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EXHAUST EMISSIONS OF LOW LEVEL BLEND ALCOHOL FUELS FROM
TWO-STROKE AND FOUR-STROKE MARINE ENGINES

By

James M. Sevik Jr

A THESIS

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Mechanical Engineering

MICHIGAN TECHNOLOGICAL UNIVERSITY

2012

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This thesis has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Mechanical Engineering.

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Preface

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Figures 7 of [1] and Figure 9 of [2] are reprinted with permission of SAE International. Full permission can be seen in A.3.

Nomenclature

ABYC – American Boat and Yacht Council

BRP – Bombardier Recreational Products

CLD - chemiluminescence detector

CO₂ – carbon dioxide

CO – carbon monoxide

ECM – engine control module

ECU – engine control unit

FID – flame ionization detector

ICOMIA – International Council of Marine Industry Associations

NDIR – non dispersive infra-red

NDUV – non dispersive ultra-violet

NMMA – National Marine Manufacturers Association

NO₂ – nitrogen dioxide

NO – nitrogen monoxide

NO_x – oxides of nitrogen

RVP – Reid vapor pressure

THC – total hydrocarbon

WOT – wide open throttle

Abstract

The U.S. Renewable Fuel Standard mandates that by 2022, 36 billion gallons of renewable fuels must be produced on a yearly basis. Ethanol production is capped at 15 billion gallons, meaning 21 billion gallons must come from different alternative fuel sources [3]. A viable alternative to reach the remainder of this mandate is iso-butanol. Unlike ethanol, iso-butanol does not phase separate when mixed with water, meaning it can be transported using traditional pipeline methods. Iso-butanol also has a lower oxygen content by mass, meaning it can displace more petroleum while maintaining the same oxygen concentration in the fuel blend [3].

This research focused on studying the effects of low level alcohol fuels on marine engine emissions to assess the possibility of using iso-butanol as a replacement for ethanol. Three marine engines were used in this study, representing a wide range of what is currently in service in the United States. Two four-stroke engine and one two-stroke engine powered boats were tested in the tributaries of the Chesapeake Bay, near Annapolis, Maryland over the course of two rounds of weeklong testing in May and September. The engines were tested using a standard test cycle and emissions were sampled using constant volume sampling techniques.

Specific emissions for two-stroke and four-stroke engines were compared to the baseline indolene tests. Because of the nature of the field testing, limited engine parameters were recorded. Therefore, the engine parameters analyzed aside from emissions were the operating relative air-to-fuel ratio and engine speed.

Emissions trends from the baseline test to each alcohol fuel for the four-stroke engines were consistent, when analyzing a single round of testing. The same trends were not consistent when comparing separate rounds because of uncontrolled weather conditions and because the four-stroke engines operate without fuel control feedback during full load conditions. Emissions trends from the baseline test to each alcohol fuel for the two-stroke engine were consistent for all rounds of testing. This is due to the fact

the engine operates open-loop, and does not provide fueling compensation when fuel composition changes. Changes in emissions with respect to the baseline for iso-butanol were consistent with changes for ethanol. It was determined iso-butanol would make a viable replacement for ethanol.

1. Introduction

There is a need to understand the effect of increasing alcohol fuel concentrations on the marine recreational industry. As the percentage of ethanol content in fuel available at the gas pump increases, adverse effects on marine engines not capable of compensating for an increase oxygen concentration, can occur. For example, enleanment of the engine can take place, causing catastrophic damage.

1.1 Renewable Fuel Standard

In 2005, the Renewable Fuel Standard (RFS) was created under the Energy Policy Act. The RFS was the first renewable fuel mandate, specifically stating the quantity of a renewable fuel needed to be produced each year [4]. In 2007, the Energy Independence and Security Act (EISA) expanded the RFS in multiple ways. The EISA expanded a section to include diesel, increasing the amount of renewable fuel required to be blended into transportation fuels to 36 billion gallons by 2022, and renewable fuels were placed into distinctive categories. Under the RFS, corn-based ethanol is capped at 15 billion gallons by 2015, requiring the remaining 21 billion gallons to come from other biofuels [5].

1.2 Well to Wheels

Ethanol and iso-butanol are both alcohol fuels, derived from renewable resources such as corn, grass, and waste biomass [6]. Both ethanol and iso-butanol create difficulties when going from the original source, to the wheels of motorists. Ethanol is 100% miscible in water, and will phase separate from gasoline if introduced to water. Iso-butanol is only 8.5% miscible in water, and therefore will not phase separate as easily as ethanol. However, iso-butanol is corrosive, similar to ethanol.

Ethanol and iso-butanol blended fuels have their own characteristic route when analyzed in a well to wheel perspective; that is, the process taken from the initial steps

where the oil is drawn from the ground to filling the consumer's tank. Figure 1.1 shows a flow chart of the process used to produce ethanol blended fuels.

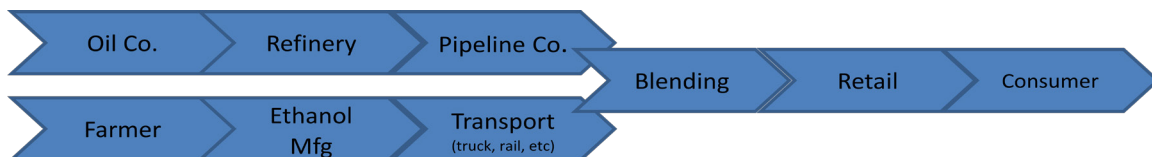


Figure 1.1: Well-to-wheel analysis of ethanol blended fuels

Accordingly, Figure 1.2 shows the well to wheel analysis of iso-butanol blended fuels. As seen, there are inherently more steps involved to produce ethanol blended gasoline than iso-butanol blended gasoline.

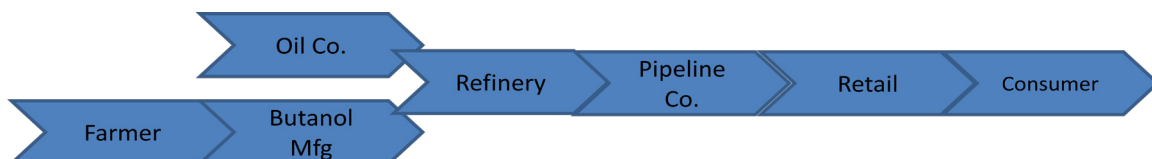


Figure 1.2: Wheel-to-wheel analysis of iso-butanol blended fuels

The main difference between the two fuels is seen at the blending step. Because of ethanol's miscibility, it cannot be blended at the refinery. Blending fuel at the refinery has intrinsic advantages as opposed to blending at the pump. The overall cost of the fuel decreases because there are less intermediary steps with getting the fuel to the consumer. Blending at the refinery allows for a higher quality fuel to be produced because there is tighter control of the blending process, as opposed to blending the fuel at the pump. Eliminating the need to transport the fuel, using means such as truck or rail, reduces the overall greenhouse gas emissions over the lifecycle of the fuel. In total, this allows for a higher quality fuel for the consumer, potentially improving fuel economy and reducing the risk of low quality fuel for the auto, marine, and small engine industry.

1.3 Oxygen Concentrations

With the removal of lead as a fuel oxygenate in the 1970's, fuel refiners were forced to find different materials to boost the octane rating of gasoline. Methyl tertiary butyl ether (MTBE) and ethanol were used in the late 1970's and early 1980's as an oxygenate replacement to lead [7]. In 1998 the US's yearly production of MTBE was up to 2.8 billion gallons, and concerns about environmental and health risks of MTBE increased. The California Air and Resources Board (CARB) produced the Reformulated Gasoline (RFG) guidelines, to be implemented in three phases [8]. Effective in 2003, the third phase of the CARB RFG set a cap on oxygenate in gasoline to 3.5wt%. With the prohibition of MTBE following in 2004, ethanol was found to be the only viable source to reach the 3.5wt% limit, required by some states [7].

For comparison purposes, pure ethanol has 35% oxygen by mass, while iso-butanol has 21.5% oxygen by mass. Accordingly, the lower heating value of ethanol and iso-butanol are 20.0 and 32.96 MJ/kg, respectively. As seen in Figure 1.3, iso-butanol provides the same oxygen concentration at 16Vol% as 10Vol% ethanol, while displacing 6% more petroleum based fuels [3]. For comparison purposes, an 83Vol% blend of iso-butanol will yield the same oxygen concentration by mass as a 50Vol% blend of ethanol. Iso-butanol provides the opportunity to meet the same oxygen concentrations as ethanol blends, while further displacing petroleum based fuels, consequently decreasing foreign oil dependence. Also seen in Figure 1.3, iso-butanol maintains a higher lower heating value as blend ratio with neat gasoline is increased.

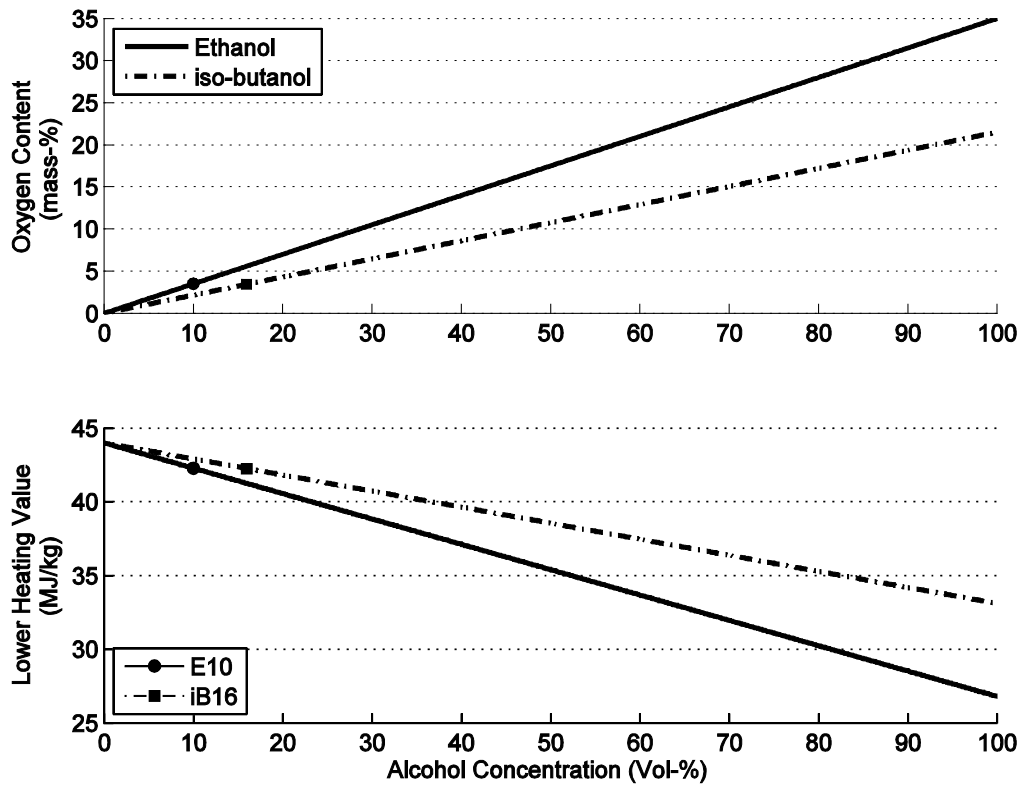


Figure 1.3: Oxygen content and lower heating value of alcohol blended fuels

To further reinforce data presented in Figure 1.3, Table 1.1 shows specific blends of ethanol and iso-butanol, with their respective oxygen concentrations. Based off of 2011 estimates, the United States consumes 18.84 million barrels of oil per day [9]. Replacing 10Vol% ethanol with 16.1Vol% iso-butanol would displace 3.03 million barrels of oil consumed daily.

Table 1.1: Oxygen content of varying blends of ethanol and iso-butanol

	10% Ethanol	16.1% Iso-butanol	15% Ethanol	24.2% Iso-butanol
Oxygen Content (Wt%)	3.5	3.5	5.2	5.2

1.4 Research Goals and Objectives

The goal of this research was to study the effects of low level blend alcohol fuels on two-stroke and four-stroke marine engine emissions. There were four main objectives in this study:

- Develop baseline emissions using indolene fuel
- Perform tests with 10% ethanol and compare with baseline data
- Perform tests with 16% iso-butanol and compare emissions trends with the baseline and 10% ethanol data
- Based off of emissions results, determine if iso-butanol will be a viable substitute for ethanol, as well as being an amiable fuel to fill the gap in the RFS

Three marine engines were tested in this research, which provide a representative sample of the engines currently in service in the marine recreational industry. Field testing was performed in the tributaries of the Chesapeake Bay near Annapolis, Maryland. Each boat was tested over an adapted ICOMIA test cycle, with emissions being sampled using constant volume sampling techniques. A Sensors Inc. Semtech-DS five gas emissions analyzer was used to analyze emissions from the constant volume samples.

Testing was performed in May and September of 2012, providing a comparison for emissions results. Two constant volume emissions samples were taken per fuel, for each boat. Two tests were performed to evaluate repeatability on a test-to-test basis. Engine and boat speed data sets were also recorded to reveal any variability incurred during field testing.

2. Background/Literature Review

In the recreational marine industry, there is a growing concern over the increasing alcohol content in fuels available from the pump. Many engines in the marine industry, regardless of fuel delivery strategy, operate in an open-loop manner. An engine operating in an open-loop manner does not offer any compensation when there is a change in the oxygen content of the fuel, whereas an engine operating closed-loop provides feedback and changes fueling when oxygen concentrations change via a wideband sensor. As the percentage of alcohols increases in the fuel, open-loop engines run the risk of enleanment, which can cause catastrophic engine failure. In addition, increasing alcohol concentration has a direct impact on emissions.

2.1 Effects of Alcohol Fuels on Emissions

The following literature review aims to show the effects of alcohol fuels on both two-stroke and four-stroke engines, which operate in closed-loop and open-loop operation. Because numerous literature sources for marine engines are not readily available, literature utilizing engines with similar technologies are referenced.

Alcohol fuels such as pure ethanol (E100) and pure iso-butanol (iB100) have clear distinct advantages over neat gasoline. E100 and iB100 have a higher octane rating than neat gasoline, making them more resistant to engine knock [3]. E100 and iB100 also have a higher flame speed, decreasing burn duration. Conversely, alcohol fuels are corrosive, which can be detrimental to an engine and fuel system. These differences from the neat gasoline baseline will affect engine-out emissions

2.1.1 Impact of Ethanol Fuels on Regulated Tailpipe Emissions – Four-Stroke Engines [10]

For this study, researchers used a 2006 Chrysler Town & Country minivan featuring a 3.3 liter closed-loop, port fuel injected, liquid cooled, spark ignited engine. A series of EPA FTP 75 test cycles were performed on a chassis dynamometer, a test cycle which is used to perform emissions certification for light duty vehicles. Constant volume

emissions sampling techniques were performed using an AVL GEM 110 analyzer with Rosemount analyzers for total hydrocarbon (THC), oxides of nitrogen (NO_x), carbon dioxide (CO₂), and carbon monoxide (CO). This flex-fuel vehicle was tested running 0%, 10%, 20%, and 85% ethanol by volume.

The emissions of interest recoded in this study were THC, CO, CO₂, and NO_x, seen in Table 2.1. A decrease in THC, CO, CO₂, and NO_x emissions were seen for increasing ethanol content in the test fuel. Decreases in THC and CO were due to higher flame speeds of alcohol fuels. NO_x decreased due to the charge cooling effect of alcohol fuels. NO_x and THC trends will be insightful for the four-stroke engines, which operated closed-loop except for wide open throttle conditions.

Table 2.1: Emissions change with respect to E0, for increasing alcohol concentration

	THC (%)	CO (%)	CO ₂ (%)	NO _x (%)
(E10-E0)/E0	-45.17	-83.24	-3.50	-57.48
(E20-E0)/E0	-58.49	-83.40	-3.25	-60.16
(E85-E0)/E0	-60.51	-82.07	-8.93	-74.08
(E20-E10)/E10	-24.30	-0.92	0.26	-6.29

2.1.2 In-Use Performance Testing of Butanol-Extended Fuel in Recreational Marine Engines and Vessels [1]

Field testing was performed for this study, and two different engines were tested. A 15ft Mako Center Console fishing boat was equipped with a BRP Evinrude E-Tec™ two-stroke outboard engine, featuring spray-guided direct fuel injection, stratified charged fuel delivery. A 24 foot SeaDoo Challenger boat was also tested, utilizing twin four-stroke liquid cooled supercharged 215HP SeaDoo Rotax™ engines, and featuring a single overhead cam. Testing took place in Chesapeake, Virginia using the five-mode weighted ICOMIA test cycle. A Marine Portable Bag Sampling System (MPSS) was used to measure emissions of THC, NO_x, and CO. As standard with the marine industry, emission values were reported on a THC+NO_x basis for certification gasoline and 16% iso-butanol.

For the Evinrude E-TEC™ engine, seen in Figure 2.1, there was an increase in NO_x for the iB16 case. Engines running open-loop operation typically see an increase in NO_x emissions because oxygen is being introduced with the fuel, and the engine cannot compensate for the increased oxygen concentration. This pushes combustion closer to higher temperature stoichiometric levels. The changes in THC emissions were not appreciable with a change in fuel.

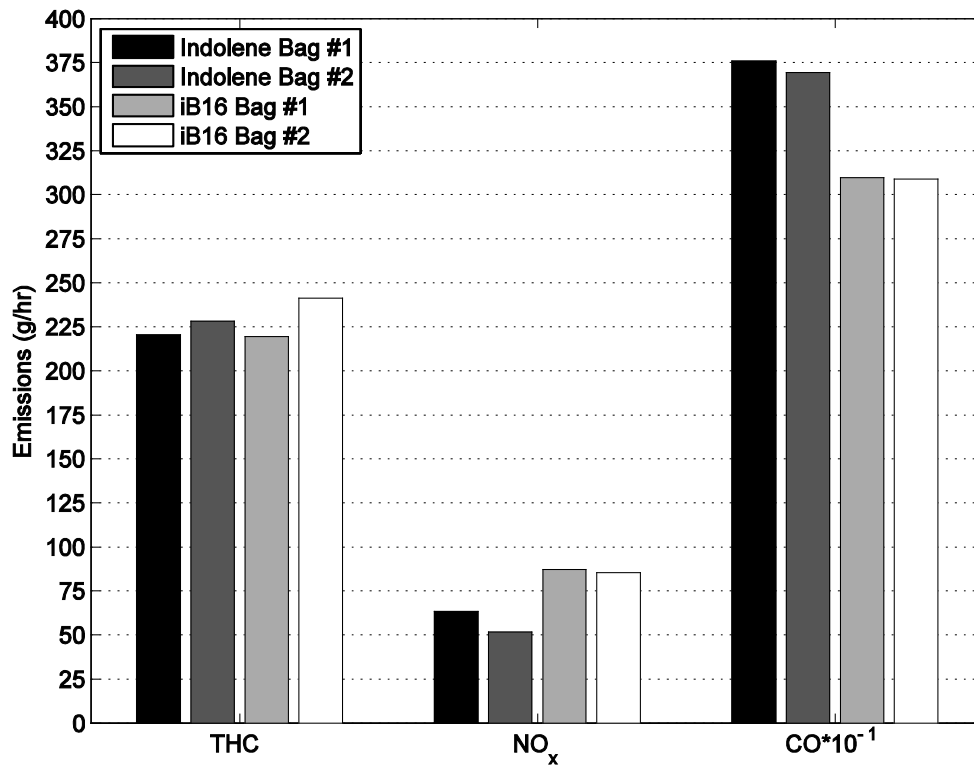


Figure 2.1: Evinrude E-TEC™ THC, NO_x, and CO emissions for indolene and iB16

Seen in Figure 2.2, THC emissions for the four-stroke SeaDoo Rotax™ engine decreased for iB16, with respect to the indolene baseline. THC decreased because the SeaDoo Rotax engine operates open-loop for all five modes of the ICOMIA test cycle, and with an increased oxygen concentration in the fuel, the engine operates closer to stoichiometric conditions. The increase in NO_x emissions can also be explained by the

engine operating closer to stoichiometric conditions, increasing combustion temperatures allowing for more diatomic N_2 to dissociate and form NO_x .

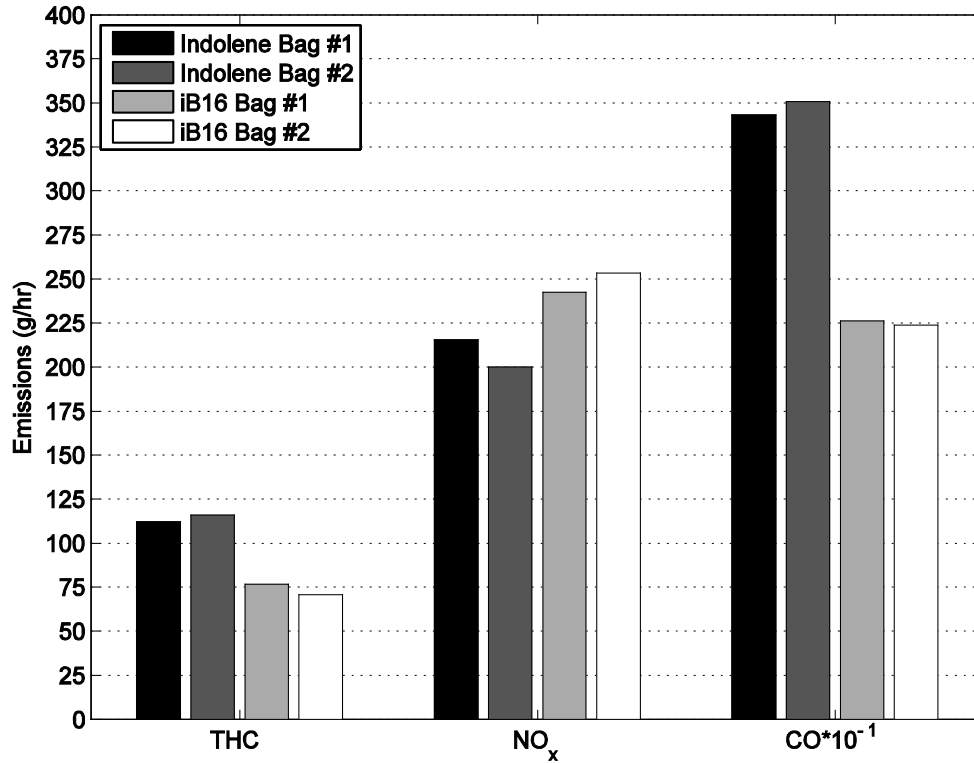


Figure 2.2: SeaDoo Rotax™ THC, NO_x , and CO emissions for indolene and iB16

Trends discussed for both the two-stroke and four-stroke engines will help to reinforce findings performed in this research. Results from the four-stroke SeaDoo Rotax will be important, because the four-stroke engines tested operate in an open-loop manner during wide open throttle (WOT) conditions.

