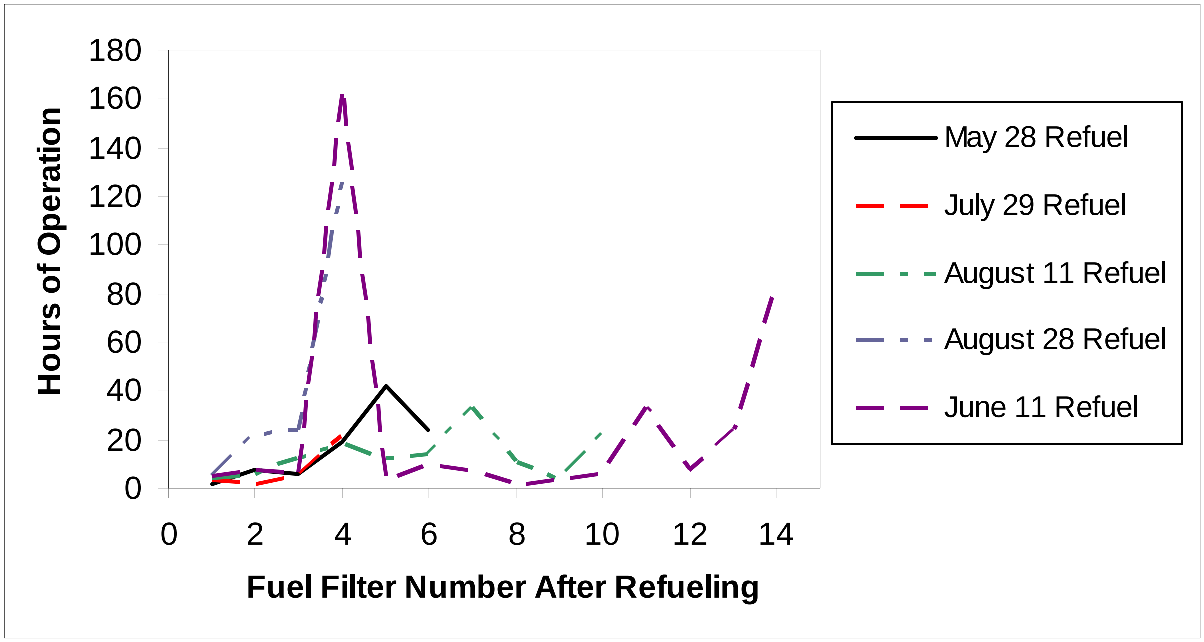


Figure 8: Primary fuel filter lifetime after refueling with B20, 2008 (top) and 2009 (bottom)

4. Conclusions, Recommendations and Potential Economic Impacts

We continued our 2008 project 'Shipboard Testing of B20' [10], collecting fuel consumption, exhaust temperature, and oxides of nitrogen (NO_x), oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2) emissions data. Analysis of the 2009 B20 data and comparisons to the 2008 B20 and standard diesel data leads to the following conclusions:

- During 2008, B20 and standard diesel exhibit similar fuel consumption rates. The drop in fuel economy predicted by the USEPA analysis is small enough that its existence may be hidden by the noise in the data. The 2009 B20 data interestingly enough indicate generally lower fuel consumption at low to medium engine speeds when compared to the 2008 B20 data and fuel consumption rates similar to the 2008 B20 data at high engine speeds.
- Some of the B20 2008 and 2009 data indicate higher fuel consumption rates than standard diesel at high engine speeds. Clogging in the fuel filters while using B20 may cause higher readings from the fuel logging system.
- NO_X, CO_2, CO, and O_2 emissions were similar between the B20 and standard diesel and between the B20 data collected in 2008 and 2009.
- Scatter in the NO_X emissions values may hide any increase in NO_X values caused by the use of B20.
- NO_X values for B20 in 2009 at medium engine speeds (600 to 800 RPM) were slightly higher than the NO_X values for B20 in 2008 or the standard diesel. These data were collected while the ship was undertaking mid-water trawling for a fisheries stock assessment study. This type of work may place an extra load on the main engine, increasing NO_X (as well as CO_2) emissions.
- Overall, CO_2 values for the B20 data from 2009 are slightly lower than the data collected in 2008, indicative of the lower fuel consumption rate.
- As Pope noted in his 2008 report, unburned hydrocarbons (HC) were too low for our equipment to measure during the constant engine speed conditions we have outlined here. The CO concentrations are also low and therefore difficult for the emissions probe to accurately measure. The emissions probe's lack of accuracy at such low CO concentrations contributes to the high level of scatter seen in the CO data.
- We continue to see no material compatibility problems (e.g. weeping or failing hosing, o-rings, etc.) since we started using B20 in July of 2008.
- We continue to see an increase in filter usage. While this increase in fuel filter usage may be due to experimental design, we will explore the use of prefiltering of B20 to cut down on filter clogging.

