Final Report:
Emissions Comparison of a Marine Vessel Under Autonomous and Manual Control

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Abstract

The International Maritime Organization has specified a goal of reducing greenhouse gas emissions from international shipping by at least 50% by 2050 compared to 2008 emissions levels. Thus, a number of strategies are currently being explored to achieve emissions reductions. One such strategy is autonomous technology, which has the potential to reduce emissions from marine vessels by optimizing routes for speed, scheduling, and external effects including wind and currents. This study compares emissions from a marine vessel operated in both autonomous and manual modes. A 41ft diesel powered research vessel was outfitted with an autonomous control system and measurement instrumentation for determining gaseous emissions of carbon dioxide (CO_2), carbon monoxide (CO), oxides of nitrogen (NOx), Total Unburned Hydrocarbons (THC), and oxides of sulfur (SOx). It was determined that the autonomous tests resulted in increased emissions of CO2, NOx, and SOx due to a higher average engine load during autonomous operation. This finding was at least partially caused by additional transients of higher engine loading in autonomous control compared to manual control. If a minimization of emissions and fuel consumption were desired, reconfiguring the speed control loop for those specific goals could be considered.

Introduction

The International Maritime Organization has specified a goal of reducing greenhouse gas emissions from international shipping by at least 50% by 2050 compared to 2008 emissions levels. It is well understood that carbon dioxide greenhouse gas emissions are directly proportional to hydrocarbon fuel consumption. Thus, a number of strategies are currently being explored to achieve emissions reductions including hull, propeller, and engine optimization, alternative fuels, and autonomous technology. Aside from alternative fuels which aim to reduce or eliminate total lifecycle greenhouse gas emissions, all other strategies seek to reduce emissions by reducing fuel consumption and increasing ship efficiency.

Interest, investment, and development of autonomous maritime shipping is still in the earlier stages of development but continues to gain momentum. Properly designed, autonomous technology has the potential to reduce emissions from marine vessels by optimizing routes for speed, scheduling, and external effects including wind and currents. Given the nonlinear relationship between vessel speed and fuel consumption due to hull drag, any optimization that reduces engine loading or vessel speed would dramatically reduce greenhouse gas and other engine emissions.

Currently, no known published studies exist comparing the measured emissions profiles of vessels under autonomous and manual human control. This study aims to compare emissions from a marine vessel operated in both these modes. For this work, a 41ft diesel powered research vessel was outfitted with an autonomous control system and measurement instrumentation for determining gaseous emissions. A standardized survey route was chosen and emissions of carbon dioxide (CO_2), carbon monoxide (CO), oxides of nitrogen (NOx), Total Unburned Hydrocarbons (THC), and oxides of sulfur (SOx) were measured.

Experimental Description

Vessel

The Maine Maritime Academy Research Vessel (R/V) Quickwater was used to conduct testing. The 41ft Coast Guard cutter-class, twin-screw workboat is equipped with two 307 hp Cummins V903 diesel engines. The Quickwater is shown in Figure 1. The vessel was equipped with Kral OMX-20 fuel flow meters and PMAS MH95SPEC42 mass air flow meters to facilitate emissions calculations. Flow rates were monitored and saved using NI LabVIEW.

Figure 1. The Research Vessel Quickwater.

Automation

The R/V Quickwater is equipped with a SeaMachines SM300 control system as shown in Figure 2. The SM300 is integrated into the existing vessel controls and electronics and allows for autonomous and remote control of the vessel. A SM300 Remote Helm Controller allows for remote manual control of the vessel. Autonomous control is achieved with a SM300 User Interface Laptop. The user interface allows for mission planning, deployment, and monitoring of autonomous operation. Autonomous mode features include depth avoidance, depth safety areas, seakeeping, and collision avoidance to ensure vessel safety.

Figure 2: SeaMachines SM300 Control System.