2.1.3 Impact of E22 on Two-Stroke and Four-Stroke Snowmobiles [11]

Testing was performed using three snowmobiles, each with varying engine technologies. A 2009 Arctic Cat Z1 Turbo Touring featured a two-cylinder, four-stroke liquid cooled, turbo-charged, intercooled engine utilizing closed-loop, throttle body fuel injection. A 2009 Yamaha Apex featured a liquid cooled four-cylinder, four-stroke

engine, running open-loop with port fuel injection. A 2010 Polaris Rush featured a two-cylinder, two-stroke liquid cooled engine, running open-loop and semi-direction injection. A four mode test cycle was performed, using a water brake dynamometer to set all speed and load points. A Horiba MEXA 1600D emissions analyzer was used to sample raw exhaust emissions while running 0% and 22% ethanol.

Testing performed on the Yamaha Apex, seen in Figure 2.3, showed a decrease in THC and CO emissions and an increase in CO₂ emissions, with respect to baseline tests. Because the engine operates open-loop, lambda on a per mode basis will approach stoichiometric conditions, leaning out the air-fuel ratio. THC and CO emissions are both decreased in leaner operation. The increase in oxygen content delivered with the fuel to the combustion event also contributed to an increase in CO₂ emissions.

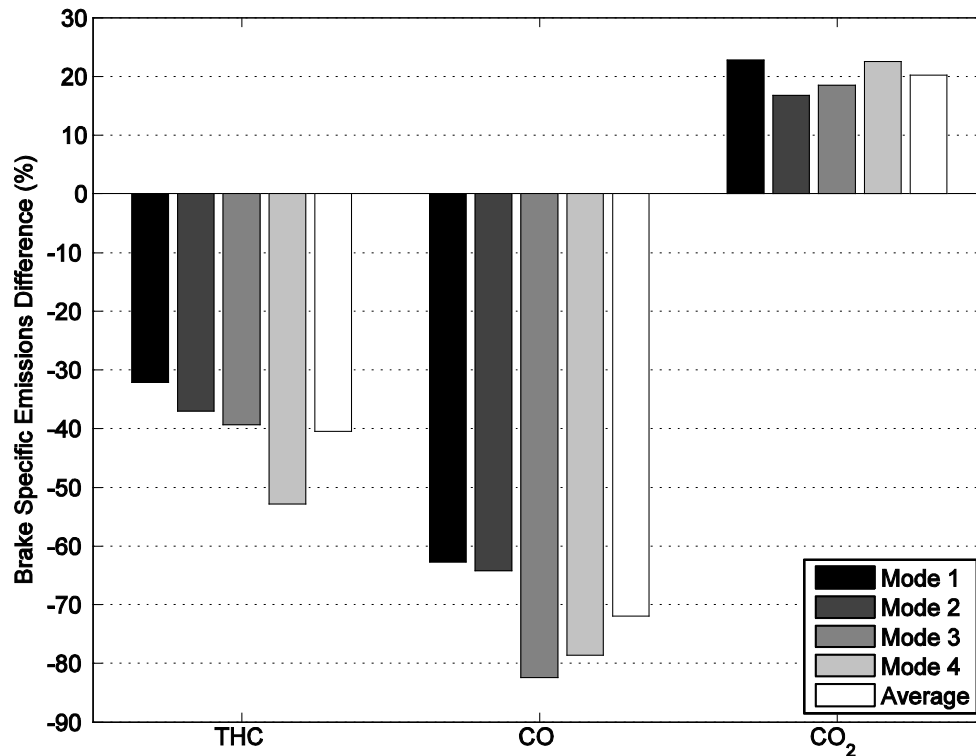


Figure 2.3: Brake specific change in emissions on the Yamaha Apex

Testing performed on the Polaris Rush, seen in Figure 2.4, showed a decrease in THC and CO emissions and an increase in CO₂ emissions, with respect to baseline tests. The Polaris Rush saw similar trends in changes of exhaust emissions, because both engines operate open loop, offering no compensation for changing oxygen content of the fuel. Changes at Mode 1 for the Polaris Rush are smaller with respect to other snowmobiles in this study because of the fuel calibration, controlled by a resistor. Polaris includes resistors for E0 and E10 operation, which change fueling management; the E10 resistor was used for E22 operation, not accounting for the higher ethanol content of E22.

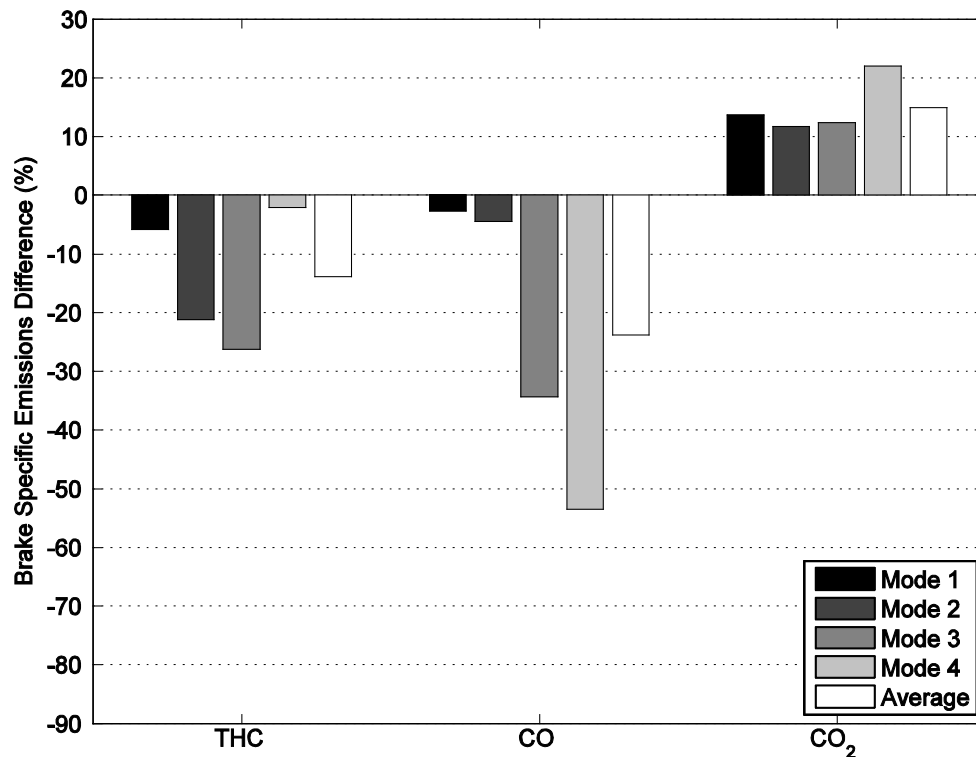


Figure 2.4: Brake specific change in emissions on the Polaris Rush

Testing performed on the Arctic Cat Z1 Turbo Touring, seen in Figure 2.5, shows a decrease in THC and CO emissions, while an increase in CO₂ emissions. Emissions trends for this engine follow the two aforementioned snowmobiles, but with a smaller

change with respect to the baseline tests. This is due to the closed-loop operation of the engine, keeping an air-to-fuel ratio closer to that of the stock factory calibration.

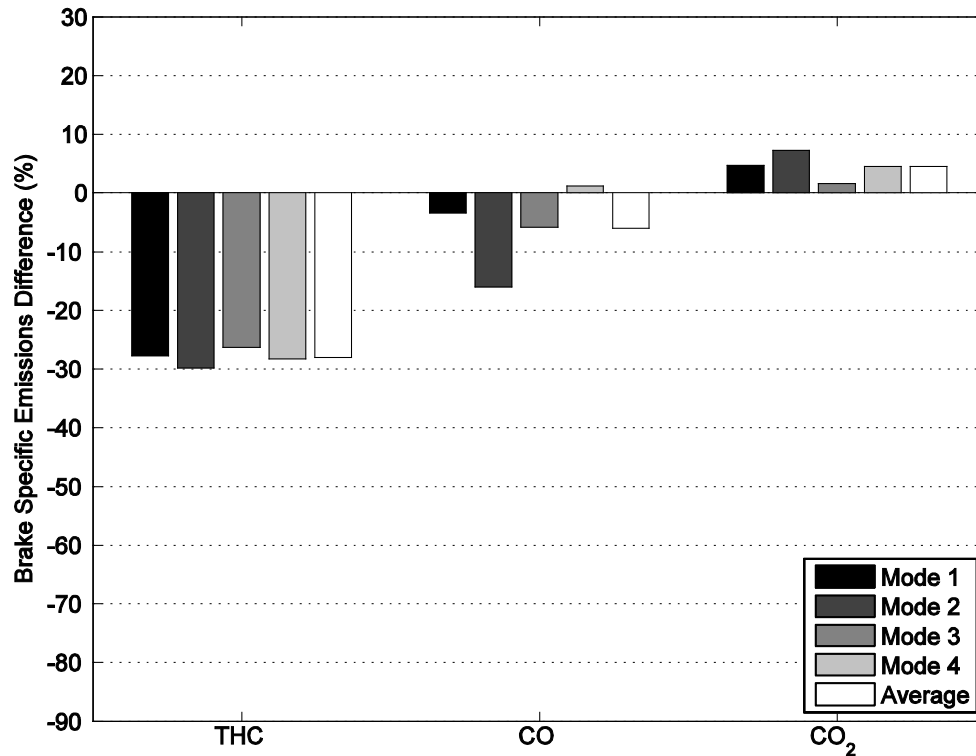


Figure 2.5: Brake specific change in emission on the Arctic Cat Z1 Turbo Touring

2.1.4 Effect of Alcohol Blended Fuels on the Emissions and Field Performance of Two-Stroke and Four-Stroke Engine Powered Two Wheelers [12]

For this study, four two-stroke, single cylinder, 145cc scooters were tested over the same fuels on a Mileage Accumulation Chassis Dynamometer (MACD), accumulating mileage all the way up to 20,000 km. THC, CO, CO₂, and NO_x emissions were analyzed using a Horiba MEXA 9400D emissions analyzer. Each scooter was tested with operation on 0%, 5%, 10% ethanol.

Research performed on two-stroke scooters focused on the impact of increasing alcohol concentrations, as engine age increased. Seen in Figure 2.6, there was an increase

in THC emissions as engine age increased, regardless of fuel. This can be explained by clearances of the engine becoming larger, increasing crevice volumes which aid in the THC formation process.

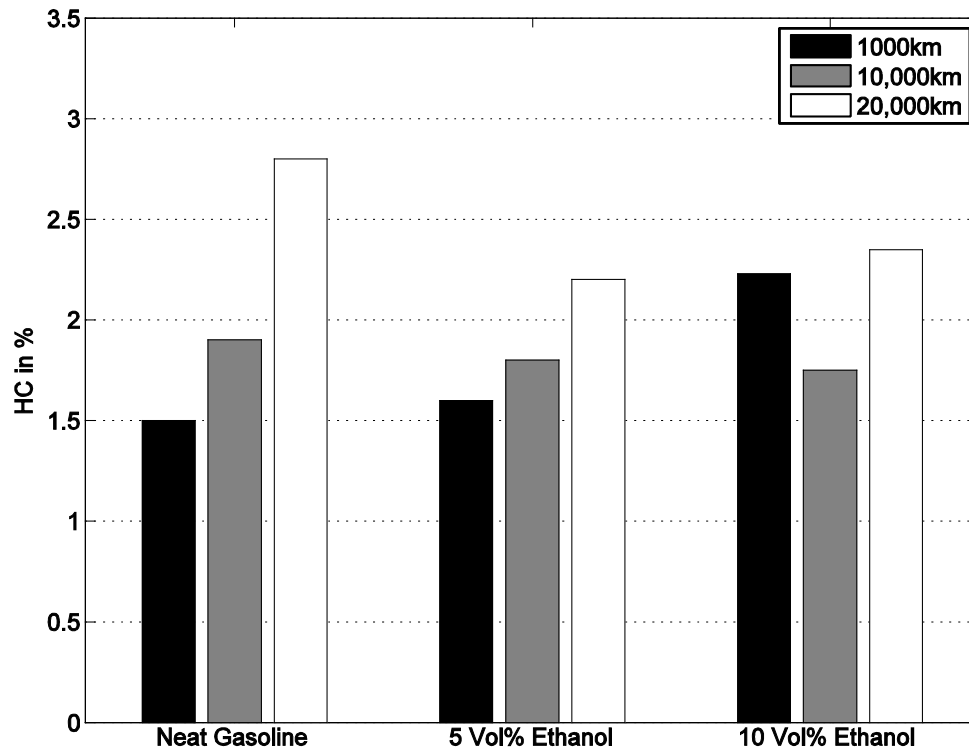


Figure 2.6: HC emissions of two-stroke scooters with varying alcohol blends

Seen in Figure 2.7, there was a decrease in CO emissions for the E5 and E10 case, as engine age increased past the 1000km mark. As oxygen was introduced with the fuel, more oxygen was available for the combustion process, reducing CO. The author attributes the increase in CO emissions with age for indolene operation to hydrocarbon buildup on the exhaust port. The author does not provide explanation why there is an increase in CO with increasing alcohol content, for the 1000km test.

Trends seen in this study for CO and THC will be important in understanding the two-stroke emissions data, because both engines deliver fuel in a similar manner, while also operating open-loop.

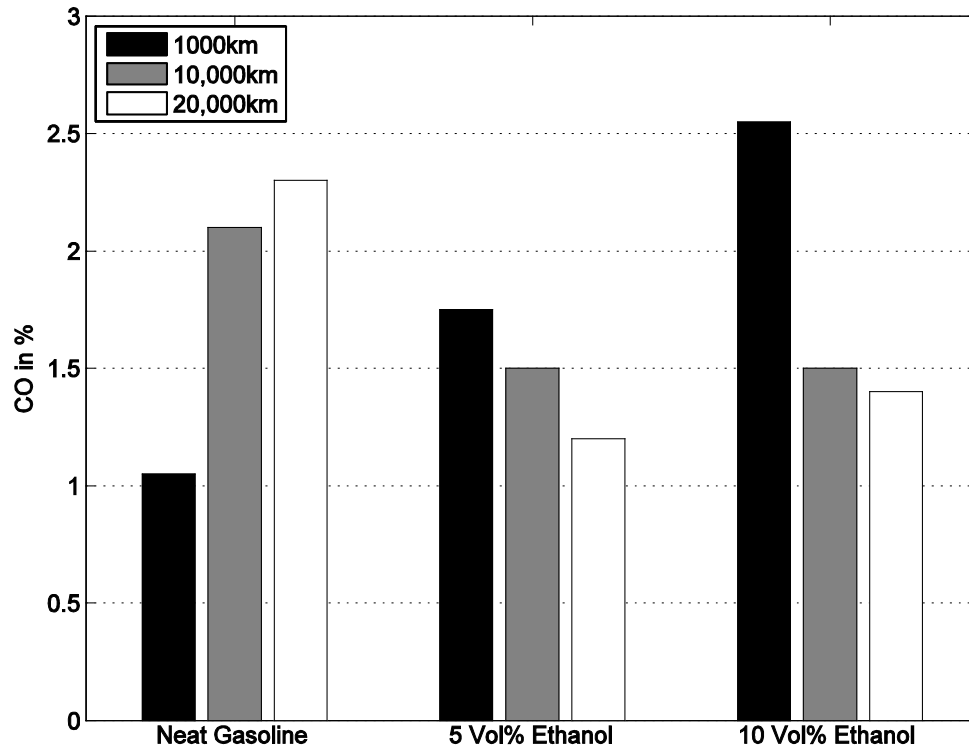


Figure 2.7: CO emissions of two-stroke scooters with varying alcohol blends

2.1.5 Influence of the Alcohol Type and Concentration in Alcohol-Blended Fuels on the Combustion and Emission of Small Two-Stroke SI Engines [2]

The exhaust emissions of hand-held maintenance equipment are of importance, because of the users close interaction with the exhaust. For this study, a 45.6 cc two-stroke, crankcase scavenged, external mixture formation power tool was used. Crank resolved cylinder pressure data sets were recorded, as well as exhaust back pressure. Constant volume emissions sampling techniques were used, utilizing an AVL SORE AMAi60-COMBI and AVL SESAM i60 FR 5Hz Fourier Transform Infrared Spectroscope (FTIR) for emissions analysis. Varying blends of ethanol, 1-butanol, and 2-

butanol were tested, separated into two categories of research octane number (RON) 95 and Alkylate fuel, which differ in their hydrocarbon fractions. The Alkylate fuel was developed specifically for use in hand-held power tools, by reducing the percentage of aromatic compounds to nearly zero to reduce the amount of aromatic hydrocarbons produced, such as benzene. Accordingly, the Alkylate fuel contained twice the amount of iso-Paraffin compounds as the RON 95 fuel. The RON 95 fuel is an example of what is available commercially.

With testing performed running a 45.6 cc handheld powertool, there was a definitive decrease in THC and NO emissions with increasing alcohol concentration regardless of base fuel, as seen in Figure 2.8. Because fuel delivery is controlled with a carburetor, the engine cannot compensate for an increased oxygen concentration of the fuel. A decrease in THC emissions for ethanol, 1-butanol, and 2-butanol were seen, caused by the engine operating in a more efficient combustion zone, near stoichiometric. A clear decrease in NO emissions was also seen for ethanol, 1-butanol, and 2-butanol. Cylinder pressure data recorded for this study shows that there was a decrease in burn duration, with increasing alcohol concentrations. The author states that the shorter burn duration allowed for the fuel to be oxidized quicker, but does not provide an analysis past that.

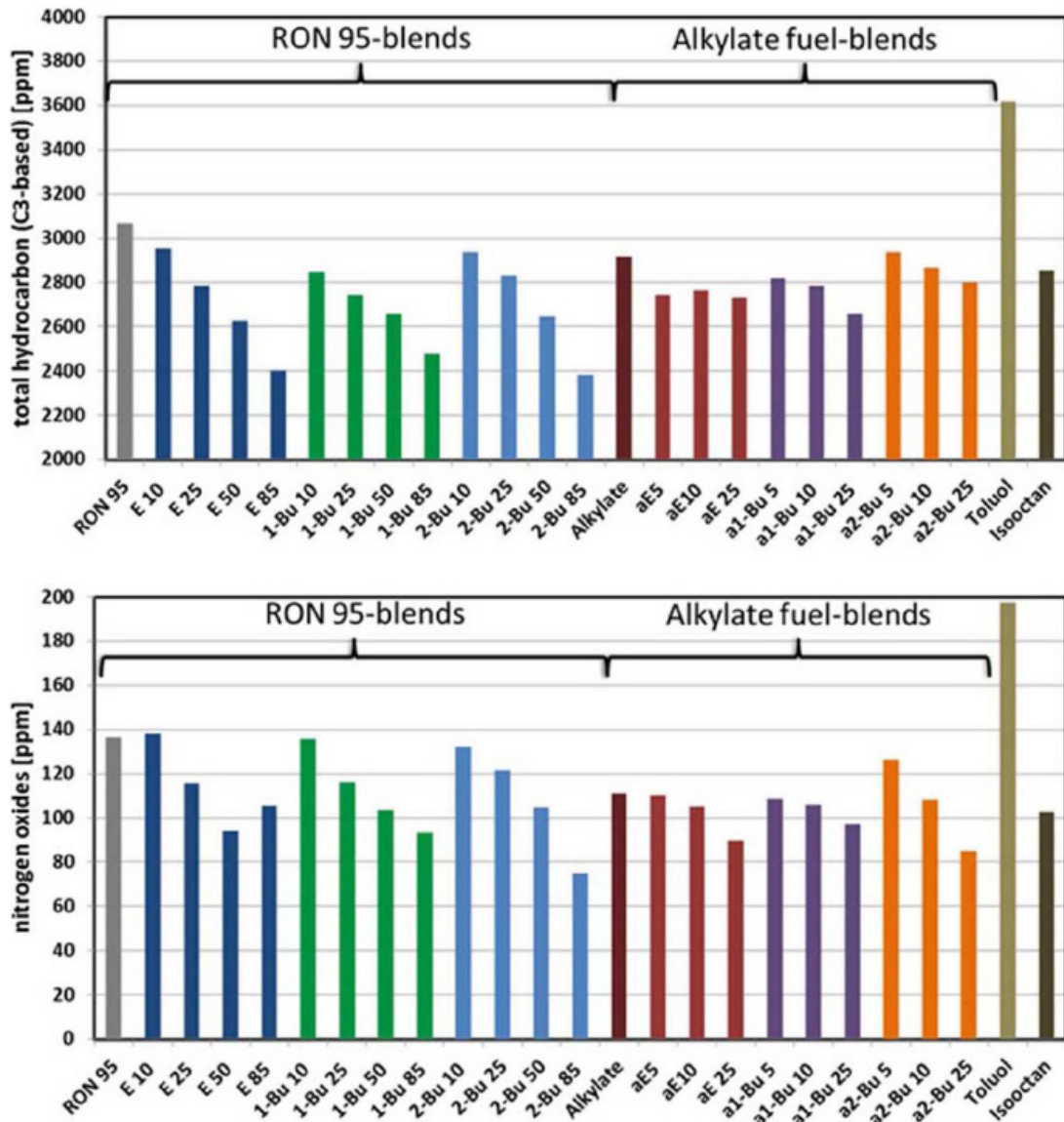


Figure 2.8: THC and NO emissions for 45.6cc handheld power tool [2]

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The NO trends shown in Figure 2.8 will provide insight to emission trends recorded for the two-stroke outboard engine. The NO trend seen in Figure 2.8 with increasing alcohol concentration is contradictory to that of Figure 2.1. Although both engines are two-stroke, differing engine technologies such as fuel injection and carburetion, may be the root cause of the difference.