Recommendations:

- Fuel tanks must be thoroughly cleaned before using biodiesel as recommended by both the Washington State Ferry Biodiesel project and the BioMer Canadian Tour Boat Biodiesel project [8, 9]. Due to our inspection process, required by our primary funding agency, the National Science Foundation, our tanks have to be cleaned and inspected every four years. Due to this requirement our tanks were relatively clean prior to filling them with B20. When we first cleaned the tanks, they were extremely filthy. Biodiesel is a strong solvent.

If tanks are not cleaned before its use, fuel filters will become rapidly clogged.

- Our 2009 B20 fuel consumption data would seem to indicate that biodiesel's lower energy content [1] is offset by lower fuel consumption due to increased engine lubricity, as hypothesized by the Canadian BioMer project [9]. Our data would seem to indicate that users of B20 should not see an increase in fuel consumption and may see a drop in fuel consumption.

- Both the BioMer project and the Washington State Ferry project noted increased fuel filter usage [8,9]. While we certainly experienced increased fuel filter usage we are not sure if the increased usage was due to biodiesel, our fine mesh sized fuel filters, or operational changes made to accommodate the fuel logging system. The BioMer project recommended using coarser fuel filters [9], a change we are not willing to make. The Washington State Ferry projected hypothesized that bacterial growth was triggering sludge formation and fuel filter clogging and recommended adding a biocide to the fuel to kill bacteria [8]. We wonder if simply using the 'right' fuel conditioner might solve this problem. Our plans to test for a solution to this problem are as follows: First we will go back to changing our fuel filters when fuel pressure was in the 20-30 psi range. While our fuel consumption data will not be accurate, we will see if our filters last into the 100-200 hour range as they did when we used standard diesel. If they do, then simply having a clean fuel tank before using biodiesel and using a fuel conditioner will prevent filter clogging. If fuel filter usage is still higher than with standard diesel, we will see if changing fuel conditioners and using a biocide impacts our filter usage. If these additives do not work we will consider prefilter our B20 before use.

Economic Impact:

Biodiesel (B20) will be mandated in Minnesota in the near future [3] and may be required in Wisconsin [4]. Our experience with the use of this fuel on the R/V Blue Heron would seem to indicate that as long as precautions are taken, such as cleaning fuel tanks and using fuel conditioners, there should be little impact on commercial maritime operations. Our use of fine fuel filters (2-micron) and the necessity of more frequent fuel filter changes in order to acquire accurate fuel consumption data prevents us from definitively saying that fuel filter usage will increase when using B20 biodiesel.

References

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Appendix A

Main Engine Speed, Fuel Flow Rate, Main Engine Exhaust Temperature, and Emissions Data