Emissions Measurements

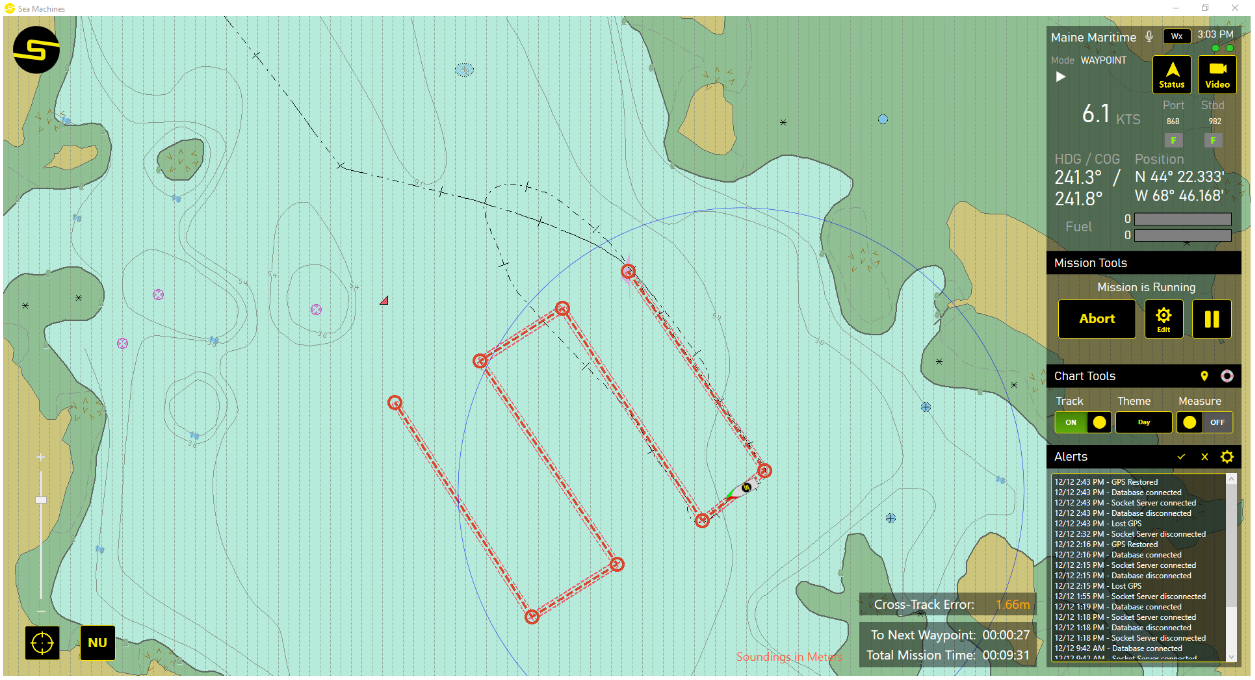
An MKS 2030 hot-cell Fourier-transform infrared spectrometer (FTIR) was used to measure gaseous emissions of nitrogen oxides (NOx), CO2, CO, sulfur oxides (SOx), and total unburned hydrocarbons (THC). The FTIR utilizes a liquid nitrogen cooled MCT detector and was operated at 0.5cm^{-1} spectral resolution and a sampling rate of 1 sample per second.

Gaseous emissions were continuously monitored from the exhaust of the port engine of the vessel, 2 ft after the turbocharger and before the water-jacketed portion of the exhaust. The raw exhaust sample from the exhaust port in the engine room was routed through a 10ft heated stainless steel line, heated filter, Air Dimensions H-Series dual heated head pump, and through another 10ft heated line, routed through the engine room bulkhead to the FTIR housed in the forward cabin of Quickwater. The installed instrumentation is shown in Figure 3. Sample response time due to piping was estimated at approximately 5 seconds for each instrument.

Figure 3: MKS 2030 hot-cell Fourier-transform infrared spectrometer (FTIR) and control hardware for exhaust sampling installed in the forward cabin of the Quickwater.

Test Plan

The vessel test plan consisted of a short survey route approximately 2.25km long with four 450m legs and 150m turns. The survey was conducted in Smith Cove at the mouth of the Bagaduce River. The test plan is shown in Figure 4. Vessel speed was chosen at 6 knots resulting in a test duration of 12 minutes. Two iterations of the planned route were conducted in both manned and autonomous control, starting in autonomous mode and switching between control modes for each run (i.e. autonomous, manned, autonomous, manned). All tests were completed within a 1-hour time span. No significant changes in weather or water currents occurred during the tests.