2.2 Literature Review Summary

Four of the five studies show a clear decrease in THC emissions as alcohol concentration increased, with respect to the baseline gasoline. For engines operating open-loop, an increase in oxygen concentration in the fuel causes the global lambda values to approach stoichiometric conditions. There were more oxygen atoms present to oxidize the fuel during these conditions, allowing for more efficient combustion. Engines operating closed-loop were able to compensate for changes in oxygen concentration. A strong decrease in THC emissions for the Chrysler Town & Country vehicle was seen due to higher flame speeds, allowing for a more complete combustion event. It is also theorized that oxygenated THC's deteriorate in the exhaust stream, but this is not a well understood or documented phenomenon.

NO emissions varied from study to study, appearing to be predominantly controlled by engine technology. Four-stroke engines operating closed-loop showed a consistent decrease in NO emissions with increasing oxygen concentration. The engine is able to compensate for an increase in oxygen concentration introduced by the fuel, and holds lambda at a constant stoichiometric condition. Engines that operate open-loop cannot compensate for changes in oxygen concentration. As the mixture is leaned out towards stoichiometric conditions, the NO formation mechanism is triggered by the increase in combustion temperatures.

There is a different trend between the two-stroke emissions, as seen by Wasil et al. [1] and Bertsch et al. [2]. The first engine is a spray guided direct injection two-stroke, which finely controls the fuel delivery process. The second engine is a two-stroke carbureted engine, with fuel delivery being controlled by the pressure difference across the carburetor. The E-Tec engine, although not truly closed-loop, has provisions built into the engine allowing for fuel flow to be changed based off operating conditions. Conversely, the 45.6cc handtool does not provide any compensation for differing fuels. In order to make the same power level with an alcohol fuel, more fuel needs to be delivered. Increasing the amount of alcohol fuel delivered decreases combustion

temperatures because of the charge cooling effect introduced when inducting an alcohol fuel through the crank case.

3. Experimental Setup

The goal of this research was to investigate the effects of alcohol fuels on marine engines. Three different engines from different manufactures were tested, providing a representative sample of the engines available in the marine industry today. Tests were performed on a baseline certification test fuel and subsequent runs were performed running E10 (10% ethanol 90% gasoline by volume) and iB16 (16% iso-butanol 84% gasoline by volume). The two oxygenated fuels have the same oxygen concentration by mass, as specified by the EPA. Each boat was tested on the water using an adapted five-mode ICOMIA test cycle.

Each engine was tested on all three fuels, with two cycles being performed per fuel. Performing two test cycles per fuel enables test-to-test repeatability to be studied for each given fuel. Post catalyst emissions were sampled using Bombardier Recreational Products (BRP) MPSS [1], which places raw exhaust gas into special emissions bags. From there, a Sensors-Inc. Semtech five-gas raw emissions analyzer sampled the weighted emissions from Tedlar© emissions bags.

3.1 ICOMIA Test Cycle

The International Council of Marine Industry Associations (ICOMIA) developed a five mode weighted test cycle used to certify marine engines, known as the ICOMIA test cycle [13].

Table 3.1 outlines the different engine speed, torque, and emissions weightings for each mode.

An example calculation of a weighted emission constituent is seen in Equation 3.1; CO is used for this case, but the weightings apply to any emissions constituent.

$$CO_{weighted} = CO_{Mode1} * 0.06 + CO_{Mode2} * 0.14 + CO_{Mode3} * 0.15 + CO_{Mode4} * 0.25 + CO_{Mode5} * 0.40 \dots\dots\dots Eqn 3.1$$

Table 3.1: Weighting factors for ICOMIA Test Cycle (ISO #8178)

Mode	% RPM	% Torque	% Weighting Factor for Emissions
1	100	100	6
2	80	71.6	14
3	60	46.5	15
4	40	25	25
5	Idle	0	40

For the testing in Annapolis, MD, a maximum engine speed was found for each engine. From there, the maximum engine speed was given the respective weighting for each respective mode. Since engine torque was not able to be controlled during the field testing, torque was allowed to vary based off of water and throttle conditions. The EPA sets a Not-To-Exceed (NTE) zone, seen in Figure 3.1, for typical operation of recreational craft, based off of various operating conditions [1]. Given these guidelines, it was assumed the engine torque never deviated outside of the NTE zones. Therefore, an adaptation of the five-mode ICOMIA test cycle was performed in the field, subsequently referred to as the adapted ICOMIA test cycle.

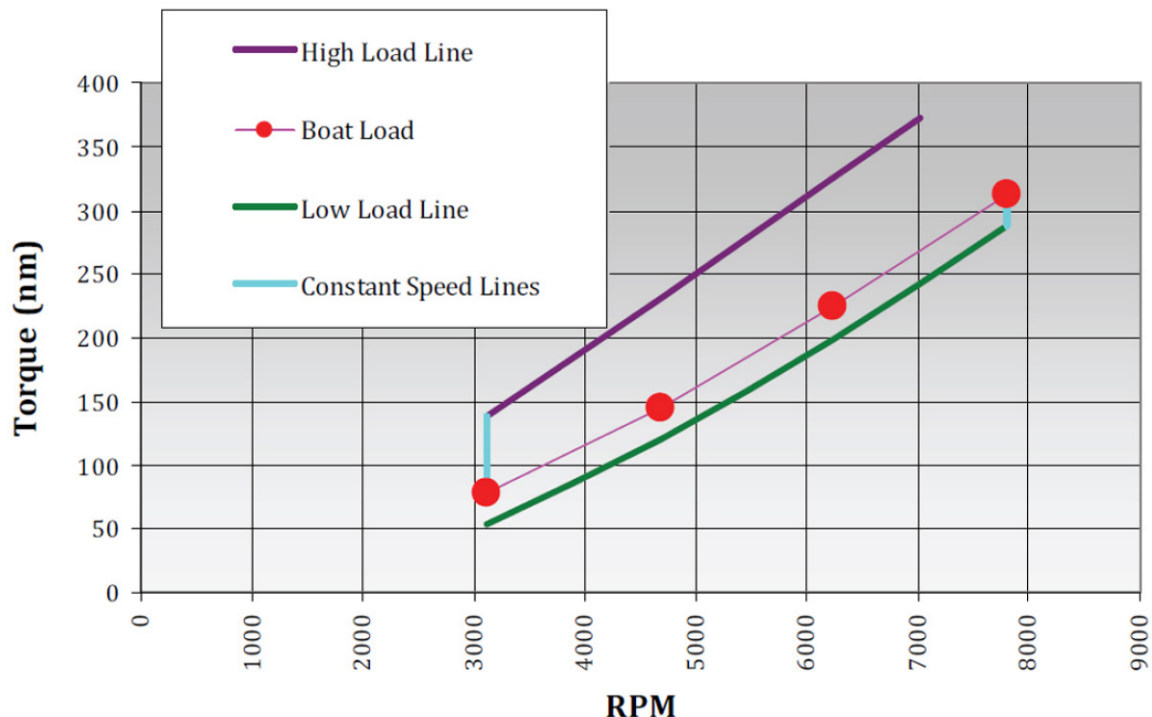


Figure 3.1: Not-To-Exceed Zones, as defined by the EPA [1]
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3.2 Test Vessel Description

The engines tested during this research represent a broad range of technologies in the industry. Two-stroke carbureted and four-stroke fuel injected engines were tested, running different types of feedback strategies. The two-stroke engine ran open-loop operation at all times, providing no feedback to the engine when the oxygen concentration of the fuel changed. The four-stroke engines ran closed-loop operation, except at Mode 1. The closed-loop operation allowed for the engine to change fueling rates to the fuel injectors through the use of a wideband oxygen sensor. Table 3.2 displays parameters for each engine tested.

Table 3.2: Boat and engine specifications

Boat Manufacturer	Malibu	Alamar	Promarine
Engine Manufacturer	INDMAR	Volvo Penta	OMC
Displacement (l)	6.0	5.7	2.6
Rated Power (Hp)	362	320	150
Operation	Four-Stroke	Four-Stroke	Two-Stroke
Feedback	Closed-loop except at Mode 1	Closed-loop except at Mode 1	Open-loop
Number of Cylinders	8	8	6
Fuel Delivery	Port Fuel Injected	Port Fuel Injected	Carbureted
BoreXStroke (mm)	101.6 X 92	101.6 X 88.4	91.44 X 65.74

3.2.1 INDMAR

Pictured in Figure 3.2 is the Malibu Wake Setter ski boat which featured an INDMAR 6.0l L96 engine. The INDMAR shares the same design as the GM Generation IV small block engine. This engine features variable exhaust valve timing, allowing for the exhaust valve timing to be varied based off of operating conditions. Exhaust valve timing is retarded at launch for increased low end torque, and advanced during full speed operation to increase power. The engine operates in a closed-loop fashion, except for Mode 1, when the engine goes to open-loop. During open-loop operation, the fuel delivery goes to a pre-determined value in the engine control unit (ECU), which helps to cool the catalytic converters. Three-way catalysts are used to aid in meeting emissions regulations.



Figure 3.2: Malibu Wakesetter ski boat featuring an INDMAR engine

3.2.2 Volvo Penta

Pictured in Figure 3.3 is the Alamar Aluminum Hull boat which featured a Volvo Penta 5.7l Gxi engine. The Volvo Penta shares the same design as a GM Generation IV small block engine, featuring steel cylinder heads and block, to aid in corrosion resistance. Engine diagnostics are controlled using an ECU, which controls fuel delivery, spark timing, and performs various other diagnostics. Three-way catalysts are used to aid in meeting emissions regulations. This engine also operates closed-loop, except for full load conditions, when the engine goes open-loop. During open-loop operation, the fuel delivery goes to a pre-determined value in the ECU, which helps to cool the catalytic converters.



Figure 3.3: Alamar Aluminum Hull boat featuring a Volvo Penta engine

3.2.3 OMC

Pictured in Figure 3.4 is the Promarine Fiberglass Inc Intruder boat. This hull is equipped with an OMC Johnson Legacy outboard engine. This 2.6l, 6 cylinder, loop charged engine features two, triple throat carburetors, with float feed for fuel delivery. This engine is not equipped with an after-treatment system and thus emissions compliance relies on the set tune of the engine. This engine also does not come equipped with an ECU.



Figure 3.4: Promarine "Intruder" boat featuring an OMC outboard engine

3.3 Fuel Flow and Power

In order to convert raw emissions concentrations to a specific mass basis, fuel flow and power values were needed. For the INDMAR and Volvo Penta engines, fuel flow and power values were recorded from the ECU. A serial cable attached to the ECU allowed representatives from INDMAR and Volvo Penta to display ECU values on a laptop. Subsequent emissions values for the INDMAR and Volvo Penta are displayed on a g/kW-hr basis. An AVL PLU 120 fuel flow meter was used to measure fuel flow to calculate fuel consumption in g/hr for the OMC. Power values were not available for the OMC, because this engine is not equipped with an ECU. Therefore, all emissions values for the OMC are displayed on a g/hr basis.

3.4 Field Test Setup

The research discussed was performed in Annapolis, Maryland in the tributaries of the Chesapeake Bay. The location near the Chesapeake contained a long tributary that did not have many boaters, allowing for continuous testing without interruption of other boating traffic.

Testing was performed in various weather conditions, ranging from clear blue skies to cloudy blustery days. Ambient temperatures were near 60°F and 80°F for testing performed in May and September, respectively.

Annapolis, Maryland was chosen for this testing, as a historical meeting place. Numerous marine manufacturers come to Annapolis to perform research, because of the long boating season.

3.5 Sensors-Inc. Semtech-DS Onboard Vehicle Emissions Analyzer

A Sensors-Inc. Semtech-DS five-gas raw emissions analyzer was used to sample all gaseous emissions from Tedlar© emissions bags [14]. The Semtech-DS unit features a flame ionization detector (FID) for total hydrocarbon (THC) measurements, a Non-Dispersive Ultraviolet (NDUV) analyzer for nitrogen oxide (NO) and nitrogen dioxide (NO₂) measurements, a Non-Dispersive Infrared (NDIR) analyzer for carbon monoxide (CO) and carbon dioxide (CO₂) measurements, and an Electrochemical sensor for oxygen (O₂) measurements. Table 3.3 outlines the range of measurement, accuracy, resolution, and data sampling rate for each associated emission constituent. Properties for NO₂ measurement are not listed, because a span gas for NO₂ was not available.

Table 3.3: Properties of Semtech-DS analyzers

Constituent	Range of measurement	Accuracy	Resolution	Data Rate
THC	0-100 ppmC ₁ 0-1,000 ppmC ₁ 0-10,000 ppmC ₁ 0-40,000 ppmC ₁ (User Defined)	±2.0% ±2.0% ±2.0% ±2.0%	0.1 ppmC ₁ 1.0 ppmC ₁ 1.0 ppmC ₁ 10.0 ppmC ₁	Up to 4Hz
NO	0-3000, 0-900, 0-300 ppm	±2.0%	0.1ppm	1Hz
CO	0-8%	±3.0%	10ppm	0.833Hz
CO ₂	0-20%	±3.0%	0.01%	0.833Hz
O ₂	0-25%	±1.0%	0.1%	N/A

An optional external charcoal filter was installed downstream of the FID analyzer, onto the back of the Semtech-DS unit. The purpose of this filter was to reduce the level of hydrocarbon emissions which could contaminate the NDUV and NDIR analyzers. The charcoal filter does not affect the measurement of CO, CO₂, or NO.

3.6 Marine Portable Bag Sampling System

The Marine Portable Bag Sampling System (MPSS) was originally developed by Bombardier Recreational Products (BRP) for use in previous studies with the National Marine Manufacturers Association (NMMA) [1]. The MPSS samples gaseous emissions from the exhaust manifold of the particular engine, at a constant flow rate. The exhaust sample first enters a particulate filter, and is then sent to a mechanical chiller, which uses a peristaltic pump to remove any condensate. THC emissions are measured using a FID, NO/NO₂ emissions are measured using a chemiluminescence detector (CLD), and CO emissions are measured using a NDIR. After the analyzers, the emissions sample is routed to a Tedlar® emissions sampled bag. An internal timer is used to properly weight the amount of emissions introduced to the Tedlar® bag, based off of exhaust mass flow rate for each mode, measured using an adjustable flow rotometer. Two five-mode weighted bag samples are recorded for each fuel, in order to better assess test-to-test variability.

3.7 SoMat™ Portable Data Acquisition System

A SoMat™ Portable Data Acquisition System was used to measure engine speed, boat speed, relative humidity, ambient temperature, and barometric pressure. Data sets recorded from the SoMat™ were used to validate the test-to-test consistency for each boat.

3.8 Test Procedure

3.8.1 Test Fuels

For testing performed in May and September, three fuels were tested: indolene, E10, and iB16. Table 3.4 shows all of the fuels tested for both rounds of testing.

Table 3.4: Properties of fuels tested in Annapolis, MD

	Indolene	E10	E10 (Field Blended)	iB16
Specific Gravity	0.7365	0.7397	0.7474	0.7489
Composition (C,H,O) Wt%	86.2, 13.8, 0	82.9, 13.1, 4.0	80.0, 13.8, 3.9	83.0, 13.0, 4.0
Octane Number (R+M)/2	92.4	89.7	91.0	88.7
RVP (psi)	9.0	8.8	6.7	8.5
Lower Heating Value (MJ/kg)	42.51	39.75	39.25	38.89

For testing performed in May, the shipment of E10 from the fuel manufacturer did not arrive in time for testing. Due to constraints with getting the research completed on schedule, a splash blend of E10 was created with fuel from local ExxonMobil and Shell gas stations. Because it was known ethanol will phase separate in the presence of water, a graduated bottle was used to measure the volume of ethanol that phase separated. Figure 3.5 shows the phase separation between water and ethanol. Using a graduated bottle, a solution of 10ml water and 90ml ExxonMobil 87 octane gasoline was created. The water was added to the fuel to force the ethanol to phase separate from the gasoline, allowing for the amount of ethanol in the fuel to be determined. After shaking the bottle vigorously and allowing for separation, there was indication the ExxonMobil gasoline had 7-8%

ethanol. In order to reach the 10% ethanol concentration, E85 from a local Shell Gas Station was added to achieve a field blended E10. Once the correct volumes for the 87 octane and E85 fuels were determined, batches of fuel were purchased from the same ExxonMobil and Shell gas stations. Enough fuel was purchased to create a 55 gallon batch, mixed in a clean 55 gallon drum.

After testing was performed, a sample of this fuel was shipped for analysis. Following the ASTM D5599 test standard, it was determined the field blended E10 contained 10.69% ethanol, by volume, validating the in-field blending technique. The field blended E10 was only used for May testing; testing performed in September used E10 from the fuel manufacturer.

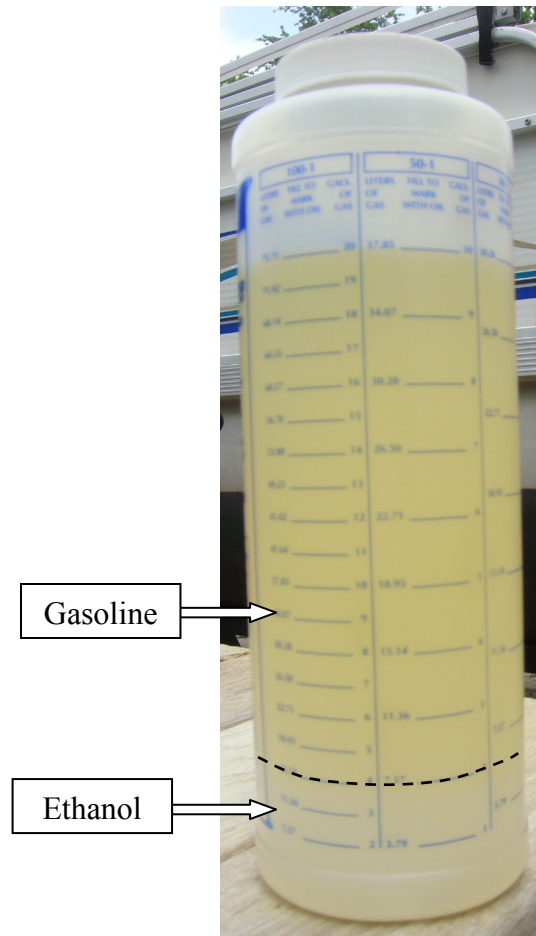


Figure 3.5: Graduated bottle showing phase separation between ethanol and water

3.8.2 Engine Warm-Up Procedure

Before emissions were sampled for each fuel, each engine was warmed up to full operating temperature. The location where each mode of the adapted ICOMIA test cycle was performed was 15 minutes away from the marina, giving the engine ample time to reach and maintain full operating temperature. WOT speed runs were performed for each fuel to locate the maximum engine speed of each boat. For all three fuels, maximum engine speed remained constant for each boat. During this warm-up period, the trim of the boat was set based off of varying weather conditions including: wind speed, ambient temperature, and water conditions. This ensured the engine was able to achieve the same speed for each mode.

3.8.3 Setting Constant Engine Speed

In order to ensure consistency from test-to-test, engine speed on a per mode basis was held constant. The INDMAR featured a factory installed Precision Speed Control, allowing the user to define engine speed. The Volvo Penta engine featured a standalone Zero Off Speed Controller, allowing the user to define engine speed [15]. The engine speed for the OMC was controlled by adjusting the throttle position to achieve the desired engine speed. Because this engine was not equipped with an ECU, the engine speed control methods described above were not able to be employed. The OMC engine speed fluctuated less than 5% for each fuel and mode of testing.

3.8.4 Emissions Sampling: MPSS

Gaseous emissions were sampled using the MPSS in pre and post catalyst locations, when applicable. Figure 3.6 and Figure 3.7 show pre and post catalyst emissions sampling locations for the INDMAR and Volvo Penta engines, respectively. Figure 3.8 shows the emissions sampling location for the OMC engine. Because this engine runs without after-treatment, only one sample probe was used.