2008 Data can be found in reference [10]

2009 B20 Data

Time		ME Speed	ME Flow Rate	Emissions				Exhaust Temp
From	To	RPM	GPH	O2 %	CO ppm	NOx ppm	CO2 %	deg C
6/13/2009 3:54	6/13/2009 10:40	**1297**	**29.00**					
6/13/2009 10:45	6/13/2009 11:13	**475**	**2.89**					
6/13/2009 11:17	6/13/2009 16:11	**473**	**1.92**					
6/13/2009 16:31	6/13/2009 18:28	**474**	**1.12**					
6/14/2009 21:17	6/14/2009 22:28	**477**	**0.13**					
6/14/2009 22:52	6/15/2009 0:37	**477**	**0.76**					
6/15/2009 2:11	6/15/2009 11:07	**1294**	**32.97**					
6/15/2009 11:17	6/15/2009 11:49	**478**	**1.35**					
6/16/2009 3:11	6/16/2009 7:03	**897**	**18.21**					
6/16/2009 7:44	6/16/2009 12:11	**477**	**0.65**					
6/16/2009 12:55	6/16/2009 15:43	**475**	**0.97**					
6/16/2009 16:36	6/16/2009 17:45	**475**	**0.82**					
6/17/2009 14:16	6/17/2009 22:35	**476**	**0.05**					
6/17/2009 22:40	6/17/2009 22:58	**1187**	**24.11**					
6/17/2009 23:00	6/18/2009 0:03	**477**	**0.71**					
6/18/2009 0:20	6/18/2009 0:59	**589**	**8.15**					
6/18/2009 1:15	6/18/2009 1:53	**986**	**15.83**					
6/18/2009 1:57	6/18/2009 4:50	**957**	**14.93**					
6/19/2009 0:54	6/19/2009 2:10	**658**	**12.17**					
6/19/2009 6:06	6/19/2009 10:08	**1300**	**32.59**					
6/19/2009 10:11	6/19/2009 11:20	**476**	**3.92**					
6/19/2009 11:23	6/19/2009 13:13	**475**	**3.83**					
6/19/2009 13:30	6/19/2009 15:28	**476**	**5.12**					
6/19/2009 21:51	6/20/2009 0:51	**1314**	**30.08**					
6/20/2009 0:56	6/20/2009 5:08	**477**	**3.73**					
6/20/2009 5:23	6/20/2009 9:38	**476**	**5.58**					
6/20/2009 9:55	6/20/2009 11:14	**475**	**9.96**					
6/20/2009 11:43	6/20/2009 12:25	**478**	**4.46**					
6/20/2009 18:52	6/20/2009 22:33	**1302**	**28.31**					
6/20/2009 22:38	6/21/2009 2:30	**467**	**1.01**					
6/21/2009 2:42	6/21/2009 4:01	**1046**	**10.60**					
6/21/2009 4:05	6/21/2009 7:47	**964**	**14.96**					
6/21/2009 8:13	6/21/2009 9:01	**1278**	**19.75**					
7/14/2009 18:38	7/14/2009 23:35	**1252**	**35.15**					
7/14/2009 23:49	7/15/2009 0:48	**824**	**18.77**					
7/15/2009 1:20	7/15/2009 3:15	**810**	**19.08**					
7/15/2009 3:25	7/15/2009 9:12	**1220**	**33.62**					
7/15/2009 23:36	7/16/2009 0:03	**627**	**8.49**					
7/16/2009 0:16	7/16/2009 1:03	**526**	**5.83**					
7/16/2009 1:30	7/16/2009 2:11	**604**	**8.41**					