Mode WAYPOINT

6.1 KTS

Port 868 Stbd 982

HDG / COG 241.3° / 241.8°

Position N 44° 22.333' W 68° 46.168'

Fuel 0 0

Mission is Running

Cross-Track Error: 1.66m

To Next Waypoint: 00:00:27

Total Mission Time: 00:09:31

```
12/12 2:43 PM - GPS Restored
12/12 2:43 PM - Database connected
12/12 2:43 PM - Socket Server connected
12/12 2:43 PM - Database disconnected
12/12 2:43 PM - Lost GPS
12/12 2:32 PM - Socket Server disconnected
12/12 2:16 PM - GPS Restored
12/12 2:16 PM - Database connected
12/12 2:15 PM - Socket Server connected
12/12 2:15 PM - Database disconnected
12/12 2:15 PM - Lost GPS
12/12 1:55 PM - Socket Server disconnected
12/12 1:19 PM - Database connected
12/12 1:18 PM - Socket Server connected
12/12 1:18 PM - Database disconnected
12/12 1:18 PM - Socket Server disconnected
12/12 9:42 AM - Database connected
12/12 9:42 AM - Socket Server connected
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Figure 4: Survey route plan as shown on the SeaMachines SM300 User Interface.

Results

Emissions are often presented as mass normalized by energy for regulatory and many reporting purposes. Figure 5 shows energy weighted mass emissions of carbon dioxide (CO_2) from FTIR measurements for both repetitions of the automated and manual vessel test runs. The energy weighting is normalized by fuel lower heating value energy because no engine power output measurement was available. The error bars depict measurement uncertainty. Run to run repeatability is easily visualized from the figure and exhibited a coefficient of variation between 1% and 5% for nearly all measurements reported here. Figure 5 serves to validate CO_2 measurements and fuel flow rates as CO_2 emissions are directly proportional to fuel consumption. Therefore, normalizing CO_2 emissions by fuel flow energy should result in identical energy weighted emissions for all tests. This result is observed within measurement and repeatability uncertainty.

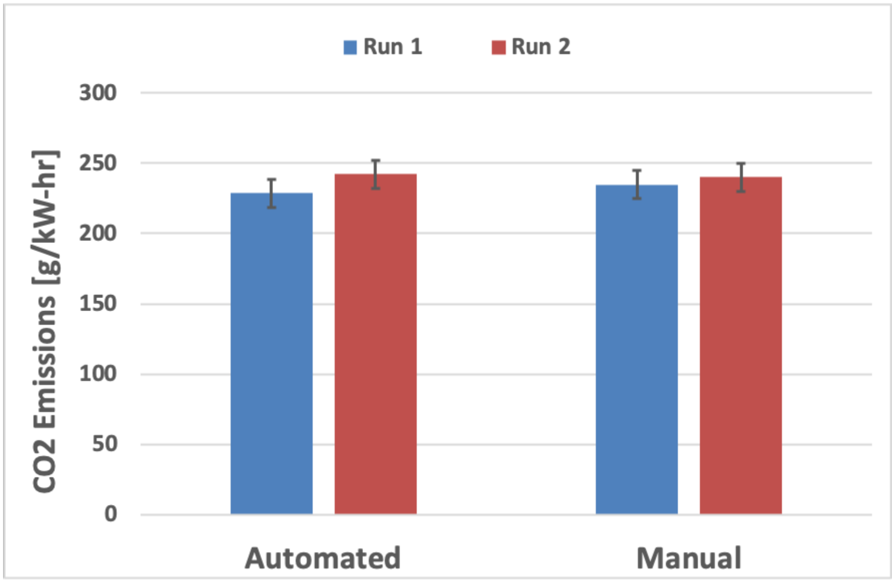