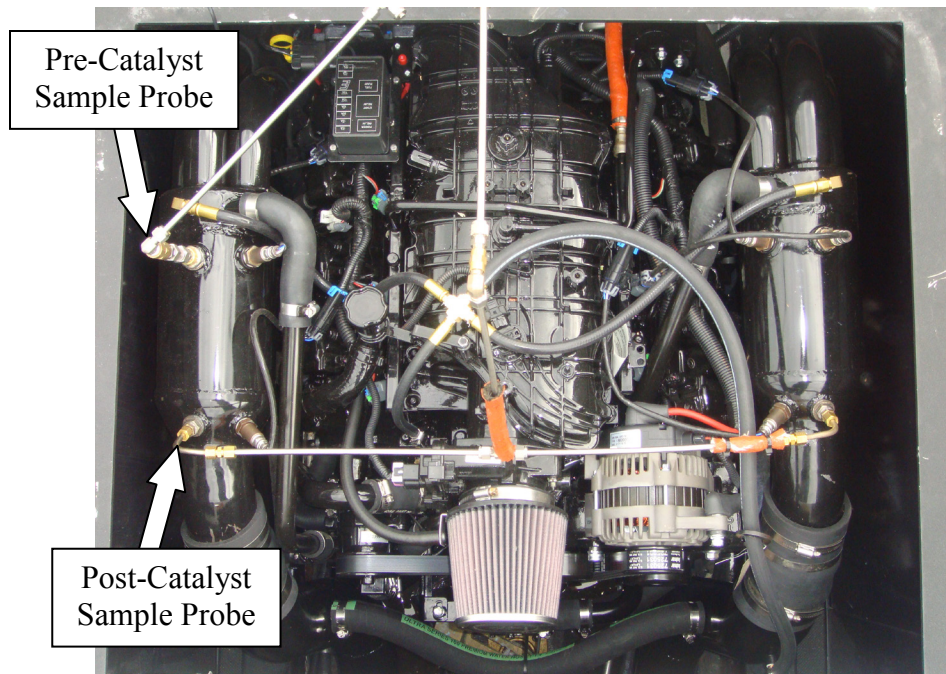


Figure 3.6: Pre and post-catalyst emission probes for the INDMAR

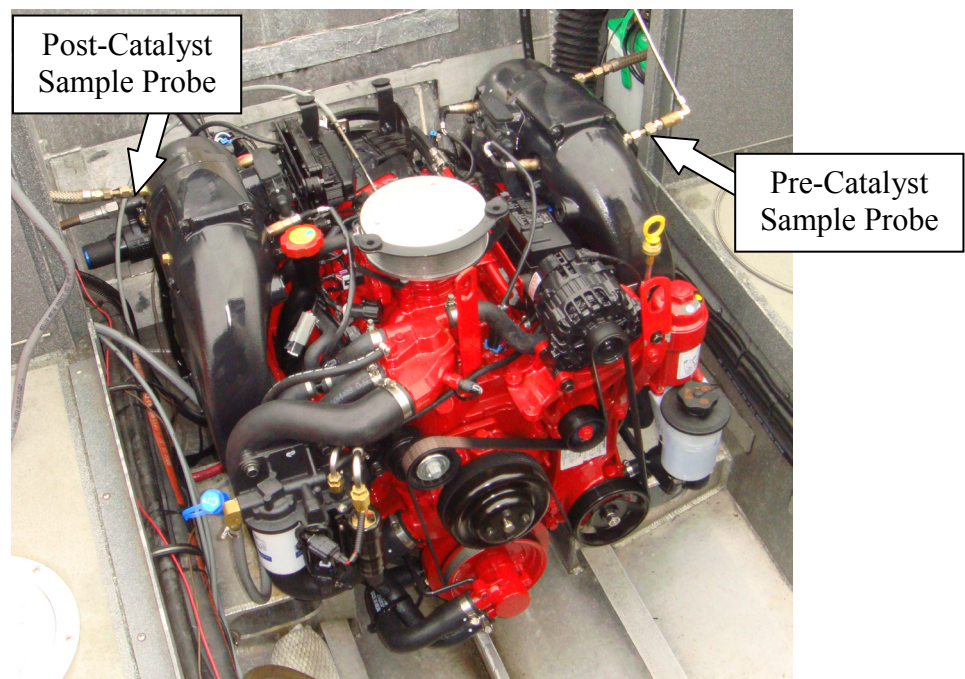


Figure 3.7: Pre and post-catalyst emission probes for the Volvo Penta

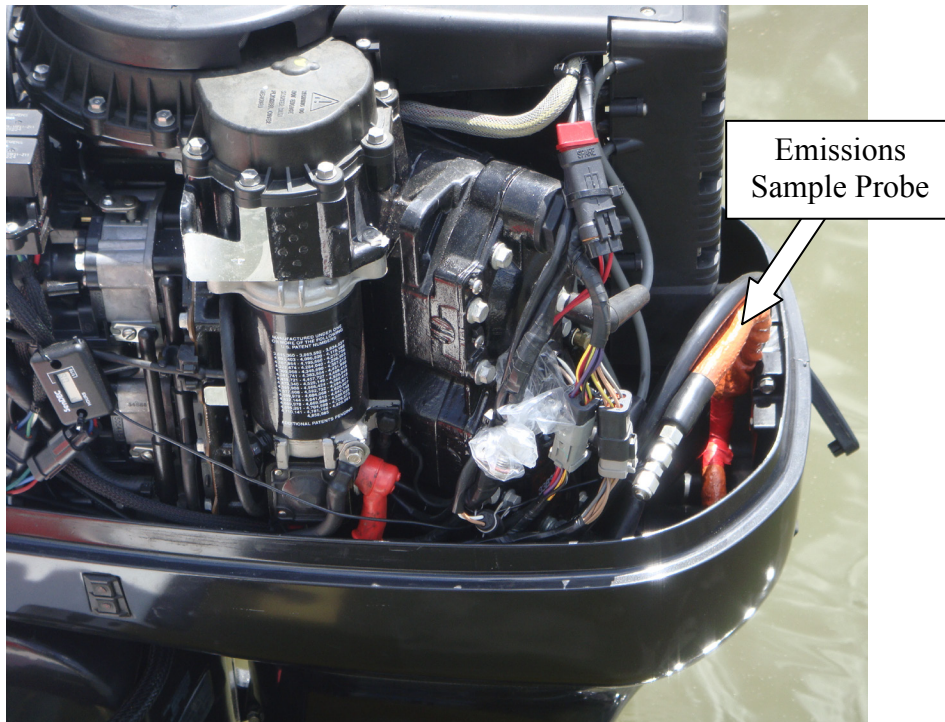


Figure 3.8: Gaseous emissions sample probe for the OMC

The MPSS uses the pre-catalyst sample locations to determine engine exhaust flow rate using an adjustable flow rotometer, on a per mode basis. Calculations are performed to determine the amount of time to sample emissions for each mode. An internal timer is set on the MPSS controlling sample volume, ensuring the Tedlar© emissions bag accurately represents the weighted five mode adapted ICOMIA test cycle. Post-catalyst emissions, when applicable, are sampled and run through the five-gas analyzer built into the MPSS. For the case of the OMC, one sample location serves the same purpose as pre and post catalyst sampling. These values are then recorded to a data file for post-processing. For each mode, the boat was run at the specific mode conditions and once a steady state speed was achieved, emissions were sampled.

3.8.5 Emissions Sampling Procedure

The Semtech-DS was used to sample emissions from the Tedlar© emissions bags, which were filled by the MPSS. All bags were sampled within three hours of filling with emissions. A quad blend gas was used to calibrate the Semtech-DS before and after each

measurement. A gas of known concentrations was run through each analyzer, and the measured difference was taken into account for in the software and applied to each measurement.

Table 3.5 shows the concentrations for each gas constituent in the quad blend, used to span the Semtech-DS unit for testing performed in May and September. This blend was not used for testing in September when sampling OMC emissions.

Table 3.5: Quad blend span gas used in May and September

Gas Constituent	Concentration
CO	8.00%
CO ₂	12.00%
NO	794.9ppm
THC	2023ppmC ₁

Table 3.6 shows the concentrations for each gas constituent in the quad blend, used to span the Semtech-DS unit for testing performed in September, used with the OMC only. This bottle of span gas was not available during May testing due to complications with shipping from the supplier. The higher concentrations of the THC allowed for a better response of the FID analyzer when measuring THC in the exhaust. Because the response of a FID analyzer is linear, the lower THC span concentration used in May was not believed to significantly impact the exhaust THC measurement.

Oxides of nitrogen values are defined NO, and not NO_x. For this testing, the Semtech-DS was only spanned for NO, and therefore is the only calibrated oxide of nitrogen constituent.

Table 3.6: Quad blend gas used in September testing for the OMC

Gas Constituent	Concentration
CO	8.15%
CO ₂	12.20%
NO	1481.0 ppm
THC	7780 ppmC ₁

Below is the procedure used to sample emissions from the Tedlar© bags:

- Allow one hour for the analyzer to reach full operating temperature, and perform pre-test span and zero
- Connect Swagelock connector on the end of the heated sample line to Swagelock connected on the Tedlar© emissions bag
- Before recording sample, allow Semtech-DS to sample emissions for 30 seconds. Wait for the emissions constituent values to reach a steady state value
- Record emissions for 90 seconds for the INDMAR and Volvo Penta. Record emissions for 60 seconds for the OMC
- Perform post-test zero and span after sampling emissions for one fuel
- Perform pre-test zero and span before changing fuels

Emissions on the two-stroke engine were sampled for a shorter period of time, because of the smaller engine displacement. The OMC engine had a lower exhaust flow rate than the two four-stroke engines, resulting in a smaller sample volume.

When an emissions bag was finished with sampling, a vacuum pump was used to remove any remaining sample. The bag was then filled with nitrogen and a vacuum pump was used to remove the nitrogen. This purge method was performed twice for each bag and then the bag was reused.

3.8.6 Complications with Bag Sampling

There were inherent issues introduced with bag sampling emissions. The amount of sample volume in each bag varied from test-to-test, because each boat would create different exhaust flow rates. Because of the different bag volumes, it became difficult to sample each bag for the same period of time for each engine. If a measurement error was made, extra precautions needed to be put into place to ensure the bag sample was still useable. For instance, during September testing a high THC concentration span gas was used for one sample, resulting in large variability in the THC measurement. The

Semtech-DS was recalibrated for a lower THC concentration span gas, and the Tedlar® bag was sampled, closely monitoring the overall sample volume left in the bag.

THC hangup also became an issue when sampling gaseous emissions. THC hangup occurs when THC particles from the exhaust sample stick to the sample container, such as the constant volume Tedlar® bag.

The OMC engine produced THC values over an order of magnitude higher than either of the four-stroke engines. As a result, one of the Tedlar® bags used for one test with the Volvo Penta had higher THC's, because of THC hangup from the OMC engine. Correction factors were applied to this isolated incident, as discussed in 4.5.2.

4. Results and Discussion

4.1 Emissions Measurement Repeatability and Stability

To show emissions measurement repeatability and stability, a series of plots and tables are included below.

4.1.1 INDMAR

Figure 4.1 shows the INDMAR engine speed on a per mode basis, for each fuel. As seen in Figure 4.1, there is minimal deviation in engine speed for each mode. Table 4.1 shows the time averaged emissions constituent values, with one standard deviation over the 60 second averaging period. Subsequent plots of each emission constituent and boat speed for the second round of testing can be seen in the appendix in Figure A.4 and Figure A.9.

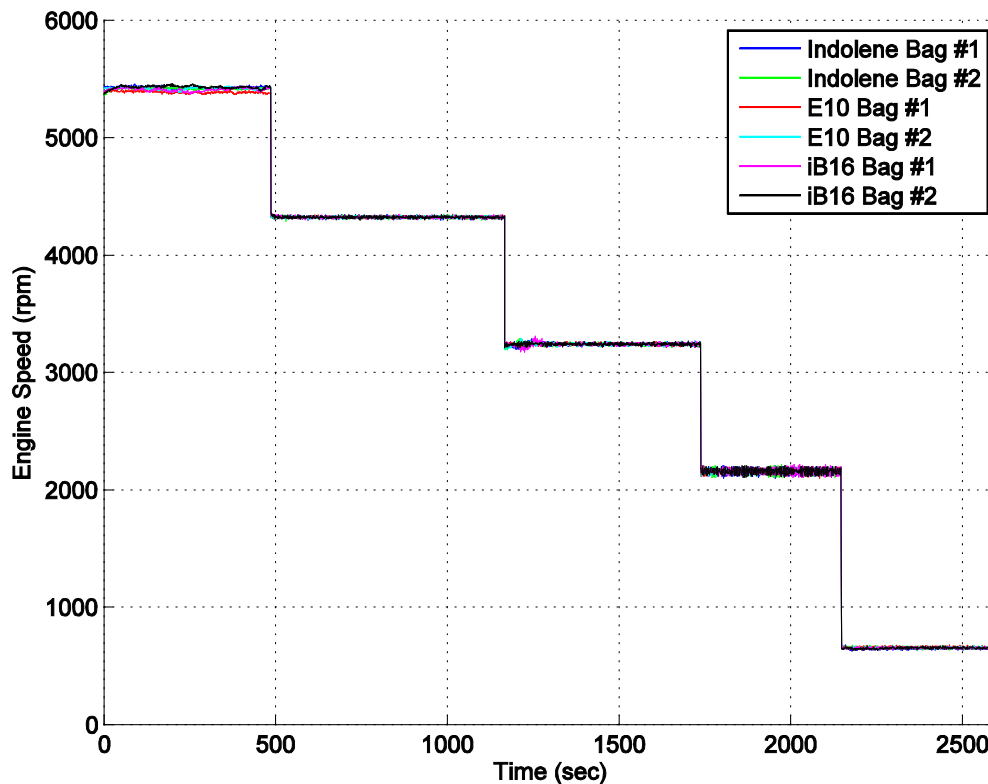


Figure 4.1: INDMAR engine speed – round 1

Table 4.1: INDMAR averaged emissions with one standard deviation – round 1

	CO (%)	NO (ppm)	THC (ppmC ₁)
Indolene Bag #1	1.776±0.002	68.5±0.3	759.0±4.0
Indolene Bag #2	1.667±0.002	80.6±0.6	729.0±4.0
E10 Bag #1	1.840±0.001	115.0±1.0	895.0±4.0
E10 Bag #2	1.698±0.002	122.2±1.2	822.0±4.0
iB16 Bag #1	1.627±0.002	83.9±0.3	660.0±4.0
iB16 Bag #2	1.680±0.001	85.8±0.4	630.0±4.0

Figure 4.2 shows the boat speed for the INDMAR from May testing.

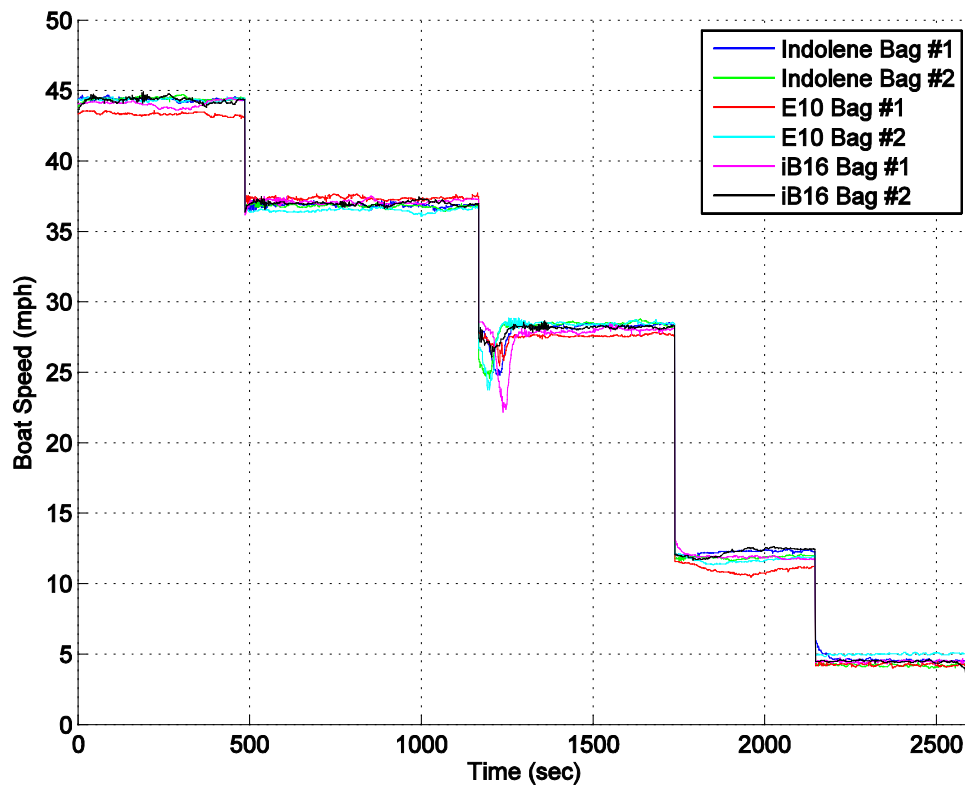


Figure 4.2: INDMAR boat speed – round 1

4.1.2 Volvo Penta

Figure 4.3 shows the Volvo Penta engine speed on a per mode basis, for each fuel. When data sets were taken for the second round of testing, there was a noisy tachometer

signal; therefore the data sets were filtered to achieve the best result possible. An average was taken of the peaks for the engine speed signal, for each mode. Engine and boat speed plots are not available for the first round of testing due to corrupt data files. Table 4.2 shows the time averaged emissions constituent value, with one standard deviation over the 60 second averaging period. A subsequent data table of round 2 emissions standard deviation is available in the appendix, seen in Table A.2.

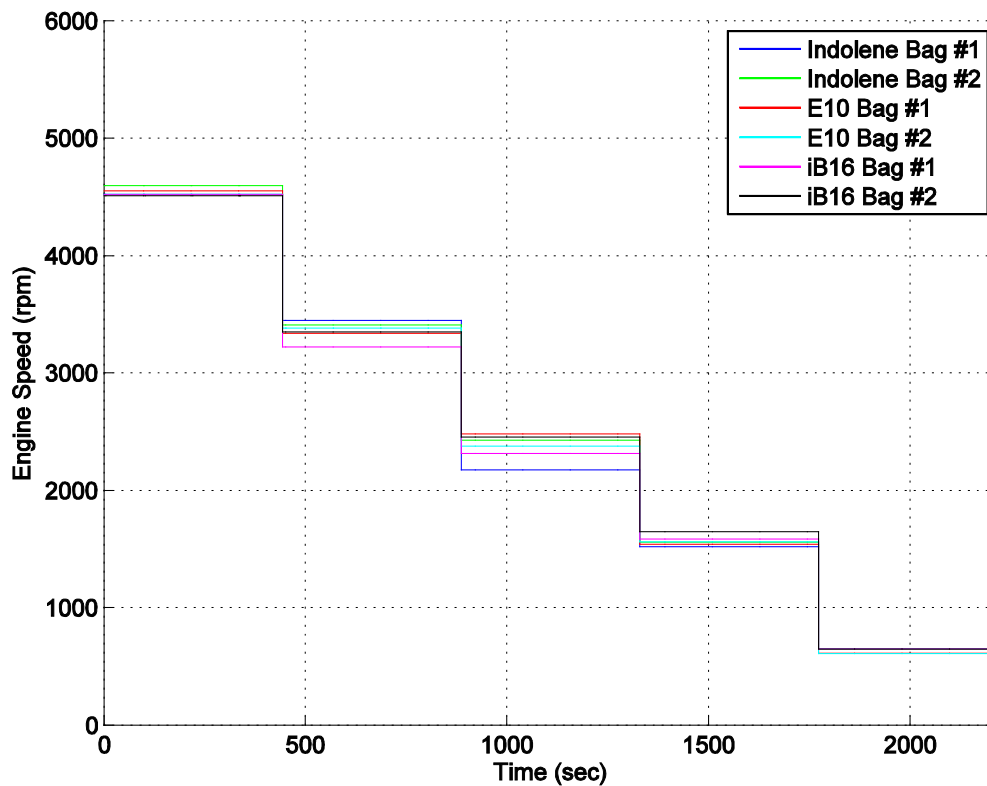


Figure 4.3 Volvo Penta engine speed – round 2

Table 4.2: Volvo Penta averaged emissions with one standard deviation – round 1

	CO (%)	NO (ppm)	THC (ppmC ₁)
Indolene Bag #1	1.660±0.001	60.21±0.4	511±4
Indolene Bag #2	1.547±0.001	70.01±0.6	500±4
E10 Bag #1	0.951±0.001	102.1±1.0	365±4
E10 Bag #2	0.735±0.001	108.9±1.3	299±4
iB16 Bag #1	0.852±0.001	70.6±0.3	318 ±4
iB16 Bag #2	1.028±0.001	73.1±0.4	374±5

Figure 4.4 shows the boat speed for the Volvo Penta from September testing.

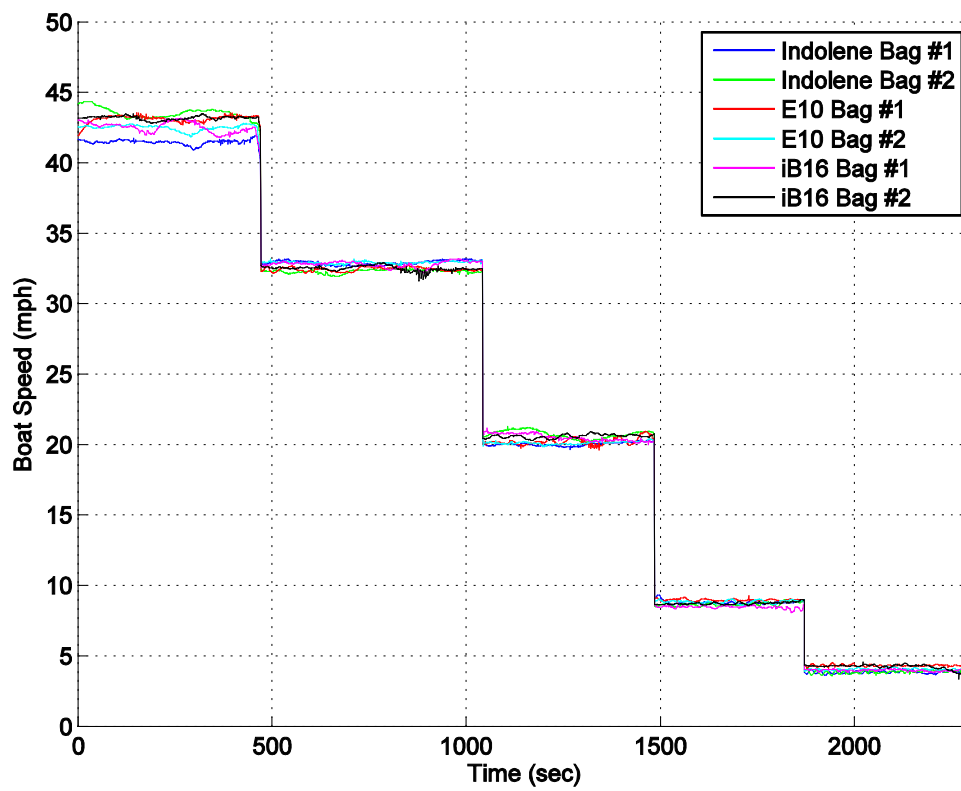


Figure 4.4: Volvo Penta boat speed – round 2

4.1.3 OMC

Figure 4.5 shows the OMC engine speed on a per mode basis, for each fuel. Table 4.3 shows the time averaged emissions constituent values, with one standard deviation over the 60 second averaging period. Subsequent plots of each emission constituent and boat speed for both rounds can be seen in the appendix in Figure A.6 and Figure A.10. Although a standard deviation of up to 50ppmC₁ THC seems large by comparison to the four-stroke engines, the raw concentration of THC for the OMC is three orders of magnitude larger. The standard deviation reflects the ± 10 ppmC₁ resolution of the FID at high concentrations.