Time		ME Speed RPM	ME Flow Rate GPH	Emissions				Exhaust Temp deg C
From	To			O2 %	CO ppm	NOx ppm	CO2 %	
7/16/2009 2:30	7/16/2009 3:07	**513**	**5.65**					
7/16/2009 3:25	7/16/2009 4:06	**652**	**12.09**					
7/16/2009 4:25	7/16/2009 5:00	**530**	**6.52**					
7/16/2009 5:15	7/16/2009 5:59	**627**	**10.23**					
7/16/2009 6:50	7/16/2009 7:29	**635**	**10.95**					
7/16/2009 7:41	7/16/2009 8:18	**544**	**7.85**					
7/16/2009 8:26	7/16/2009 9:07	**623**	**9.27**					
7/16/2009 9:18	7/16/2009 9:56	**569**	**8.60**					
7/16/2009 10:19	7/16/2009 10:50	**621**	**7.33**					
7/16/2009 11:04	7/16/2009 11:41	**536**	**6.89**					
7/16/2009 11:51	7/16/2009 12:28	**643**	**9.21**					
7/16/2009 12:39	7/16/2009 13:18	**512**	**4.05**					
7/16/2009 13:33	7/16/2009 14:07	**684**	**11.02**					
7/16/2009 20:38	7/16/2009 21:07	**475**	**3.70**					
7/16/2009 21:58	7/16/2009 22:18	**620**	**8.22**					
7/16/2009 22:27	7/16/2009 23:03	**564**	**7.69**					
7/16/2009 23:11	7/16/2009 23:53	**620**	**7.28**					
7/17/2009 0:02	7/17/2009 0:40	**515**	**7.00**					
7/17/2009 0:48	7/17/2009 1:29	**624**	**7.34**					
7/17/2009 1:38	7/17/2009 2:10	**637**	**9.10**					
7/17/2009 2:22	7/17/2009 2:48	**621**	**9.78**					
7/17/2009 3:19	7/17/2009 3:42	**521**	**6.93**					
7/17/2009 4:35	7/17/2009 5:02	**1211**	**24.88**					
7/17/2009 5:49	7/17/2009 8:16	**803**	**14.11**					
7/17/2009 9:54	7/17/2009 11:03	**788**	**14.09**					
7/18/2009 19:02	7/18/2009 20:16	**1301**	**33.63**					
7/18/2009 22:04	7/19/2009 8:10	**1241**	**24.52**					
7/19/2009 8:13	7/19/2009 9:33	**1354**	**28.47**					
7/19/2009 9:48	7/19/2009 12:07	**1353**	**29.22**					
7/19/2009 12:27	7/19/2009 12:40	**479**	**1.85**					
7/19/2009 12:45	7/19/2009 13:57	**1257**	**24.21**					
7/19/2009 13:59	7/19/2009 14:15	**1298**	**26.74**					
7/19/2009 14:18	7/19/2009 14:52	**1238**	**23.25**					
7/19/2009 14:54	7/19/2009 18:31	**1219**	**23.35**					
7/19/2009 18:43	7/19/2009 19:43	**1248**	**25.35**					
8/4/2009 20:16	8/4/2009 21:18	**475**	**2.01**	**16.8**	**390.2**	**281.4**	**2.3**	**112**
8/4/2009 22:23	8/4/2009 22:35	**691**	**12.92**	**12.7**	**556.2**	**1,794.5**	**4.6**	**223**
8/4/2009 23:24	8/5/2009 1:50	**689**	**16.50**	**14.0**	**477.1**	**1,578.2**	**3.9**	**193**
8/5/2009 2:33	8/5/2009 3:12	**729**	**23.18**	**12.4**	**572.4**	**2,045.2**	**4.8**	**241**
8/5/2009 3:32	8/5/2009 3:46	**752**	**24.71**	**13.3**	**538.9**	**1,714.7**	**4.3**	**213**
8/5/2009 3:50	8/5/2009 4:29	**654**	**20.46**	**14.2**	**476.1**	**1,541.6**	**3.8**	**185**
8/5/2009 4:32	8/5/2009 10:27	**471**	**4.65**	**17.1**	**338.8**	**406.6**	**2.1**	**103**
8/5/2009 23:35	8/6/2009 0:24	**811**	**9.39**	**14.3**	**412.2**	**1,683.1**	**3.7**	**237**
8/6/2009 0:35	8/6/2009 1:24	**1290**	**25.49**	**10.7**	**538.7**	**2,217.2**	**5.7**	**400**
8/6/2009 1:32	8/6/2009 1:54	**681**	**6.14**	**15.5**	**384.9**	**1,447.3**	**3.0**	**199**