Figure 5: Energy weighted mass emissions of carbon dioxide (CO_2) from FTIR measurements for both repetitions of the automated and manual vessel test runs. Error bars depict measurement uncertainty.

For this study, it is more beneficial to compare total mass emissions from automated and manual vessel operation to determine potential emissions reductions. Figure 6 presents total mass emissions of carbon dioxide (CO_2) from FTIR measurements. Run to run repeatability error of less than 2.5%, determined by coefficient of variation, suggests that there is a statistically significant increase in total CO_2 emissions from the vessel operated in autonomous mode. Since CO_2 emissions are directly proportional to fuel consumption, this finding indicates that the vessel consumed more fuel and was thus operated at a higher load and greater speed on average in autonomous mode compared to manual mode. This finding is corroborated by a summation of fuel consumption for all test runs. Total fuel consumption for the autonomous runs was 9% higher than for the manual runs, in agreement with changes in CO_2 measurements within measurement and repeatability error. Furthermore, a simple theoretical calculation of CO_2 mass emissions can be calculated according to the equation:

$$m_{CO2} = m_{fuel} Y_{CO2} \frac{M_{CO2}}{M_C}$$

Where m_{fuel} is fuel consumption, Y_{CO2} is the mass fraction of carbon in the fuel, M_{CO2} the molar mass of a CO_2 molecule, and M_C the molar mass of a carbon atom. This calculation results in CO_2 emissions in good agreement with measurements within error, further validating the accuracy of fuel flow rates and CO_2 emissions measurements.

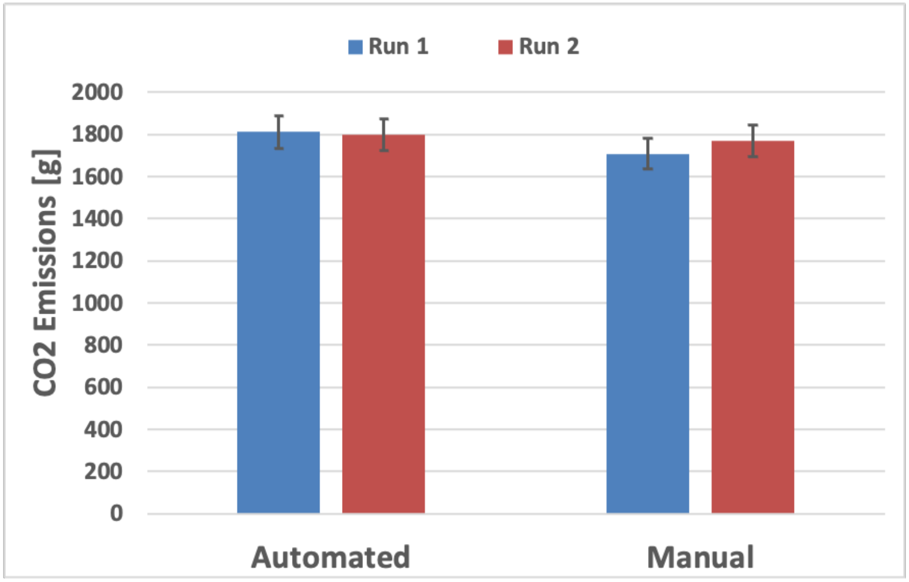

Figure 6: Total mass emissions of carbon dioxide (CO_2) from FTIR measurements for both repetitions of the automated and manual vessel test runs. Error bars depict measurement uncertainty.

Figure 7 shows total mass emissions of oxides of nitrogen (NOx) from FTIR measurements. Measurement precision, determined by coefficient of variation, suggests that there is a statistically significant increase in total NOx emissions from the vessel operated in autonomous mode. This result further agrees with the finding of an increase in CO_2 emissions as a higher engine load would result in greater combustion temperature, thereby resulting in increased NOx emissions.