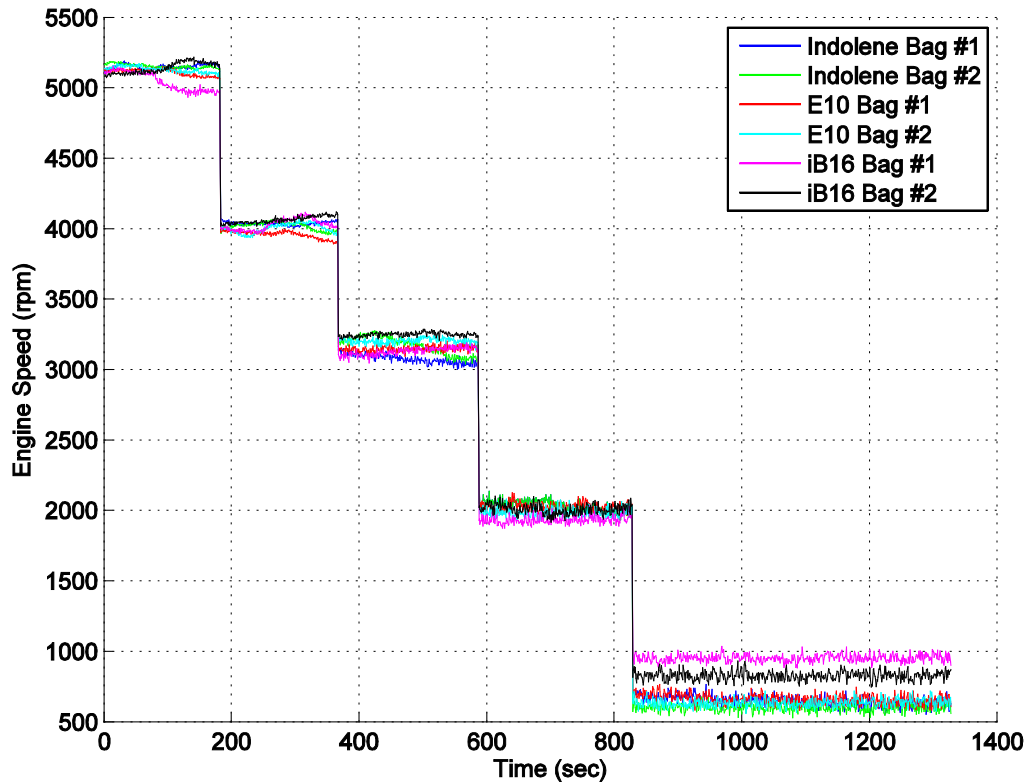
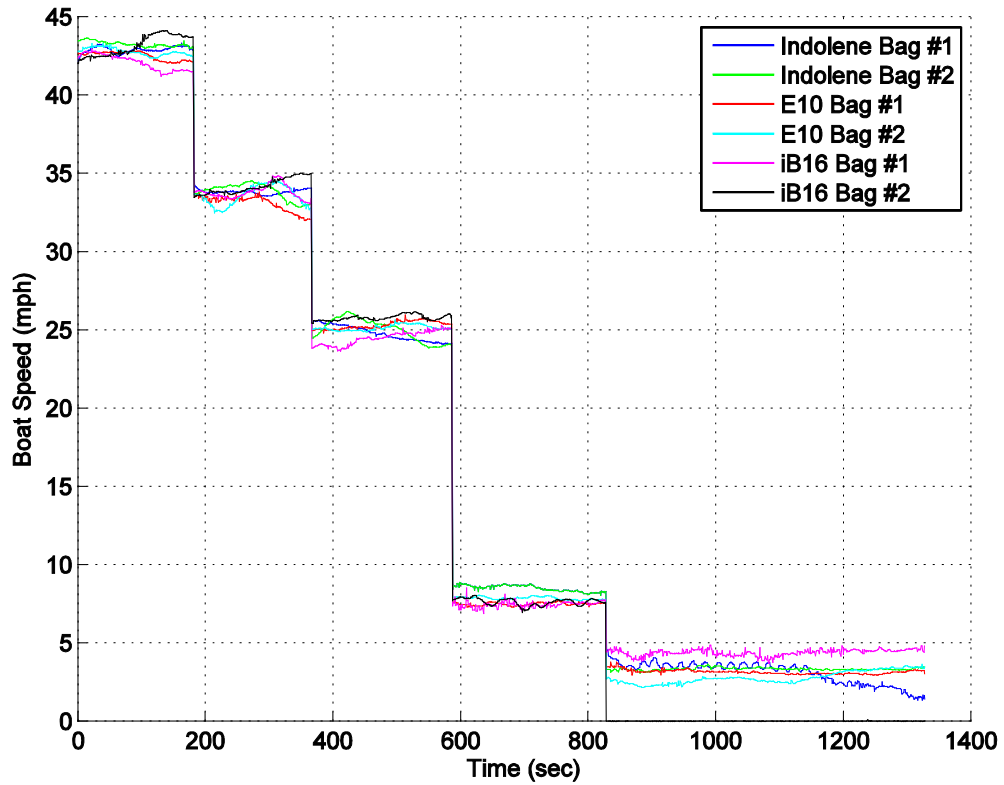


Figure 4.5: OMC engine speed – round 1

Table 4.3: OMC averaged emissions with one standard deviation – round 1

	CO (%)	NO (ppm)	THC (ppmC ₁)
Indolene Bag #1	3.954±0.003	54.4±0.3	28610±40
Indolene Bag #2	3.838±0.002	71.4±0.2	28310±30
E10 Bag #1	3.210±0.003	15.0±0.2	24810±40
E10 Bag #2	3.247±0.002	13.5±0.1	26690±40
iB16 Bag #1	2.898±0.002	16.4±0.4	26160±50
iB16 Bag #2	2.804±0.002	15.7±0.1	24800±20

Figure 4.6 shows the boat speed for the OMC from May testing.

**Figure 4.6: OMC boat speed – round 1**

4.2 Hours of Operation

The marine industry sets specific guidelines for the useful life of engines, based on the class of engine. All three engines were aged in the summer months between the May and September testing, running the same iB16 fuel used for this study. Table 4.4 shows the useful life of each engine, and the amount of hours put onto each engine for the duration of this study.

Table 4.4: Hours of operation for all three engines

	Useful Life (hrs)	Beginning of study (hrs)	End of study (hrs)	Hours added (hrs)	Percent of Useful Life (%)
INDMAR	480	3	48	45	9
Volvo Penta	480	9	61	52	11
OMC	350	2	43	41	12

As seen in Table 4.4, none of the engines in this study were near the end of their useful life. To make a beginning-of-life to end-of-life comparison of emissions from May to September based off of engine hours would not be representative. Therefore, any difference seen in engine-out emissions between May and September testing reflects the variability between rounds of testing due to environmental impact, such as water conditions, wind speed, ambient temperature, boat speed, and boat trim. Some minor differences due to engine break-in may also be present.

4.3 May and September Ambient Conditions

Table 4.5 shows the ambient test conditions for testing performed in Annapolis, MD in the months of May and September. While the ambient temperature and pressure remained relatively constant during each round, relative humidity varied due to different weather fronts. The large change in weather conditions directly affected test results, affecting the variability between rounds of testing,

Table 4.5: Average ambient test conditions for May and September

	Ambient Temperature (°F)	Relative Humidity (%)	Ambient Pressure (mbar)
May	61	33-70	1018
September	80	33-57	1025

4.4 Baseline Indolene Emissions

4.4.1 INDMAR

Table 4.6 shows the raw emissions for the INDMAR engine running indolene for both rounds of testing. Emissions values shown below for each round are averaged over two emissions bag samples.

Table 4.6: Raw emissions for INDMAR – indolene

Emission Constituent	CO (%)	NO (ppm)	THC (ppmC ₁)	THC+NO (ppm)
Round 1	1.722	65.6	746	811
Round 2	2.123	116.9	722	839
Average	1.923	91.3	734	825

Table 4.7 shows specific emissions values for CO, NO, THC, and THC+NO on a g/kW-hr basis.

Table 4.7: Specific emissions for INDMAR – indolene

Emission Constituent	CO (g/kW-hr)	NO (g/kW-hr)	THC (g/kW-hr)	THC+NO (g/kW-hr)
Round 1	63.41	0.46	1.60	2.06
Round 2	85.37	0.89	1.66	2.56
Average	74.39	0.68	1.63	2.32

4.4.2 Volvo Penta

Table 4.8 shows the raw emissions for the Volvo Penta running indolene for both rounds of testing. Emissions values shown below for each round are averaged over two emissions bag samples.

Table 4.8: Raw emissions for Volvo Penta – indolene

Emission Constituent	CO (%)	NO (ppm)	THC (ppmC ₁)	THC+NO (ppm)
Round 1	1.603	59.68	507	567
Round 2	1.371	55.49	377	433
Average	1.487	57.59	442	500

Table 4.9 shows specific emissions values for CO, NO, THC, and THC+NO on a g/kW-hr basis.

Table 4.9: Specific emissions for Volvo Penta – indolene

Emission Constituent	CO (g/kW-hr)	NO (g/kW-hr)	THC (g/kW-hr)	THC+NO (g/kW-hr)
Round 1	53.63	0.38	0.98	1.37
Round 2	47.85	0.37	0.76	1.13
Average	50.74	0.38	0.87	1.25

4.4.3 OMC

Table 4.10 shows the raw emissions for the OMC running indolene. Emissions values shown below are averaged over two emissions bag samples.

Table 4.10: Raw emissions for OMC – indolene

Emission Constituent	CO (%)	NO (ppm)	THC (ppmC ₁)	THC+NO (ppm)
Round 1	3.896	44.6	28470	28520
Round 2	4.047	39.7	29270	29310
Average	3.972	42.2	28870	28910

Table 4.11 shows specific emissions values for CO, NO, THC, and THC+NO on a g/hr basis.

Table 4.11: Specific emissions for OMC – indolene

Emission Constituent	CO (g/hr)	NO (g/hr)	THC (g/hr)	THC+NO (g/hr)
Round 1	6148	13.96	2666	2680
Round 2	6220	11.89	2648	2660
Average	6184	12.93	2656	2670

4.5 E10 and iB16 Emissions and Comparison to Indolene

For this section, all lambda values are calculated using the ISO #16183 standard [16]; this calculation method is used as the de-facto standard.

Figure 4.7 shows qualitatively how THC, NO, and CO emissions vary with changes in relative air-to-fuel ratio [17]. This qualitative plot will be used to explain general emissions trends.

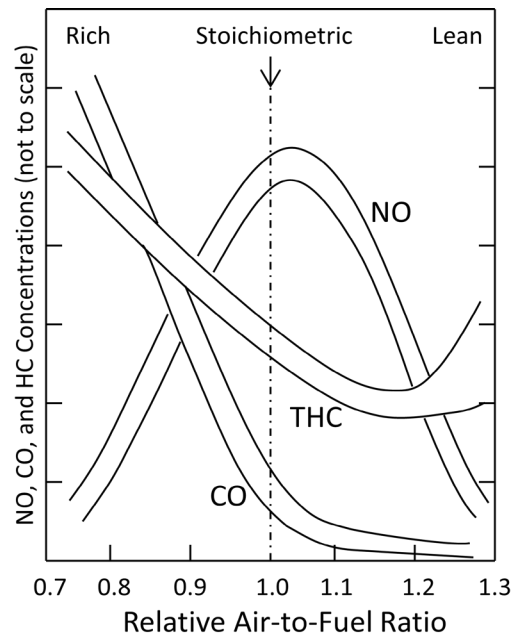


Figure 4.7: General emissions trends as a function of relative air-to-fuel ratio
Based off of Figure 11.2 in Heywood [17]

4.5.1 INDMAR

Table 4.12 shows the raw emissions for the INDMAR engine running E10 and iB16. Emissions values shown below are averaged over two emissions bag samples.

Table 4.12: Raw emissions for INDMAR – alcohol fuels

Emission Constituent	CO (%)	NO (ppm)	THC (ppmC ₁)	THC+NO (ppm)
E10 Round 1	1.769	105.5	858	964
E10 Round 2	1.873	109.7	659	769
E10 Average	1.821	107.6	759	866
iB16 Round 1	1.654	71.9	646	717
iB16 Round 2	1.820	123.3	630	753
iB16 Average	1.737	97.6	638	735

Table 4.13 shows specific emissions values for CO, NO, THC, and THC+NO on a g/kW-hr basis.

Table 4.13: Specific emissions for INDMAR – alcohol fuels

Emission Constituent	CO (g/kW-hr)	NO (g/kW-hr)	THC (g/kW-hr)	THC+NO (g/kW-hr)
E10 Round 1	64.80	0.75	1.96	2.71
E10 Round 2	76.80	0.85	1.61	2.46
E10 Average	70.80	0.80	1.78	2.59
iB16 Round 1	61.46	0.51	1.44	1.95
iB16 Round 2	80.20	1.03	1.66	2.69
iB16 Average	70.82	0.77	1.55	2.32

Figure 4.8 shows the percent change in specific emissions from indolene to each respective alcohol fuel. Values from Figure 4.8 and Figure 4.9 can be seen in Table A.4 and Table A.7, respectively.

CO emissions decreased as alcohol fuels were introduced. Because the engine operates open-loop at Mode 1, the overall air-to-fuel ratio was enleaned, as seen in Figure 4.9, decreasing CO emissions. This is exemplified in Figure 4.7, where leaning the global air-to-fuel ratio decreases CO emissions [17].

There was a general increase in NO emissions, explained by engine operation at Mode 1. While operating open-loop, the engine cannot compensate for an increase in oxygen concentration being introduced with the fuel. Therefore, the engine approached stoichiometric air-to-fuel ratios, seen in Figure 4.9, increasing combustion temperatures and promoting NO formation, as previously noted by Heywood [17]. This is consistent with research performed by Wasil [1].

There was a conflicting trend between E10 and iB16 for THC emissions. Literature by Yassine et al. [10] previously discussed clearly shows a decrease in THC emissions for closed-loop four-stroke engines. THC and CO emissions values for E10 from the Semtech-DS and MPSS were compared for testing performed in May, as seen in Table 4.14. There is a consistent trend between the two bag samples from both analyzers. Therefore, it is believed that the Semtech measurement is correct. The only way to reach a THC trend conclusion would be to perform the test again.

Table 4.14: Semtech-DS and MPSS emissions comparison – E10 May testing

	Semtech-DS		MPSS	
	THC (ppmC ₁)	CO (%)	THC (ppm C ₁)	CO (%)
Bag #1	895	1.840	744	0.555
Bag #2	821	1.699	612	0.481

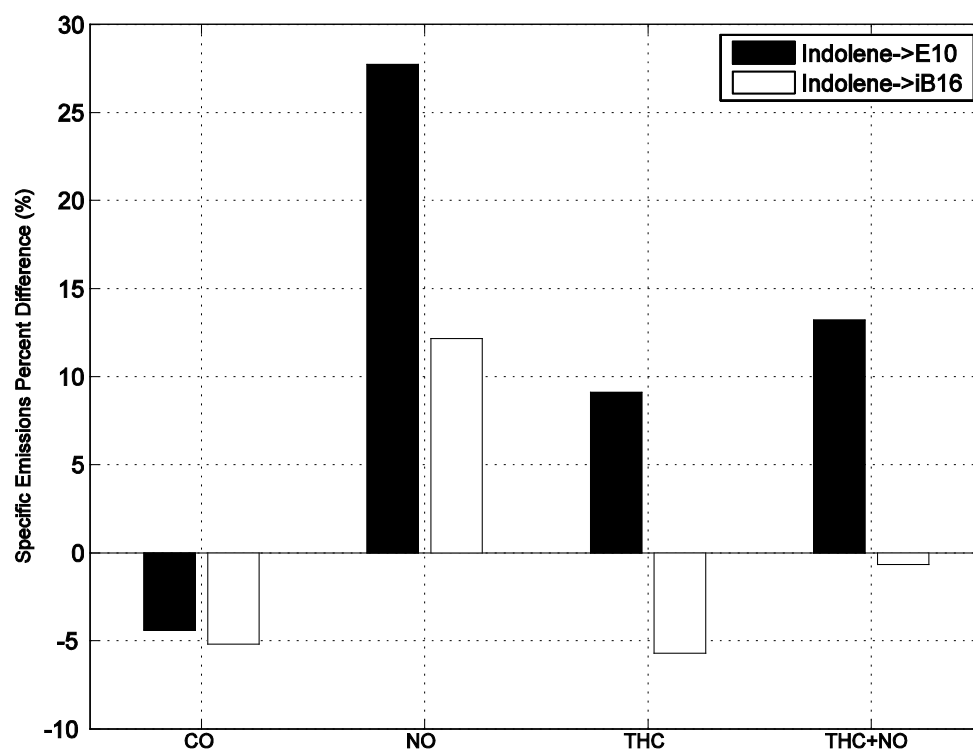


Figure 4.8: Specific emissions percent difference from indolene – INDMAR

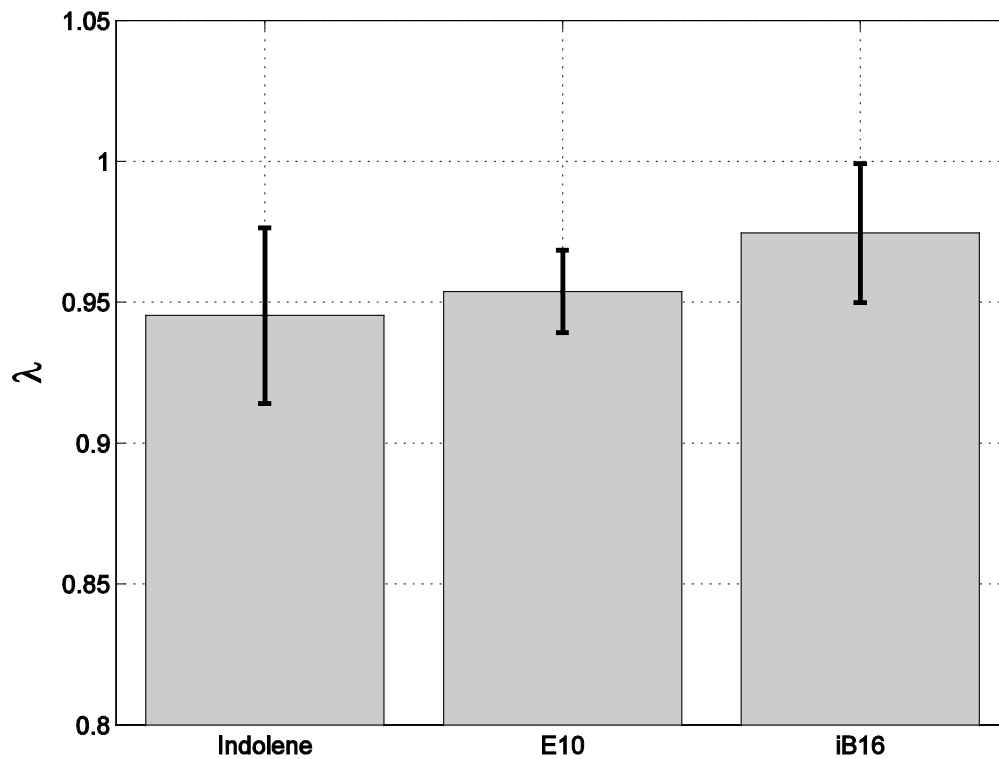


Figure 4.9: INDMAR averaged lambda values – ISO #16183

As seen in Figure 4.9, there is a difference between the lambda values for E10 and iB16, even though the oxygen concentrations by mass for E10 and iB16 are the same, as seen in Table 3.4. The difference seen between E10 and iB16 are within one standard deviation of each other. Note that one possible explanation for the difference is that the blended lower heating value of iB16 is lower than E10 by approximately 1%. Therefore in order to maintain the same power levels, the throttle position needs to be increased, increasing intake air flow rates. Additionally, changes in fuel fluid properties, such as viscosity, may impact the relative air-to-fuel ratio values as well.

Overall changes seen in THC+NO emissions are not necessarily a function of fuel composition, but of test conditions, as seen in Table 4.5. Because testing was performed in-field during two different seasons, it is difficult to show repeatability with respect to test conditions. With the exception of THC, iB16 emissions were consistent for each

emission constituent, with respect to E10 operation. Overall, iB16 emissions followed the same trends as E10.

4.5.2 Volvo Penta

Table 4.15 shows the THC correction factors applied to three Tedlar© bags for the second round of testing. The values were subtracted from the raw THC values reported by the Semtech-DS, due to bag contamination from the OMC engine.

Table 4.15: Volvo Penta THC correction factors

iB16 Bag #1	15ppmC ₁
iB16 Bag #2	30ppm C ₁
E10 Bag #2	65ppm C ₁

Table 4.16 shows the raw emissions for the Volvo Penta running E10 and iB16. Emissions values shown below are averaged over two emissions bag samples.

Table 4.16: Raw emissions for Volvo Penta – alcohol fuels

Emission Constituent	CO (%)	NO (ppm)	THC (ppmC ₁)	THC+NO (ppm)
E10 Round 1	0.843	60.5	332	393
E10 Round 2	1.279	93.2	398	492
E10 Average	1.061	76.9	365	442
iB16 Round 1	0.940	60.2	347	407
iB16 Round 2	1.187	87.3	416	503
iB16 Average	1.064	73.8	381	455

Table 4.17 shows specific emissions values for CO, NO, THC, and THC+NO on a g/kW-hr basis.

Table 4.17: Specific emissions for Volvo Penta – alcohol fuels

Emission Constituent	CO (g/kW-hr)	NO (g/kW-hr)	THC (g/kW-hr)	THC+NO (g/kW-hr)
E10 Round 1	31.08	0.43	0.75	1.18
E10 Round 2	46.58	0.65	0.76	1.51
E10 Average	38.82	0.54	0.76	1.35
iB16 Round 1	35.02	0.42	0.77	1.19
iB16 Round 2	44.02	0.62	0.87	1.54
iB16 Average	39.52	0.52	0.82	1.36

Figure 4.10 shows the percent change in specific emissions from indolene to each respective alcohol fuel. Values for Figure 4.10 and Figure 4.11 can be seen in Table A.5 and Table A.7, respectively.