Time		ME	ME	Emissions				Exhaust
		Speed	Flow Rate	O2	CO	NOx	CO2	Temp
From	To	RPM	GPH	%	ppm	ppm	%	deg C
8/6/2009 2:09	8/6/2009 2:42	**682**	**10.18**	**14.2**	**453.2**	**1,510.8**	**3.8**	**216**
8/6/2009 3:08	8/6/2009 3:21	**776**	**9.40**	**12.9**	**500.2**	**1,577.0**	**4.5**	**263**
8/6/2009 3:43	8/6/2009 4:40	**409**	**0.00**	**17.1**	**337.5**	**585.8**	**2.2**	**128**
8/6/2009 4:42	8/6/2009 9:43	**462**	**0.25**	**18.6**	**311.9**	**304.6**	**1.3**	**101**
8/6/2009 9:51	8/6/2009 11:11	**1245**	**25.56**	**10.7**	**489.5**	**2,172.8**	**5.7**	**391**
8/6/2009 11:16	8/6/2009 14:09	**475**	**1.95**	**18.1**	**286.5**	**393.4**	**1.6**	**106**
8/6/2009 19:41	8/6/2009 21:03	**474**	**0.65**	**19.1**	**251**	**340**	**1.03**	**101**
8/6/2009 21:38	8/6/2009 21:59	**718**	**13.40**					**232**
8/6/2009 22:09	8/6/2009 22:44	**773**	**11.68**					**261**
8/6/2009 23:11	8/7/2009 0:43	**744**	**12.46**					**318**
8/7/2009 1:41	8/7/2009 2:16	**764**	**16.19**					**257**
8/7/2009 2:49	8/7/2009 3:30	**749**	**11.53**					**212**
8/7/2009 3:37	8/7/2009 4:55	**423**	**0.03**					**131**
8/7/2009 5:18	8/7/2009 6:47	**475**	**3.54**					**105**
8/7/2009 6:56	8/7/2009 7:12	**779**	**12.84**					**217**
8/7/2009 7:16	8/7/2009 8:22	**474**	**3.12**					**106**
8/7/2009 8:34	8/7/2009 9:02	**474**	**2.47**					**105**
8/7/2009 9:17	8/7/2009 9:35	**1134**	**25.00**					**354**
8/7/2009 9:39	8/7/2009 10:05	**476**	**3.17**					**125**
8/7/2009 10:37	8/7/2009 11:10	**1245**	**30.53**					**388**
8/7/2009 11:13	8/7/2009 11:34	**473**	**3.41**					**146**
8/7/2009 11:45	8/7/2009 11:54	**1194**	**27.66**					**375**
8/13/2009 17:57	8/13/2009 22:16	**1245**	**28.39**	**11.2**	**514.2**	**1775.1**	**5.4**	**398**
8/13/2009 22:19	8/14/2009 8:31	**1261**	**27.28**	**11.3**	**576.5**	**1841.7**	**5.4**	**401**
8/14/2009 21:56	8/15/2009 2:26	**471**	**10.78**	**20.0**	**291.0**	**326.5**	**0.6**	**101**
8/15/2009 3:02	8/15/2009 7:43	**472**	**0.44**	**19.2**	**223.6**	**298.0**	**1.0**	**103**
8/15/2009 8:04	8/15/2009 12:30	**1252**	**32.39**					**400**
8/15/2009 18:26	8/16/2009 1:08	**474**	**0.24**					**102**
8/16/2009 1:16	8/16/2009 1:40	**1303**	**35.55**	**10.5**	**374.4**	**1,872.2**	**5.9**	**407**
8/16/2009 1:45	8/16/2009 2:39	**474**	**2.96**	**19.1**	**211.5**	**309.5**	**1.0**	**115**
8/16/2009 2:45	8/16/2009 7:38	**925**	**13.29**	**13.4**	**249.9**	**1,608.6**	**4.2**	**285**
8/16/2009 7:40	8/16/2009 9:00	**473**	**0.54**	**18.8**	**290.9**	**326.2**	**1.2**	**110**
8/17/2009 0:14	8/17/2009 1:02	**462**	**0.18**					**101**
8/17/2009 1:44	8/17/2009 5:11	**462**	**0.02**					**102**
8/17/2009 6:07	8/17/2009 9:26	**1317**	**33.64**					**418**
8/17/2009 10:30	8/17/2009 12:14	**1300**	**33.40**					**412**
8/17/2009 12:16	8/17/2009 12:57	**1423**	**25.71**					**427**
8/17/2009 12:59	8/17/2009 14:42	**1393**	**25.80**					**422**
8/18/2009 20:33	8/18/2009 21:29	**659**	**17.66**					**182**
8/18/2009 21:33	8/19/2009 1:17	**424**	**0.21**					**128**
8/19/2009 1:50	8/19/2009 2:37	**600**	**16.84**					**166**
8/19/2009 3:02	8/19/2009 6:05	**1227**	**25.55**					**395**
8/19/2009 6:12	8/19/2009 9:58	**477**	**2.90**					**105**
8/19/2009 22:17	8/20/2009 6:17	**1295**	**32.26**					**412**
8/20/2009 6:21	8/20/2009 8:13	**883**	**22.06**					**270**