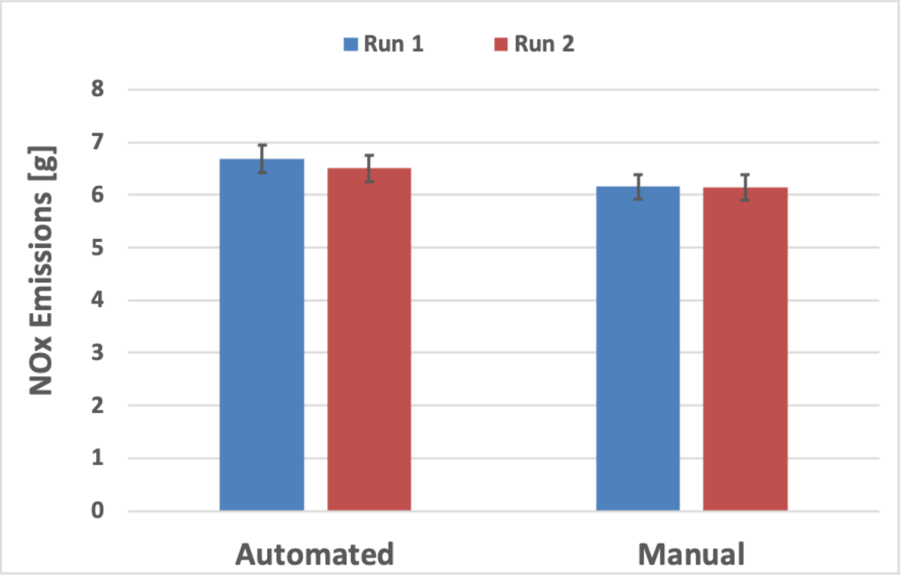

Figure 7: Total mass emissions of oxides of nitrogen (NOx) from FTIR measurements for both repetitions of the automated and manual vessel test runs. Error bars depict measurement uncertainty.

Figure 8 presents total mass emissions of carbon monoxide (CO) from FTIR measurements. No statistically significant changes in emissions were observed between automated and manual vessel operation due to a high coefficient of variation of 12% for the automated test runs, resulting in repeatability uncertainty overlap.

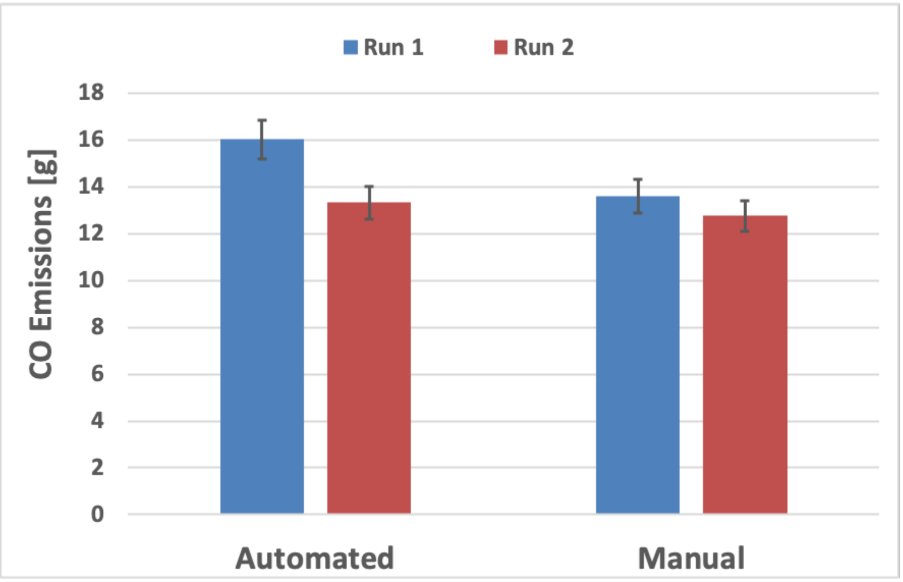

Figure 8: Total mass emissions of carbon monoxide (CO) from FTIR measurements for both repetitions of the automated and manual vessel test runs. Error bars depict measurement uncertainty.

Figure 9 presents total mass emissions of oxides of sulfur (SOx) from FTIR measurements. While measurement error is high, on the order of 100%, measurement precision determined by coefficient of variation still showed a statistically significant increase in SOx emissions with the vessel operating in autonomous mode. The presence of sulfur in diesel fuel results in SOx emissions exhibiting a proportional relationship to fuel consumption. The result further corroborates the findings of CO_2 and NOx emissions.

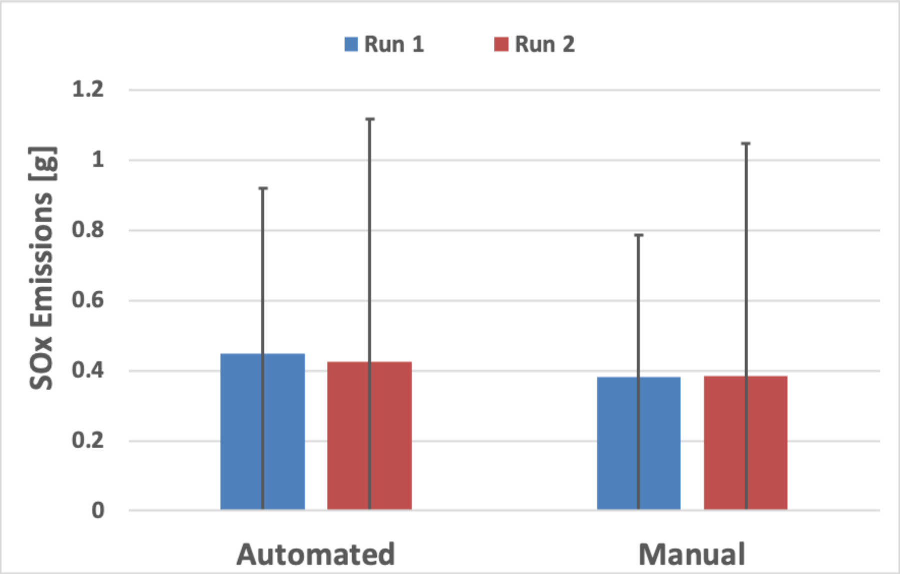

Figure 9: Total mass emissions of oxides of sulfur (SOx) from FTIR measurements for both repetitions of the automated and manual vessel test runs. Error bars depict measurement uncertainty.

Total unburned hydrocarbon emissions were measured, but exhibited a sustained downward trend and did not reach an equilibrium until several test runs were completed. Therefore, total unburned hydrocarbon emissions measurements were unreliable and are not reported in this study.