The overall decrease in CO emissions, as seen in Figure 4.10, can be attributed to leaner Mode 1 operation, as seen in Figure 4.11. CO formation is dependent upon excess fuel [17]; during Mode 1 the amount of excess fuel due to open-loop operation was decreased.

The increase in NO emissions is due to Mode 1 operation, where the engine runs rich open-loop. As oxygen is introduced with the fuel, lambda approaches stoichiometric conditions, seen in Figure 4.11, increasing combustion temperatures and NO formation. Seen in Table 4.17, there was a larger increase in NO formation for alcohol fuels for the second round of testing, with respect to the first round of testing. The increase in ambient temperature from May to September testing can be seen in Table 4.5. A higher intake charge-air temperature increased combustion temperatures, which increased NO formation. Previously discussed literature by Wasil et al. [1] has shown that open-loop four-stroke engines have an increase in NO concentrations with alcohol fuels.

Mode 1 operation caused the global air-to-fuel ratio to approach stoichiometric conditions, which decreases THC formation, as shown in Figure 4.7. There was less excess fuel during the combustion event, decreasing THC emissions.

iB16 emissions were consistent for each emission constituent, with respect to E10 operation. Overall, iB16 emissions followed the same trends as E10.

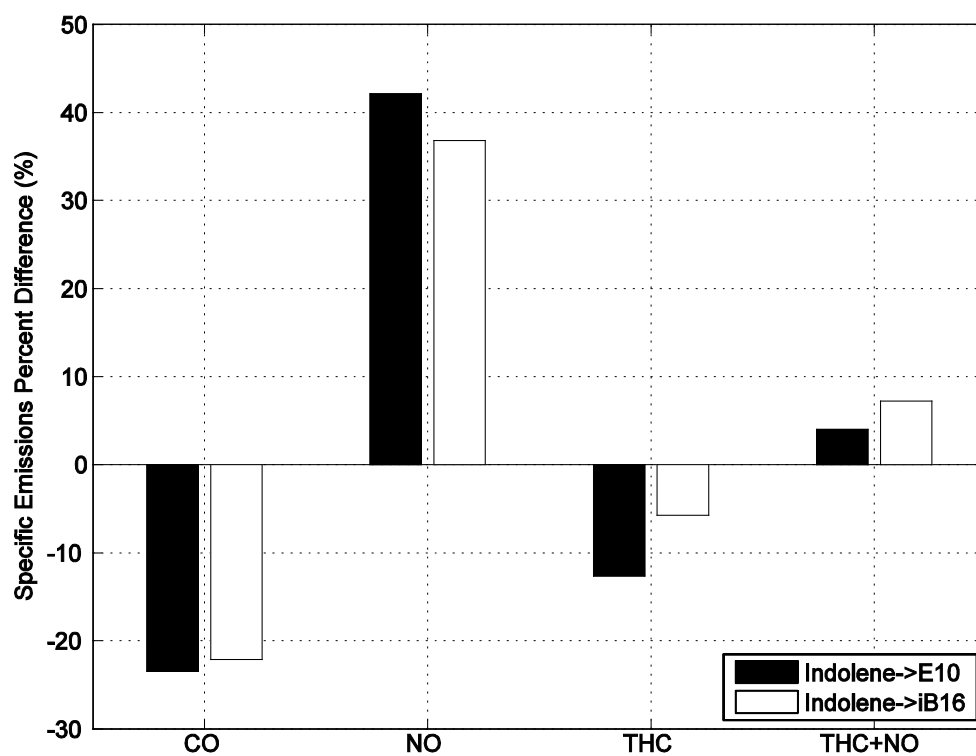


Figure 4.10: Specific emission percent difference from indolene – Volvo Penta

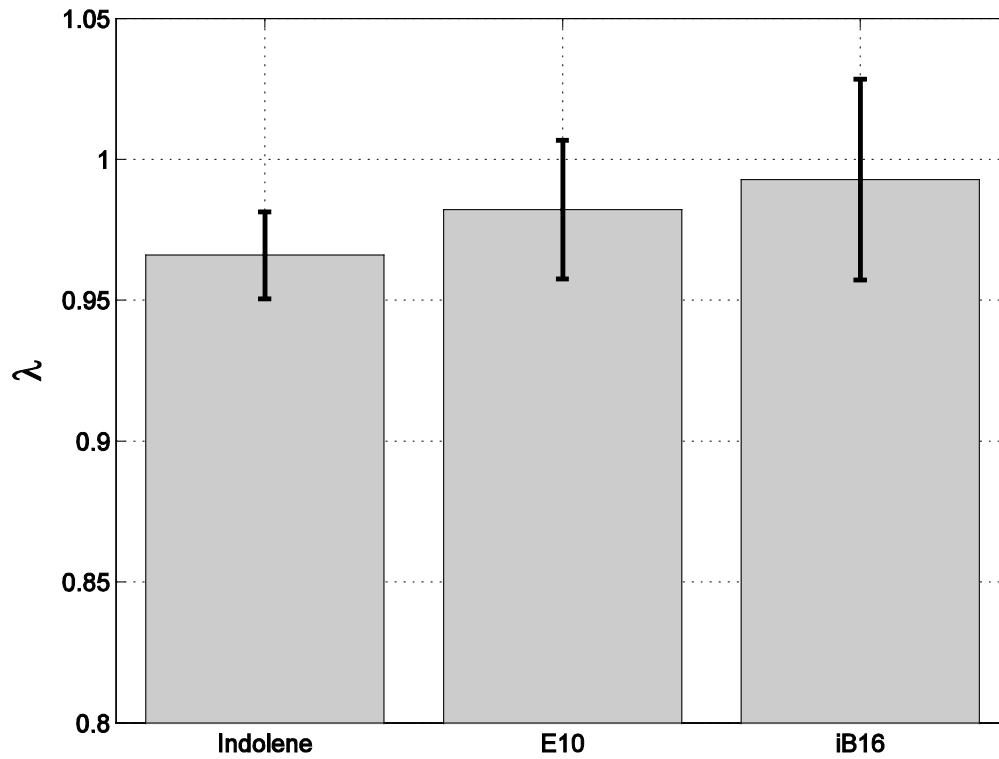


Figure 4.11: Volvo Penta averaged lambda values – ISO #16183

As seen in Figure 4.11, there is a difference between the lambda values for E10 and iB16, even though the oxygen concentrations by mass for E10 and iB16 are the same, as seen in Table 3.4. The difference seen between E10 and iB16 are within one standard deviation of each other. Note that one possible explanation for the difference is that the blended lower heating value of iB16 is lower than E10 by approximately 1%. Therefore in order to maintain the same power levels, the throttle position needs to be increased, increasing intake air flow rates. Additionally, changes in fuel fluid properties, such as viscosity, may impact the relative air-to-fuel ratio values as well.

4.5.3 OMC

Table 4.18 shows the raw emissions for the OMC engine running E10 and iB16. Emissions values shown below are averaged over two emissions bag samples.

Table 4.18: Raw emissions for OMC – alcohol fuels

Emission Constituent	CO (%)	NO (ppm)	THC (ppmC ₁)	THC+NO (ppm)
E10 Round 1	3.229	9.9	25750	25760
E10 Round 2	3.359	15.6	25330	25340
E10 Average	3.294	12.8	25540	25550
iB16 Round 1	2.851	11.5	25480	25500
iB16 Round 2	3.315	8.9	25830	25840
iB16 Average	3.083	10.2	25660	25670

Table 4.19 shows specific emissions values for CO, NO, THC, and THC+NO on a g/hr basis.

Table 4.19: Specific emissions for OMC – alcohol fuels

Emission Constituent	CO (g/hr)	NO (g/hr)	THC (g/hr)	THC+NO (g/hr)
E10 Round 1	4724	2.86	2376	2380
E10 Round 2	5266	4.71	2396	2400
E10 Average	4996	3.78	2386	2390
iB16 Round 1	4246	3.30	2298	2300
iB16 Round 2	5134	2.63	2404	2406
iB16 Average	4690	2.97	2350	2354

Figure 4.12 shows the percent change in specific emissions from indolene to each respective alcohol fuel. Values for Figure 4.12 and Figure 4.13 can be seen in Table A.6 and Table A.7, respectively.

An overall decrease in CO emissions is caused by the relative air-to-fuel ratio approaching stoichiometric conditions. As shown in Figure 4.7, CO emissions are directly related to rich operation, and as oxygen is introduced with the fuel, the relative air-to-fuel ratio is pushed closer to stoichiometric, seen in Figure 4.13. Previous literature by Subramanian et al. [12] has shown that alcohol fuels can decrease CO emissions.

A reduction in specific THC emissions is again due to lambda approaching stoichiometric conditions, seen in Figure 4.13, while running alcohol fuels. During indolene operation, the OMC engine is oxygen deficient. Therefore, there is an inadequate amount of oxygen to fully oxidize hydrogen and carbon molecules [17].

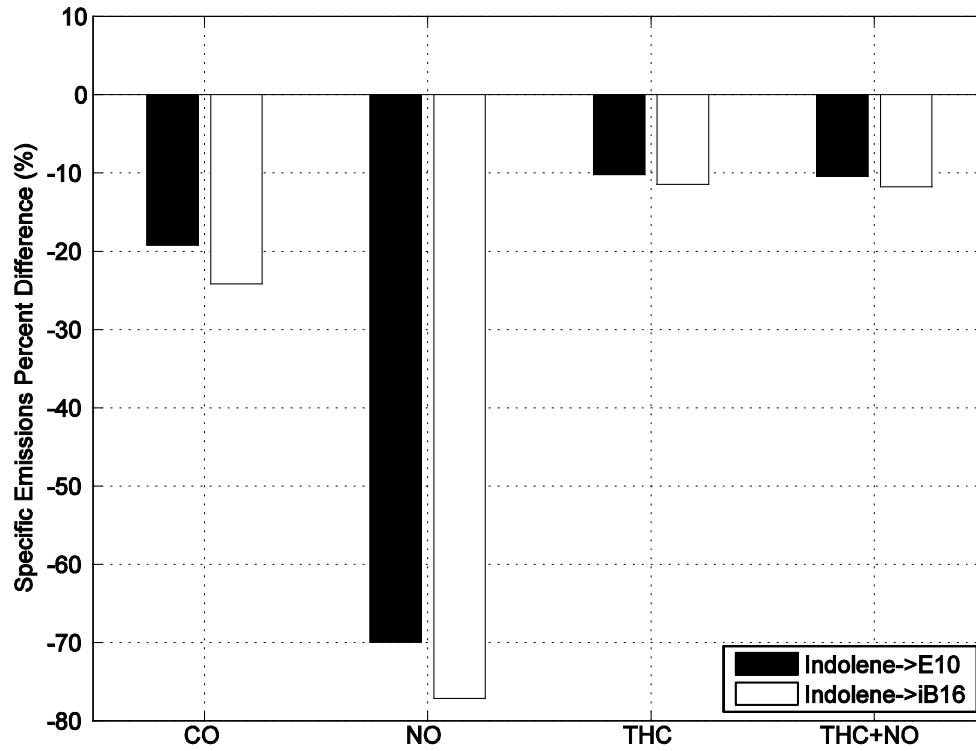


Figure 4.12: Specific emissions percent difference from indolene – OMC

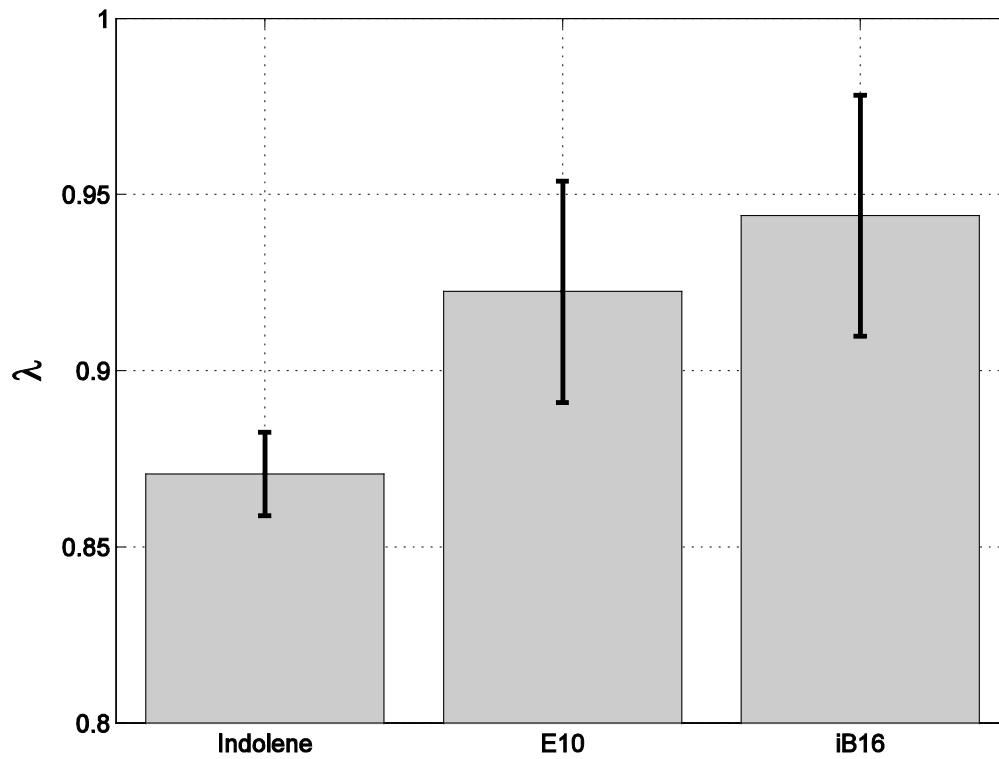


Figure 4.13: OMC averaged lambda values – ISO #16183

As shown in Figure 4.12, there was an overall decrease in NO emissions with respect to baseline indolene under alcohol operation. This trend is contradictory to that of typical two-stroke operation noted by Wasil et al. [1], where alcohol fuels increased NO formation due to higher combustion temperatures. Conversely, other studies performed by Bertsch et al. [2] and Subramanian et al. [12] show a decrease in NO emission with alcohol operation, running similar two-stroke engine technology.

In order to understand the decrease in NO emissions, the amount of energy delivered by the fuel during the combustion process needs to be investigated. Table 4.20 shows the total energy delivered by the fuel during testing.

Table 4.20: Total fuel energy delivered (kW) – OMC

Indolene	15.1
E10	13.7
iB16	13.2

As shown in Table 4.20, the amount of energy delivered is decreased because of alcohol fuels. As less energy is delivered, combustion temperatures are decreased, lowering NO formation.

As seen in Figure 4.13, there is a difference between the lambda values for E10 and iB16, even though the oxygen concentrations by mass for E10 and iB16 are the same, as seen in Table 3.4. The difference seen between E10 and iB16 are within two standard deviations of each other. Note that one possible explanation for the difference is that the blended lower heating value of iB16 is lower than E10 by approximately 1%. Therefore in order to maintain the same power levels, the throttle position needs to be increased, increasing intake air flow rates. Additionally, changes in fuel fluid properties, such as viscosity, may impact the relative air-to-fuel ratio values as well.

4.5.4 Emissions Results Summary

For the four-stroke engines, there was not a distinct trend when switching from the baseline fuel to alcohol fuel for both rounds of testing. This is due to a multitude of factors inherent to field testing, most importantly environmental test conditions, seen in Table 4.5. Although engine speed was the controlled variable in this experiment, ambient temperature ultimately influenced engine-out emissions. Emissions trends may have been more conclusive for the four-stroke engines if they operated closed-loop during Mode 1.

For the two-stroke OMC engine, there was a distinct trend when switching from the baseline test fuel to the alcohol fuels. This trend is due to the engine operating open-

loop for every mode, and not providing compensation when the fuel composition changed.

Table 4.21 shows the change in mass specific THC+NO emissions from E10 to iB16 for the four-stroke engines, on a $g/kW-hr$ basis.

Table 4.21: Specific THC+NO difference from E10 to iB16, on a $g/kW-hr$ basis

	INDMAR	Volvo Penta
Round #1	-0.76	0.01
Round #2	0.05	0.03

Table 4.22 shows the change in mass specific THC+NO emissions from E10 to iB16 for the OMC, on a g/hr basis.

Table 4.22: Specific THC+NO difference from E10 to iB16, on a g/hr basis

	OMC
Round #1	-80
Round #2	6

As seen in Table 4.21, there is not a significant change between THC+NO emissions when going from E10 to iB16. The change seen in Table 4.21 is mainly due to test-to-test variation and also from different fueling strategies employed by INDMAR and Volvo Penta; the INDMAR ran richer during Mode 1 operation. The most significant difference in THC+NO emissions are seen in Table 4.22 for the OMC. This large difference is seen because of the inherent variability within this two-stroke carbureted engine.

In total, results have shown that there is not an appreciable difference between engine-out emissions for two-stroke or four-stroke engines while running E10 or iB16. Due to aforementioned benefits, iso-butanol would make a comparable replacement for ethanol as a blend fuel.

4.6 Comparison of Lambda Calculations – Equations

Four different methods were used to calculate lambda values from emission constituents. Calculations and a comparison of the different methods are outlined below.

4.6.1 ISO #16183: Air-to-fuel Ratio Measurement Method [16]

Since real time air and fuel flow measurements were not available, estimations for lambda using sampled emissions were used. Equation 4.1 is the determination of the stoichiometric air-to-fuel ratio, based off of fuel properties. The ISO #16183 standard [16] and specifically Equation 4.2, calculates lambda based off of dry emissions concentrations.

$$A/F_{st} = \frac{138.0 \cdot (\beta + \frac{\alpha}{4} \cdot \frac{\varepsilon}{2} + \gamma)}{12.011 \cdot \beta + 1.00794 \cdot \alpha + 15.9994 \cdot \varepsilon + 14.0067 \cdot \delta + 32.065 \cdot \gamma} \dots\dots\dots Eqn4.1$$

$$\lambda_i = \frac{\beta \cdot \left(100 - \frac{c_{co} \cdot 10^{-4}}{2} - c_{HC} \cdot 10^{-4} \right) + \left(\frac{\alpha}{4} \cdot \frac{1 - \frac{2 \cdot c_{co} \cdot 10^{-4}}{3.5 \cdot c_{co2}}}{1 + \frac{c_{co} \cdot 10^{-4}}{3.5 \cdot c_{co2}}} - \frac{\varepsilon}{2} \cdot \frac{\delta}{2} \right) \cdot (c_{co2} + c_{co} \cdot 10^{-4})}{4.764 \cdot (\beta + \frac{\alpha}{4} \cdot \frac{\varepsilon}{2} + \gamma) \cdot (c_{co2} + c_{co} \cdot 10^{-4} + c_{HC} \cdot 10^{-4})} \dots\dots\dots Eqn4.2$$

Where:

A/F_{st} is the stoichiometric air-to-fuel ratio

λ is the excess air ratio

C_{CO2} is the dry CO_2 concentration, in percent by volume

C_{CO} is the dry CO concentration, in parts per million

C_{HC} is the HC concentration, in parts per million

β , α , ε , and γ are the C/C, H/C, O/C, S/C ratios of the fuel, respectively

4.6.2 Modified Spindt Method [18]

In 1965, R. S. Spindt published the *Air-Fuel Ratios from Exhaust Gas Analysis*, calculating lambda for a pure hydrocarbon fuel based off of emission constituents [18]. The Spindt method was modified in 1998 to take into account the extra hydroxyl group as a result of oxygenated fuels [19]. Equation 4.3 shows modifications to the original Spindt method.

$$\left(\frac{A}{F}\right)_{actual}^{Spindt \#2} = F_b \left[11.492 F_c \left(\frac{1 + \frac{R}{2} + Q}{1 + R} \right) + \left(\frac{120 F_h}{3.5 + R} \right) \right] - 4.313 F_o \dots\dots\dots Eqn 4.3$$

Where:

$$F_c = \frac{12.01 \cdot X}{12.01 \cdot X + 2.016 \cdot Y + 32.0 \cdot Z}$$

$$F_h = \frac{2.016 \cdot Y}{12.01 \cdot X + 2.016 \cdot Y + 32.0 \cdot Z}$$

$$F_o = \frac{32.0 \cdot Z}{12.01 \cdot X + 2.016 \cdot Y + 32.0 \cdot Z}$$

$$F_b = \frac{P_{CO} + P_{CO_2}}{P_{CO} + P_{CO_2} + P_{HC}}$$

$$R = \frac{P_{CO}}{P_{CO_2}}$$

$$Q = \frac{P_{O_2}}{P_{CO_2}}$$

P_i is the molar percentage of the i^{th} specie of the exhaust

X , Y , and Z are the C/C , H/C , O/C ratios of the fuel, respectively

4.6.3 Brettschneider Method [20]

In 1979, Johannes Brettschneider developed an adaptation to Spindt's equation, incorporating water in the ambient air, NO_x formed in the exhaust, and modification for oxygenated fuels [20]. Equation 4.4 shows the Brettschneider method for determining lambda [21]. Equation 4.4 assumes dry intake air simplifying the original Brettschneider equation and also maintains consistent with the other methods.

$$\lambda = \frac{[CO_2] + \left[\frac{CO}{2}\right] + [O_2] + \left[\frac{NO}{2}\right] + \left(\left(\frac{H_{CV}}{4} * \frac{3.5}{3.5 + \left[\frac{CO}{2}\right]} \right) - \frac{O_{CV}}{2} \right) * ([CO_2] + [CO])}{\left(1 + \frac{H_{CV}}{4} - \frac{O_{CV}}{2} \right) * ([CO_2] + [CO] + [HC])} \dots \dots \dots Eqn4.4$$

Where:

[XX] is the gas concentration in % Volume

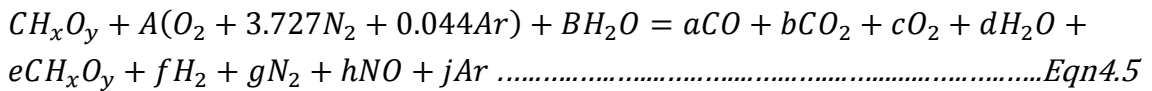
H_{CV} is the atomic ratio of hydrogen to carbon in the fuel

O_{CV} is the atomic ratio of oxygen to carbon in the fuel

4.6.4 Modified Roy Douglas Method

In 1990, Roy Douglas published *AFR and Emissions Calculations for Two-Stroke Cycle Engine*, calculating the air-to-fuel ratio for a pure hydrocarbon fuel based off of emission constituents from a two-stroke engine [22]. Since the Roy Douglas method was developed for a pure hydrocarbon fuel, modifications were needed to account for the extra hydroxyl group added with an alcohol fuel.