Time		Me Speed RPM	Me Flow Rate GPH	Emissions				Exhaust Temp deg C
From	To			O2 %	CO ppm	NOx ppm	CO2 %	
8/22/2009 7:24	8/22/2009 8:21	**479**	**7.86**					**81**
8/22/2009 8:32	8/22/2009 8:39	**946**	**19.66**					**282**
8/22/2009 8:42	8/22/2009 9:40	**928**	**19.03**					**288**
8/22/2009 9:43	8/22/2009 9:57	**1321**	**34.12**					**413**
8/22/2009 18:57	8/22/2009 22:01	**1290**	**35.10**					**407**
8/22/2009 22:09	8/23/2009 1:11	**472**	**5.62**					**104**
8/23/2009 1:15	8/23/2009 8:23	**470**	**5.10**					**101**
8/24/2009 11:16	8/24/2009 15:31	**1262**	**35.13**					**402**
8/30/2009 18:04	8/30/2009 20:22	**1324**	**29.61**					**410**
8/30/2009 20:57	8/30/2009 21:54	**1173**	**20.11**					**373**
8/30/2009 21:56	8/30/2009 22:38	**1221**	**24.62**					**387**
8/30/2009 22:42	8/30/2009 23:34	**433**	**0.06**					**143**
8/30/2009 23:36	8/31/2009 8:38	**579**	**9.18**	**16.3**	**989.0**	**1,204.3**	**2.6**	**165**
8/31/2009 19:44	8/31/2009 20:04	**668**	**7.87**	**15.6**	**652.5**	**1,299.8**	**3.0**	**194**
8/31/2009 20:06	9/1/2009 2:59	**579**	**5.84**	**16.1**	**905.8**	**1,184.8**	**2.7**	**167**
9/1/2009 3:01	9/1/2009 7:58	**600**	**8.58**	**16.8**	**532.4**	**1,183.1**	**2.3**	**172**
9/1/2009 8:15	9/1/2009 9:46	**1279**	**24.87**	**11.1**	**719.8**	**1,879.0**	**5.5**	**400**
9/1/2009 9:56	9/1/2009 10:18	**586**	**4.49**					**177**
9/3/2009 3:53	9/3/2009 5:07	**475**	**1.26**					**102**
9/3/2009 5:19	9/3/2009 6:23	**1173**	**24.25**					**374**
9/3/2009 6:25	9/3/2009 6:51	**1354**	**33.70**					**415**
9/3/2009 7:13	9/3/2009 7:52	**427**	**0.00**					**136**
9/3/2009 8:27	9/3/2009 16:45	**579**	**8.92**					**166**
9/3/2009 16:48	9/3/2009 18:05	**630**	**11.79**					**186**
9/4/2009 13:47	9/5/2009 4:20	**632**	**10.68**					**181**
9/5/2009 21:39	9/5/2009 23:40	**1208**	**18.85**					**388**
9/5/2009 23:43	9/6/2009 5:16	**1187**	**18.91**					**382**
9/6/2009 8:04	9/6/2009 8:42	**462**	**2.98**					**112**
9/6/2009 9:28	9/6/2009 10:44	**1238**	**21.17**					**396**
9/17/2009 10:33	9/17/2009 11:55	**1303**	**34.49**					**410**
9/17/2009 12:05	9/17/2009 12:46	**470**	**3.01**					**114**
9/17/2009 16:36	9/17/2009 17:51	**1296**	**24.19**					**410**
9/20/2009 8:04	9/20/2009 8:56	**488**	**3.72**	**18.1**	**643.2**	**233.5**	**1.6**	**85**
9/20/2009 8:59	9/20/2009 9:50	**487**	**3.89**	**17.4**	**367.9**	**329.4**	**2.0**	**94**
9/20/2009 10:04	9/20/2009 10:23	**946**	**12.49**	**12.7**	**401.9**	**1693.6**	**4.6**	**284**
9/20/2009 10:28	9/20/2009 10:48	**478**	**2.20**	**18.6**	**316.7**	**391.8**	**1.3**	**117**
9/20/2009 10:53	9/20/2009 11:13	**931**	**12.46**	**12.8**	**467.5**	**1739.6**	**4.5**	**275**
9/20/2009 11:27	9/20/2009 12:02	**476**	**2.02**	**19.0**	**423.7**	**356.1**	**1.1**	**119**
9/20/2009 12:24	9/20/2009 13:03	**475**	**2.66**	**19.0**	**467.9**	**368.2**	**1.1**	**117**
9/20/2009 13:07	9/20/2009 14:12	**1253**	**31.90**	**10.7**	**801.0**	**1939.3**	**5.7**	**396**
9/22/2009 9:47	9/22/2009 10:28	**477**	**3.93**					**121**
9/22/2009 10:33	9/22/2009 11:42	**1284**	**32.06**	**11.9**	**461.5**	**1,737.5**	**5.1**	**402**
9/22/2009 14:11	9/22/2009 14:37	**475**	**1.35**					**129**
9/22/2009 14:42	9/22/2009 15:30	**1296**	**25.97**					**404**