All emissions observations and fuel consumption measurements indicate that the vessel was operated at a higher average engine load during autonomous operation. This may be partially due to manually controlled tests being conducted at a slightly lower average speed than autonomous, strictly due to human ability to adjust throttle with sufficient precision compared to the automation system. The 6-knot speed setting also happened to coincide with throttle position just above throttle engagement, making human adjustment especially difficult. However, no vessel speed data was collected throughout the tests for verification of this hypothesis.

An additional observation is also evident when looking at the variability in raw emissions data over each individual run. Figure 10 and 11 show instantaneous fuel flow rates over the course of an autonomous and a manual test run, respectively. The comparison clearly illustrates that the autonomous control resulted in more transients at higher load than the manual control, resulting in greater average fuel consumption and therefore, higher emissions of CO2, NOx, and SOX. Raw emissions results corroborate these findings. The greater variability in fuel consumption and existence of transient high loads in autonomous control are likely due to small corrections in throttle made by the speed positioner control loop of the automation system. In contrast, the human vessel operators tended to manually set a throttle position corresponding to the desired average speed and then maintain that throttle position fixed throughout the test. It is likely that the autonomous control maintained speed closer to the desired 6 knots by responding to transient disturbances (as it was designed to do), at the expense of increased fuel consumption. If a minimization of emissions and fuel consumption were desired, reconfiguring the speed control loop could be considered to satisfy those requirements.

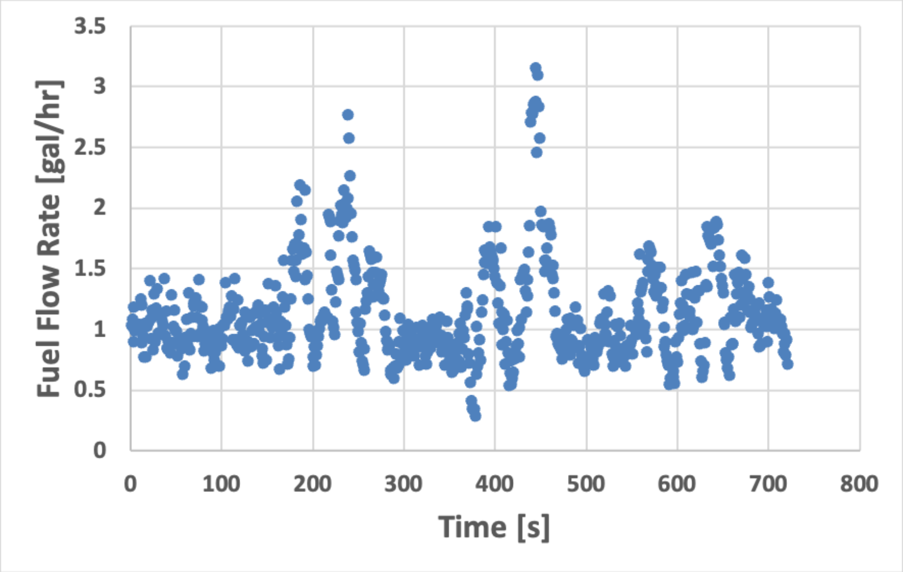

Figure 10: Instantaneous fuel flow rates of a vessel test under autonomous control.

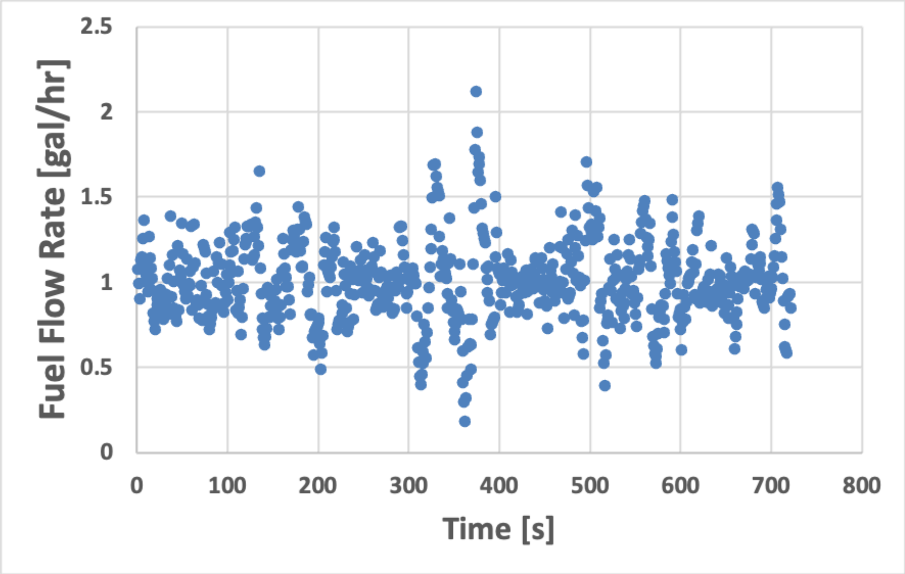

Figure 11: Instantaneous fuel flow rates of a vessel test under manual control.