With an alcohol fuel, the stoichiometric combustion equation is as follows, in Equation 4.5. The only difference with respect to the original equation is the oxygenated hydrocarbon in the exhaust and the oxygen on the fuel.



The Roy Douglas Method separates the stoichiometric combustion equation into three balances: carbon, hydrogen, and oxygen. With the addition of an oxygenated hydrocarbon, only the oxygen balance changes, seen in Equation 4.6. Therefore, the determination of the water concentration in the exhaust remains the same.

$$2A + y + B = a + 2b + 2c + d + e \cdot y + h \dots\dots\dots Eqn4.6$$

The original solution provided a relationship stating hydrogen emissions are equal to half the CO emissions. With this substitution, the oxygen balance can be rearranged to solve for the variable A , seen in Equation 4.7.

$$A = \frac{1}{2}(a + 2b + 2c + d + e \cdot y + h - y - B) \dots\dots\dots Eqn4.7$$

In order to substitute emissions concentrations in for each variable in Equation 4.7, a relationship is needed to relate each constituent to the total moles of exhaust. Equation 4.8 shows the relationship between an emission constituents concentration in the exhaust, to the total moles of exhaust, using NO as an example.

$$[NO] = \frac{100 \cdot h}{M_t} \dots\dots\dots Eqn4.8$$

Knowing the relationship between the total moles of exhaust to each individual emissions concentration, Equation 4.7 reduces down to Equation 4.9.

$$A = \frac{\frac{1}{4}[CO] + [CO_2] + \frac{x}{4}([CO] + [CO_2]) - \frac{y}{2}([CO] + [CO_2]) + \frac{1}{2}[NO] + [O_2]}{[CO] + [CO_2] + [CH_XO_Y]} \dots\dots\dots Eqn4.9$$

Using the original air-to-fuel ratio determination from [19], the modified air-to-fuel ratio equation can be seen in Equation 4.10.

$$AFR_{modified} = \frac{\frac{1}{4}[CO] + [CO_2] + \frac{x}{4}([CO] + [CO_2]) - \frac{y}{2}([CO] + [CO_2]) + \frac{1}{2}[NO] + [O_2]}{[CO] + [CO_2] + [CH_XO_Y]} \cdot K_f \dots\dots\dots Eqn4.10$$

Where Equation 4.11 is the new relation for K_f , with an oxygenated fuel.

$$K_f = \frac{138.18}{12.011 + 1.008 \cdot x + 16.00 \cdot y} \dots\dots\dots Eqn4.11$$

4.6.5 Lambda Calculations – Results

There are inherent differences for each method of determining air-to-fuel ratio. The ISO #16183 standard is used as the de-facto standard, comparing all calculations against it. The modified Spindt method, derived for four-stroke operation, is not well suited for two-stroke engines. Brettschneider's equation was considered an evolutionary improvement with respect to Spindt's method, because of the incorporation of water in the ambient air, as well as NO_x in the exhaust [20]. While the Roy Douglas method was originally derived for two-stroke operation, results have shown it is applicable for four-stroke engines as well [22].

4.7 Comparison of Lambda Calculations – Results

4.7.1 INDMAR Lambda Comparison

Figure 4.14 shows four calculations for lambda, utilizing the ISO #16183 standard, Brettschneider method, modified Spindt method, and modified Roy Douglas method. The modified Spindt method provides a 10% over-estimate of the ISO result. Figure 4.14 also shows that the modified Roy Douglas method, though derived for two-stroke engines, is in agreement with the ISO #16183 standard.

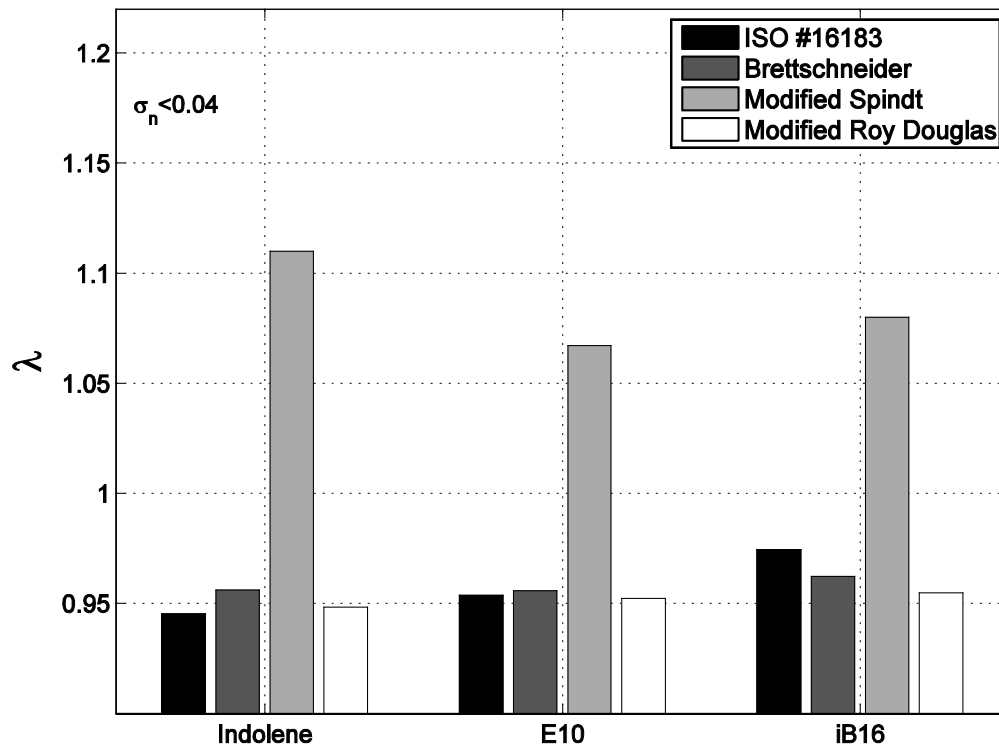


Figure 4.14: Lambda calculations comparison – INDMAR

4.7.2 Volvo Penta Lambda Comparison

Figure 4.15 shows four calculations for lambda, utilizing the ISO #16183 standard, Brettschneider method, modified Spindt method, and modified Roy Douglas method. Consistent with the INDMAR, the Spindt method provides a 10% over-estimate of the ISO method and, lambda values for the modified Roy Douglas method are in agreement with the ISO #16183 standard, seen in Figure 4.15.

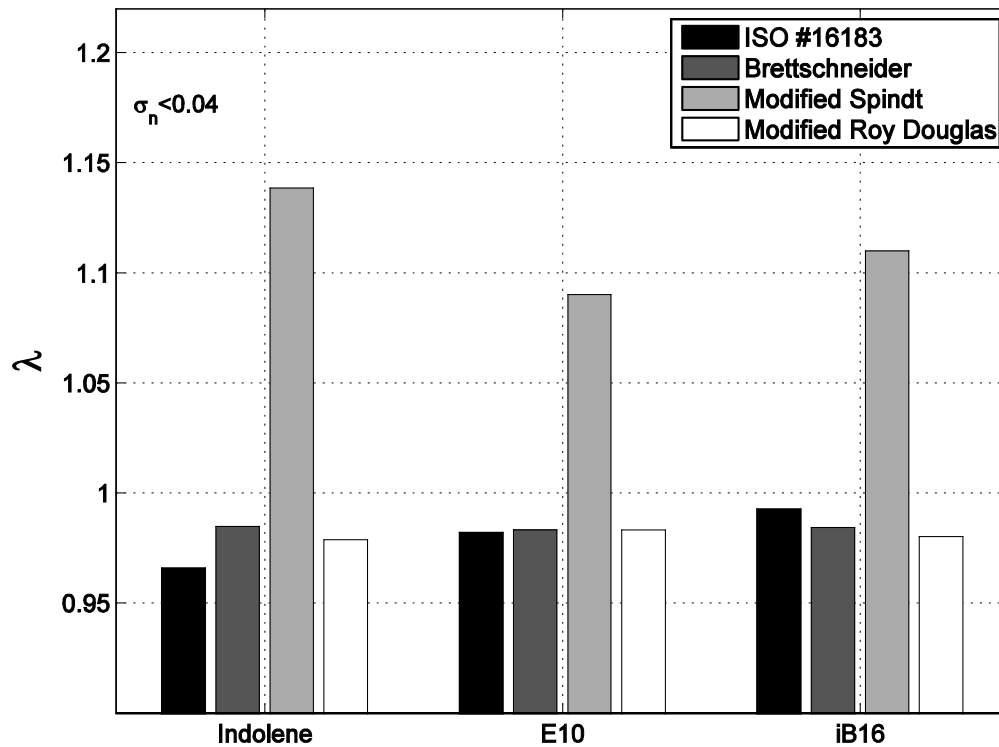


Figure 4.15: Lambda calculations comparison – Volvo Penta

4.7.3 OMC Lambda Comparison

Figure 4.16 shows four calculations for lambda, utilizing the ISO #16183 standard, Brettschneider method, modified Spindt method, and modified Roy Douglas method. The Spindt method, derived for four-stroke operation, provides an over-estimate of the global air-to-fuel ratio. As seen in Figure 4.16, the modified Roy Douglas method closely relates to the ISO standard, while the Brettschnieder equation yields a larger result.

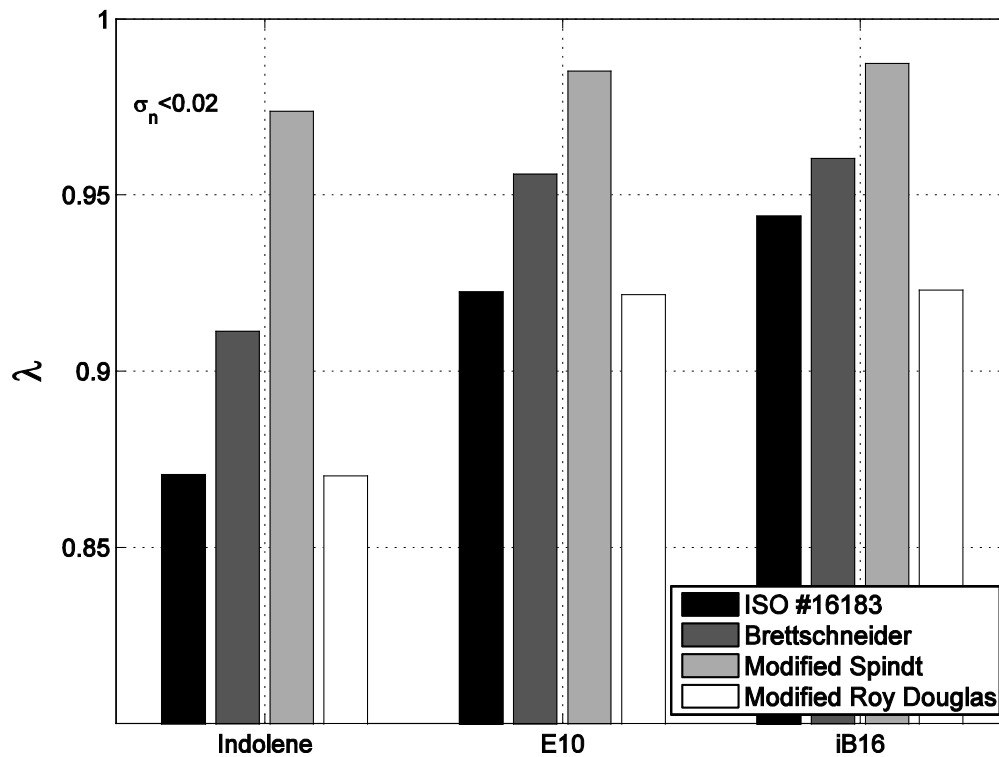


Figure 4.16: Lambda calculations comparison – OMC

As a result of two-stroke engines operating on a short-circuited, or scavenged, combustion process, analyzing the global air-to-fuel ratio of a two-stroke engine is not the best representation of the actual combustion process. Analyzing the mixture that took place in the combustion process, the burn zone air-to-fuel ratio, is the appropriate metric to measure [22].

From emissions measurement, the trapped efficiency of the air and fuel in the combustion process can be seen in Equation 4.12 and 4.13 [22], respectively. Direct substitution of air-to-fuel ratio values calculated using Equation 4.10 can be made into Equation 4.12.

$$TE_{air} = 1 - \frac{(1+AFR) \cdot [O_2]}{AFR \cdot [21\%]} \dots\dots\dots Eqn 4.12$$

$$TE_{fuel} = \frac{[CO] + [CO_2]}{[CO] + [CO_2] + [THC]} \dots\dots\dots Eqn 4.13$$

Knowing the trapped efficiencies of the air and fuel, the trapped air-to-fuel ratio can be calculated, seen in Equation 4.14.

$$AFR_{Burning\ Zone} = AFR_{Global} * \frac{TE_{air}}{TE_{fuel}} \dots\dots\dots Eqn 4.14$$

Figure 4.17 shows three methods of calculating lambda for the OMC engine: the ISO #16183 standard, the modified Roy Douglas method, and the trapped lambda using the modified Roy Douglas method.

The differences of the trapped lambda are not as pronounced for indolene operation, as they are with E10 and iB16. The effects of analyzing the trapped lambda would be more pronounced if emissions on a per-mode basis were available. For instance, the effect would be most pronounced at idle, where the short-circuited scavenging effect of a carbureted two-stroke is apparent. While the global lambda will be beyond the flammability of the fuel, the trapped lambda will be rich of stoichiometric.

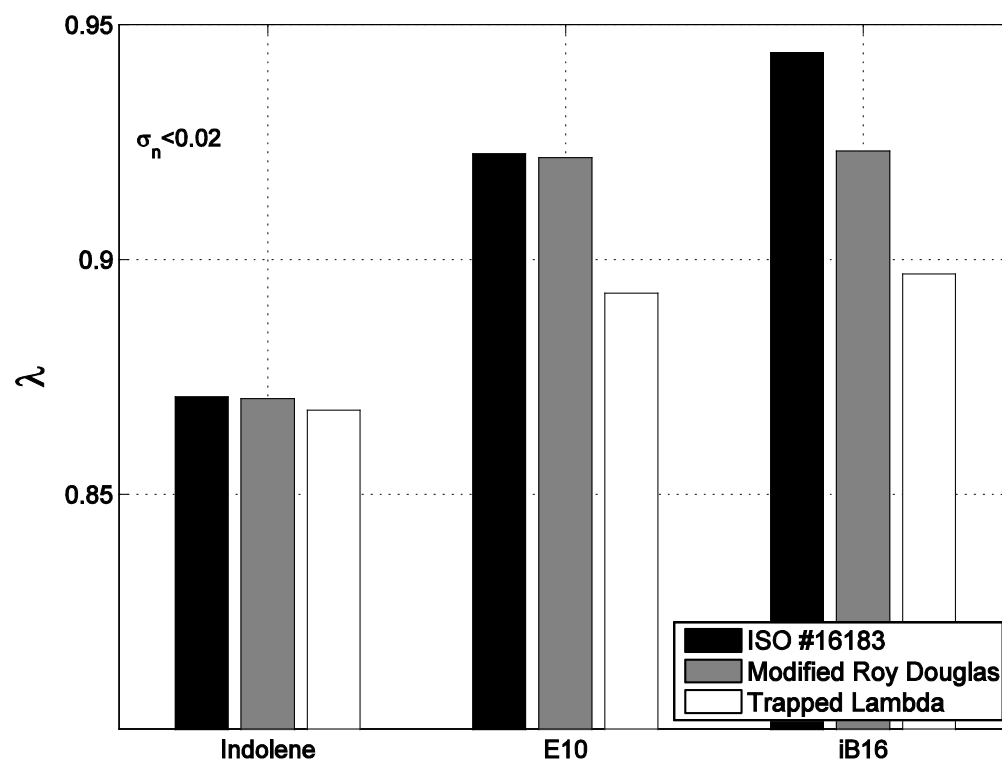


Figure 4.17: Trapped lambda comparison – OMC

5. Conclusions and Future Work

5.1 Conclusions

Constant volume emissions sampling techniques were used to assess the impact of low level blend alcohol fuels on two-stroke and four-stroke marine engine emissions. The impact of the low level blend alcohol fuels was compared to baseline tests performed using certification gasoline. The five-mode adapted ICOMIA test cycle was performed in the field on the Chesapeake Bay in Annapolis, MD. Three different marine engines were tested, which provided a representation of commercially available marine engines. Baseline emissions were developed for indolene operation, on all three engines. From there, E10 emissions were able to be compared relative to the baseline, and iB16 emissions were compared relative to the baseline and E10 emissions. The original objectives have been achieved, as outlined below:

- Due to environmental impacts, emissions trends for the four-stroke engines running low level blend alcohol fuels were not consistent with respect to the baseline between May and September testing
- Emissions trends for the two-stroke engines running low level blend alcohol fuels were consistent with respect to the baseline between May and September testing due to the open-loop operation of the engine, as well as weather conditions
- Regardless of the round of testing, the difference from the baseline indolene tests to ethanol and iso-butanol blended fuels followed the same trend

Iso-butanol provides many benefits over ethanol, such as the ability to be transported by pipeline, having a higher energy density, and the ability to be used in higher concentrations as a blend fuel while maintaining the same oxygen concentration by mass. The aforementioned emission trends discussed show that iso-butanol can be a viable substitute for ethanol as the ethanol blend cap is reached for the RFS.

5.2 Future Work

A concern when running low level blend alcohol fuels is the degradation of engine components with time. Although the engines used in this study were aged with iB16 between the months of May and September, the engines did not reach the end of their useful life, as determined by the marine industry. It would be advisable to complete a comprehensive laboratory study, isolating the degradation of engine components as durability testing is performed on marine engines.

As emissions standards become more stringent, engineers begin to research every venue possible to reduce engine-out emissions. Restrictions will soon be put into place to reduce the Reid vapor pressure (RVP) in fuels, especially for the marine industry. One way to achieve this would be to combine a tri-blend of indolene, ethanol, and iso-butanol. By blending iso-butanol at a higher ratio than ethanol, the overall RVP of a fuel can be decreased, while still maintaining the correct oxygen concentration.

To fully understand the effects of low level blend fuels on the engines tested for this thesis, laboratory testing using the five-mode ICOMIA Test Cycle would be advised, because of conflicting trends seen between the two rounds of testing. Performing this testing in a lab setting would allow for tighter control of variables that effect engine-out emissions.

Bibliography

- [1] J. Wasil, J. McKnight, R. Kolb, D. Munz, J. Adey and B. Goodwin, "In-Use Performance Testing of Butanol-Extended Fuel in Recreational Marine Engines and Vessels," in *SAE International*, Warrendale, 2012-32-0011, 2012.
- [2] M. Bertsch, K. Beck and U. Spicher, "Influence of the Alcohol Type and Concentration in Alcohol-Blended Fuels on the Combustion and Emissions of Small Two-Stroke SE Engines," in *SAE International*, Warrendale, 2012-32-0038, 2012.
- [3] T. Wallner and R. Frazee, "Study of regulated and non-regulated emissions from combustion of gasoline, alcohol fuels and their blends in a DI-SI engine," in *SAE International*, Warrendale, 2010-01-1571, 2010..
- [4] United States Environmental Protection Agency, "Fuels and Fuel Additives," [Online]. Available: <http://www.epa.gov/otaq/fuels/renewablefuels/index.htm>.
- [5] United States Congress, "Energy Independence Security Act," [Online]. Available: <http://www.gpo.gov/fdsys/pkg/BILLS-110hr6enr/pdf/BILLS-110hr6enr.pdf>.
- [6] Gevo, "Isobutanol-A Renewable Solution For The Transportation Fuels Value Chain," May 2011. [Online]. Available: <http://www.gevo.com/wp-content/uploads/2011/05/GEVO-wp-iso-ftf.pdf>. [Accessed 09 November 2012].
- [7] J. Gomez, T. Brasil and N. Chan, "An Overview of the Use of Oxygenates in Gasoline," California Environmental Protection Agency, 1998.
- [8] J. Weaver, L. Exium and L. Prieto, "Gasoline Composition Regulations Affecting LUST Sites," U.S. Environmental Protection Agency, Washington DC, 2010.
- [9] Central Intelligence Agency, "The World Factbook: US," November 2012. [Online]. Available: <https://www.cia.gov/library/publications/the-world-factbook/geos/us.html>. [Accessed 6 November 2012].
- [10] M. Yassine and M. La Pan, "Impact of Ethanol Fuels on Regulated Tailpipe Emissions," in *SAE International*, Warrendale, 2012-01-0872, 2012.
- [11] J. Weber, "Impact of E22 on Two-Stroke and Four-Stroke Snowmobiles," Michigan Technological University, Houghton, 2012.
- [12] M. Subramanian, A. Setia, P. Kanal, N. Pal, S. Nandi and R. Malhotra, "Effect of Alcohol Blended Fuels on the Emissions and Field Performance of Two-Stroke and

Four-Stroke Engine Powered Two Wheelers," in *SAE International*, Warrendale, 2005-26-034, 2005.