Appendix B

Fuel Filter Change Log

2008 Data can be found in reference [10]

2009 Fuel Filter Change Log

Refuel		Filter Change		Approx. Time on Used Filter	Remarks	Filter Number After Refueling
Date	Fuel Type	Date	Time	(hrs)		
1/26/2009	B20	5/21/2009	1425	unknown	Filter from last season	
		5/21/2009	1805	4		
		5/21/2009	2219	4		
5/28/2009	B20					
		6/3/2009	822	16	Filter carried over from previous refueling	
		6/3/2009	1000	1.5	1st filter change after refueling	1
		6/3/2009	1700	7		2
		6/3/2009	2230	5.5		3
		6/4/2009	1823	19		4
		6/6/2009	2235	42		5
		6/7/2009	2247	24		6
6/11/2009	B20					
		6/12/2009	615	13	Filter carried over from previous refueling	
		6/12/2009	1356	5	1st filter change after refueling	1
		6/12/2009	2045	7		2
		6/13/2009	145	6		3
		6/19/2009	2135	164	Cruise with lower fuel consumption	4
		6/20/2009	100	3		5
		6/20/2009	1117	10		6
		6/20/2009	1801	7		7
		6/20/2009	1926	1.5		8
		6/20/2009	2118	3		9
		6/21/2009	235	5.5		10
		7/10/2009	1217	33		11
		7/14/2009	815	7		12
		7/15/2009	835	24		13
		7/19/2009	130	85		14
7/29/2009	B20					
		8/4/2009	810	20	Filter carried over from previous refueling	
		8/4/2009	1105	3	1st filter change after refueling	1
		8/4/2009	1242	2		2
		8/4/2009	1705	5		3
		8/5/2009	1424	21		4
8/11/2009	B20					
		8/13/2009	950	49	Filter carried over from previous refueling	
		8/13/2009	1400	4	1st filter change after refueling	1

Refuel				Approx. Time On Used Filter	Remarks	Filter number after refueling
Date	Fuel Type	Date	Time	(hrs)		
		8/13/2009	1945	6		2
		8/14/2009	823	12.5		3
		8/15/2009	200	18		4
		8/15/2009	1341	12		5
		8/16/2009	415	14		6
		8/17/2009	1351	33		7
		8/18/2009	100	11		8
		8/18/2009	400	3		9
		8/19/2009	238	22.5		10
8/28/2009	B20					
		8/30/2009	800	88	Filter carried over from previous refueling	
		8/30/2009	1300	5	1st filter change after refueling	1
		8/30/2009	1946	22.5		2
		8/31/2009	1710	24		3
		9/5/2009	2044	127		4
9/16/2009	B20					