Conclusions

The objective of this project was to compare emissions from a marine vessel operated in both manual and autonomous control. For this work, a 41ft diesel powered research vessel was outfitted with an autonomous control system and measurement instrumentation for determining gaseous emissions. A standardized survey route was chosen and emissions of carbon dioxide (CO_2), carbon monoxide (CO), oxides of nitrogen (NOx), Total Unburned Hydrocarbons (THC), and oxides of sulfur (SOx) were measured.

For this study, the autonomous tests resulted in increased emissions of CO2, NOx, and SOx. All emissions observations and fuel consumption measurements indicate that the vessel was operated at a higher average engine load during autonomous operation. This may be partially due to manually controlled tests being conducted at a slightly lower average speed than autonomous tests, due to human ability to adjust throttle with sufficient precision compared to the automation system. However, no vessel speed data was collected throughout the tests for verification of this hypothesis.

It was determined that autonomous control resulted in more transients at higher load than manual control, resulting in greater average fuel consumption and higher emissions of CO2, NOx, and SOX. The greater variability in fuel consumption and existence of transient high loads in autonomous control are likely due to small corrections in throttle made by the speed positioner control loop of the automation system. In contrast, the human vessel operators tended to manually set a throttle position corresponding to the desired average speed and then maintain that throttle position fixed throughout the test. It is likely that the autonomous control maintained speed closer to the desired 6 knots by responding to transient disturbances (as it was designed to do), at the expense of increased fuel consumption. If a minimization of emissions and fuel consumption were desired, reconfiguring the speed control loop could be considered to satisfy those requirements.