- [13] "Emissions Test Cycles ISO 8178," [Online]. Available: <http://www.dieselnet.com/standards/cycles/iso8178.php>. [Accessed 2012].
- [14] "SEMTECH-DS: Gaseous Portable Emissions Measurement System," Sensors Inc., [Online]. Available: <http://www.sensors-inc.com/ds.html>.
- [15] "Products: 5" Standard Wakeboard Zero Off," Zero Off, [Online]. Available: <https://www.zerogps.com/product/5-standard-wakeboard-zero>.
- [16] ISO, [Online]. Available: http://www.iso.org/iso/catalogue_detail.htm?csnumber=32152.
- [17] J. B. Heywood, "Internal Combustion Engine Fundamentals," McGraw-Hill Inc, 1988.
- [18] D. Bresenham, J. Reisel and K. Neusen, "Spindt Air-Fuel Ratio Method Generalization for Oxygenated Fuels," in *SAE International*, Warrendale, 982054, 1998.
- [19] R. S. Spindt, "Air-Fuel Ratio from Exhaust Gas Analysis," in *Society of Automotive Engineers*, 650507, 1965.
- [20] W. M. Silvis, "An Algorithm for Calculating the Air/Fuel Ratio from Exhaust Emissions," in *SAE International*, Warrendale, 970514, 1997.
- [21] BRIDGE analyzers, inc., "White Paper No. 1 Rev. 030227," [Online]. Available: <http://www.bridgeanalyzers.com/EGA/Automotive/mediaRepos/productDocs/White%20Paper%201.pdf>. [Accessed 1 12 2012].
- [22] R. Douglas, "AFR and Emissions Calculations for Two-Stroke Cycle Engines," in *SAE Internations*, Warrendale, 901599, 1990.
- [23] "Semtech-DS," Sensors Inc., [Online]. Available: <http://www.sensors-inc.com/ds.html>. [Accessed 13 11 2012].

Appendix A

A.1 Additional Plots for Reference

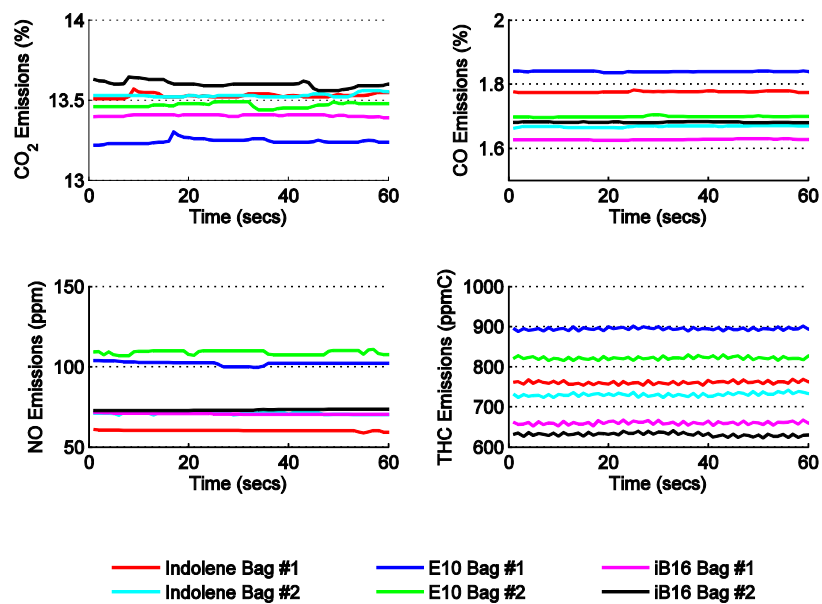


Figure A.1: Emissions stability for INDMAR – round 1

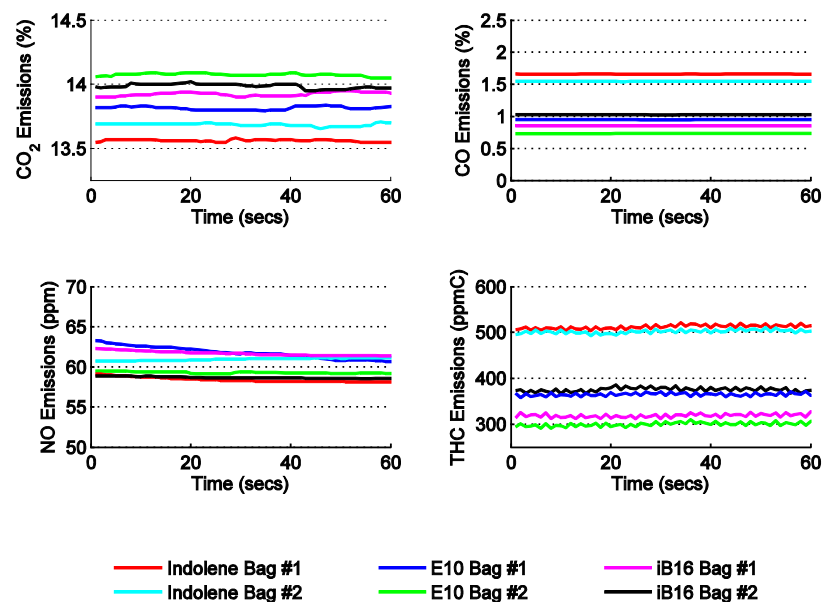


Figure A.2: Emissions stability for Volvo Penta – round 1

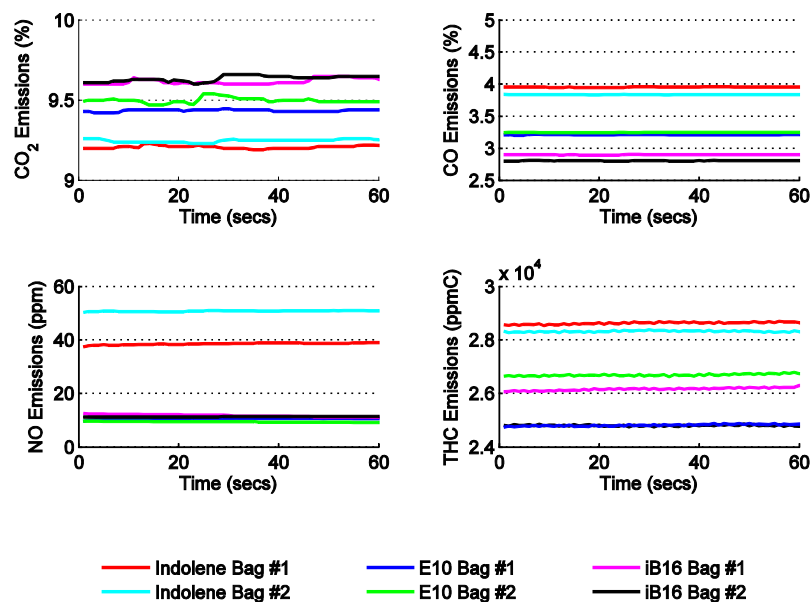


Figure A.3: Emissions stability for OMC – round 1

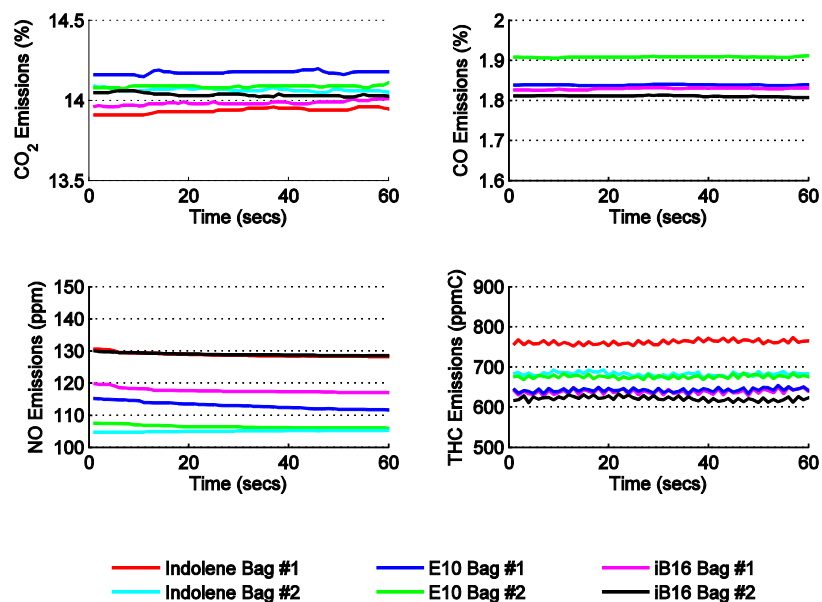


Figure A.4: Emission stability INDMAR – round 2

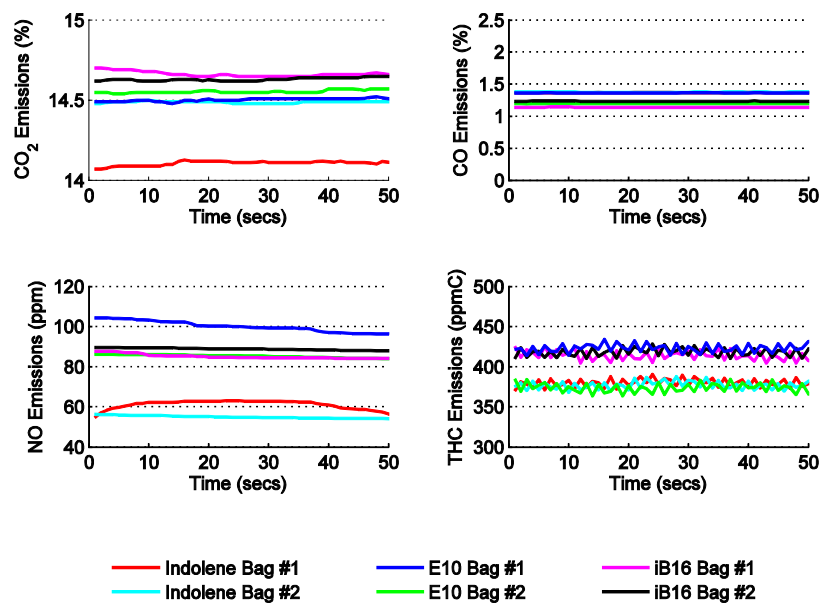


Figure A.5: Emissions stability Volvo Penta – round 2

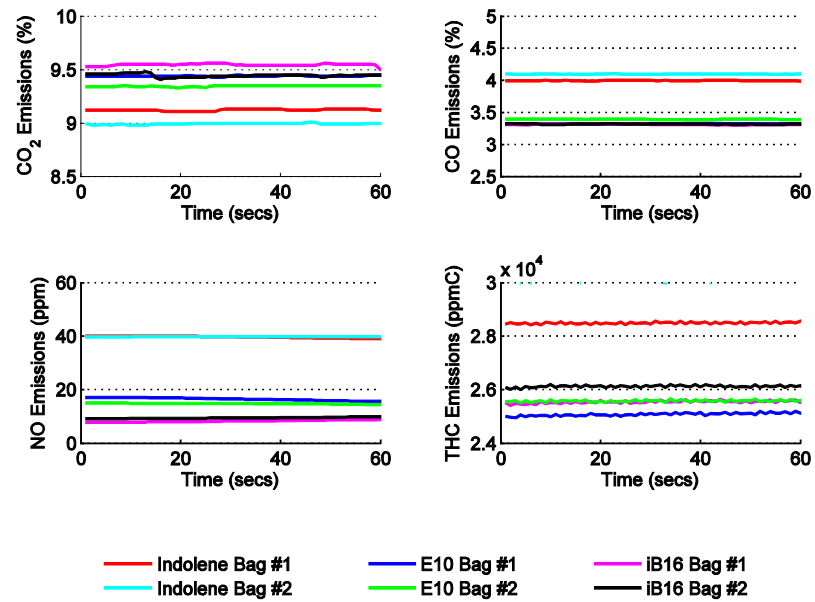


Figure A.6: Emissions stability OMC – round 2

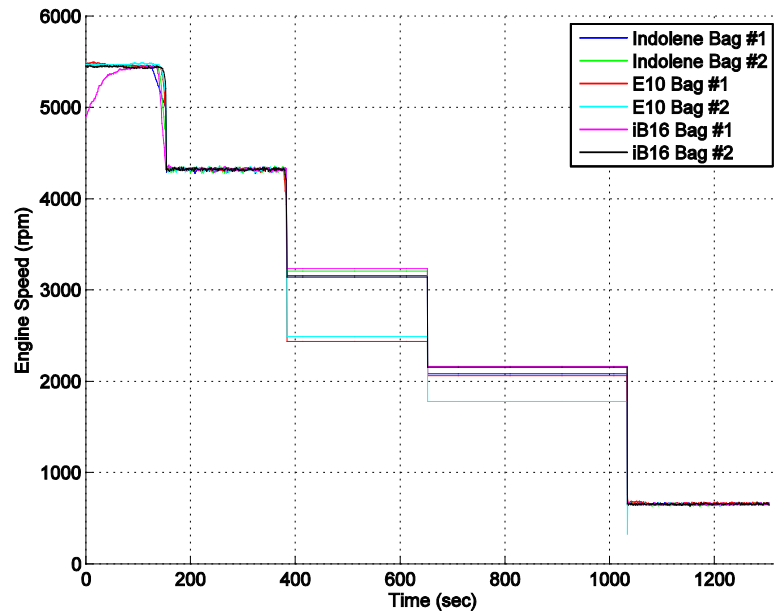


Figure A.7: INDMAR engine speed – round 2

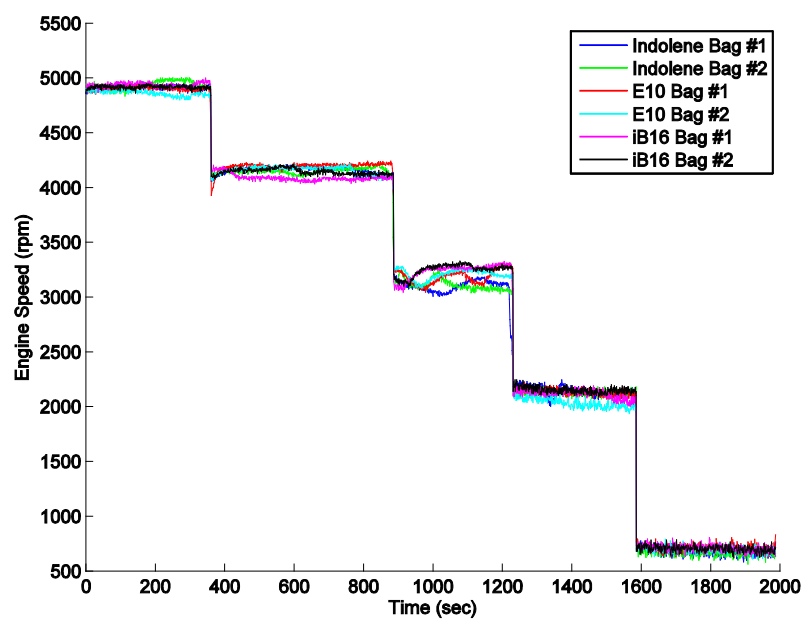


Figure A.8: OMC engine speed – round 2

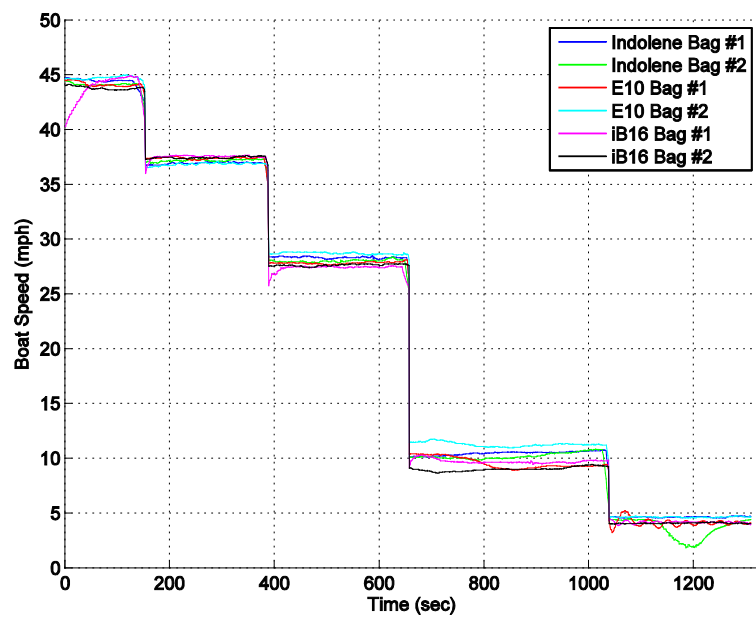


Figure A.9: INDMAR boat speed – round 2

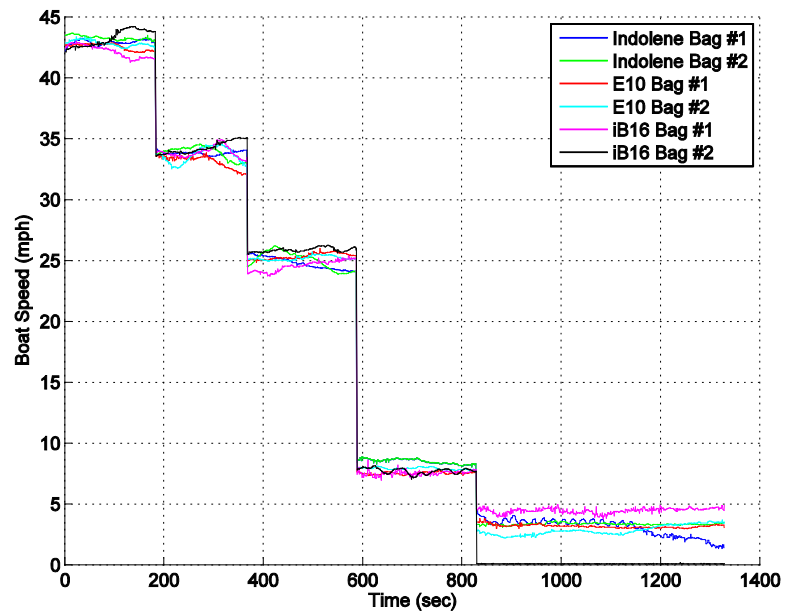


Figure A.10: OMC boat speed – round 2

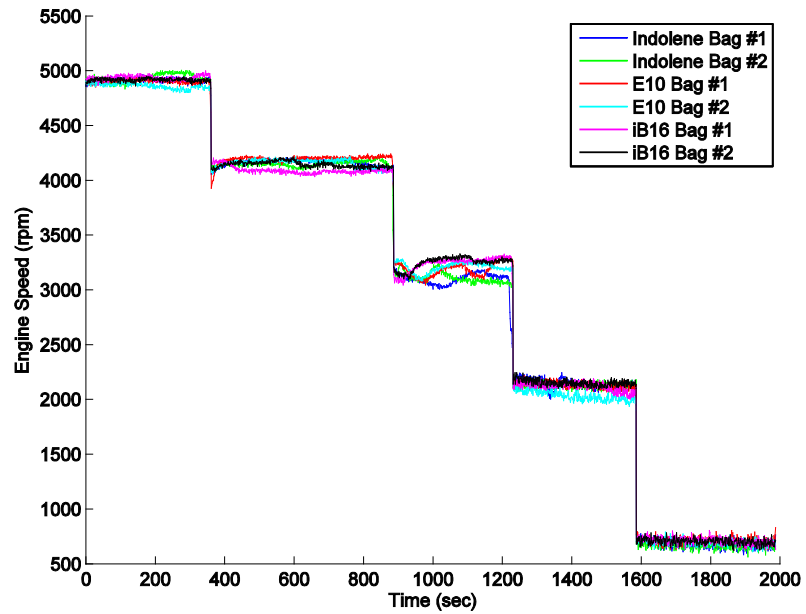


Figure A.11: OMC engine speed – round 2

A.2 Additional Data Tables for Reference

Table A.1: INDMAR averaged emissions with one standard deviation – round 2

	CO (%)	NO (ppm)	THC (ppmC ₁)
Indolene Bag #1	2.244±0.002	128.8±0.6	762±5
Indolene Bag #2	2.003±0.002	105.0±0.2	682±5
E10 Bag #1	1.838±0.001	113.0±1.1	642±5
E10 Bag #2	1.908±0.001	106.4±0.5	676±4
iB16 Bag #1	1.829±0.002	117.6±0.7	639±7
iB16 Bag #2	1.811±0.002	128.9±0.4	621±6

Table A.2: Volvo Penta averaged emissions with one standard deviation – round 2

	CO (%)	NO (ppm)	THC (ppmC ₁)
Indolene Bag #1	1.367±0.008	55.8±14.3	379±8
Indolene Bag #2	1.375±0.001	55.2±0.8	377±5
E10 Bag #1	1.362±0.001	100.9±3.2	423±6
E10 Bag #2	1.196±0.001	85.4±0.8	308±6
iB16 Bag #1	1.14±0.001	85.8±1.9	399±6
iB16 Bag #2	1.235±0.001	88.9±0.6	388±5

Table A.3: OMC averaged emissions with one standard deviation – round 2

	CO (%)	NO (ppm)	THC (ppmC ₁)
Indolene Bag #1	3.997±0.003	39.7±0.3	28488±37
Indolene Bag #2	4.098±0.002	39.8±0.1	30047±34
E10 Bag #1	3.325±0.003	16.5±0.5	25077±57
E10 Bag #2	3.392±0.002	14.8±0.2	25575±36
iB16 Bag #1	3.313±0.006	8.3±0.3	25538±50
iB16 Bag #2	3.318±0.003	9.4±0.2	26122±41

Table A.4: Specific emissions percent difference from indolene – INDMAR

Emission Constituent	CO (%)	NO (%)	THC (%)	THC+NO (%)
E10 Average	-3.91	28.60	9.68	13.87
iB16 Average	-4.58	12.93	-5.14	-0.06

Table A.5: Specific emission percent difference from indolene – Volvo Penta

Emission Constituent	CO (%)	NO (%)	THC (%)	THC+NO (%)
E10 Average	-22.36	43.32	-12.64	4.00
iB16 Average	-21.36	38.89	-5.75	7.20

Table A.6: Specific emissions percent difference from indolene – OMC

Emission Constituent	CO (%)	NO (%)	THC (%)	THC+NO (%)
E10 Average	-19.26	-69.95	-10.19	-10.48
iB16 Average	-24.21	-77.12	-11.52	-11.84

Table A.7: ISO #16183 lambda values all engines

	Indolene	E10	iB16
INDMAR	0.95	0.95	0.97
Volvo Penta	0.97	0.98	0.99
OMC	0.87	0.92	0.94

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