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September 22, 2010 — August 15, 2013

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Subcontract Report
NREL/SR-5400-60115
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This publication received minimal editorial review at NREL.

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Acknowledgements

This report and the work described herein were performed under the stewardship of the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Vehicle Technologies Office. The technical direction of Kevin Stork (Fuels Technology Team Lead) and Steve Przesmitzki is gratefully acknowledged.

The National Renewable Energy Laboratory (NREL) provided Michigan Technological University with the opportunity to perform the work. Bob McCormick was excellent to work with as the Technical Monitor and is given thanks for the collaboration, technical guidance, and most importantly, patience.

A sincere thank you and appreciation to the OEMs for their technical and hardware support.

List of Acronyms

°C	degrees Celsius
°F	degrees Fahrenheit
AFR	air fuel ratio
AKI	anti-knock index
BOL	beginning-of-life (0 miles on engine)
BSFC	brake specific fuel consumption
CFR	Code of Federal Regulations
CO	carbon monoxide
CO_2	carbon dioxide
E0	0 vol% ethanol
E10	10 vol% ethanol
E15	15 vol% ethanol
EGT	exhaust gas temperature
EOL	end-of-life (5,000 miles on engine)
GPS	global positioning system
HC	hydrocarbons
ISMA	International Snowmobile Manufacturers Association
kW	kilowatt
MAG	magneto (right side of engine/snowmobile)
MOL	middle-of-life (2,500 miles on engine)
mph	miles per hour
NO	nitrogen oxide
NOx	oxides of nitrogen
NREL	National Renewable Energy Laboratory
O_2	oxygen
OEM	original equipment manufacturer
ppm	parts per million
PTO	power take-off (left side of engine/snowmobile)
RPM	revolutions per minute
vol%	volume percent
λ	lambda (relative air/fuel ratio)

Executive Summary

Objective

E15 (15 vol% ethanol) can be used in model year 2001 and newer light-duty motor vehicles yet is not approved for use in snowmobiles or off-highway vehicles of any kind. The objective of this study was to evaluate the effects of E15 on current product and legacy snowmobile engines and vehicles that could occur due to misfueling by the vehicle owner. Three test scenarios were conducted to evaluate the impact of E15, including cold-start performance and emissions, on-snow vehicle driveability, and laboratory exhaust emissions over the useful life of the engine.

Scope of Work

Engines

Eight engines (four engine pairs) were specified for evaluation in this test program. These engines represent current and legacy product that may exhibit sensitivity to increased ethanol blended in gasoline. Two-stroke and four-stroke engines, including both fan and liquid cooled, were included in this study. Mixture preparation technologies included carburetors, port-fuel injection, and direct fuel injection.

Vehicles

Four snowmobile vehicles were utilized for the cold-start and on-snow driveability evaluations. These snowmobiles represent current and legacy products that may exhibit sensitivity to increased ethanol blended in gasoline. These snowmobiles corresponded directly to the engines specified earlier.

Fuels

Splash-blending was used to make the E15 fuel formulations. For the cold-start, driveability, and laboratory durability testing, gasolines with zero ethanol content (E0) were splash-blended with E98. The minimum octane requirement for each manufacturer was matched for these blends regardless of ethanol content. The laboratory emissions test fuels consisted of E0 (Indolene) and E15 that was formulated by splash-blending Indolene with E98 ethanol. This resulted in an elevated octane number compared to Indolene for the E15 emissions certification fuel.

Summary of Results

A limited number of snowmobile engines were evaluated for this test program; thus, the results are not statistically significant. However, the broad range of engine and mixture preparation technologies combined with the various test scenarios provide preliminary information to assess potential issues with E15 use in snowmobiles. Note that all of the engines tested were calibrated on E10 fuel (10 vol% ethanol), or at a minimum checked for proper operation on E10, prior to production. Legacy vehicles (10 years and older), typically calibrated using E0, would experience greater changes than those noted in this report when operating on E15.

Cold-Start

Cold-start tests were performed at -6.7°C (20°F), -17.8°C (0°F), and -28.9°C (-20°F). The evaluation included time to start or number of pulls to start, engine speed, exhaust gas temperature (EGT), and start-up engine emissions concentrations. A series of three evaluations at each temperature for each fuel were conducted over a three-minute interval. The following observations were drawn from the testing:

- Statistically significant differences in starting times were not observed for most vehicles. For those vehicles that experienced an increase in starting time, the higher latent heat of vaporization for ethanol may have reduced fuel evaporation in the combustion chamber, degrading cold-start performance.
- Carbon monoxide (CO) decreased 10%–20% for two of the vehicles tested, increased for one of the vehicles by 6% at -6.7°C (20°F) yet reduced 30% at -17.8°C (0°F), and remained the same for the fourth vehicle.
- Of the two engines that were able to be measured for hydrocarbon (HC) emissions, E15 tended to reduce HC concentrations at cold-start by up to 20% for one of the vehicles. HC increased by 8% at -6.7°C (20°F) and decreased by 9% at -17.8°C (0°F) for the other vehicle. HC emissions could not be measured for the two remaining engines because concentrations were outside the analyzer range.
- E15 caused engine idle speed to reduce by 5%–10% on average for those vehicles that did not control to a target RPM. The lower energy density of E15 may have led to reduced idle speed.

Driveability

Snowmobile driveability was analyzed using a subjective evaluation on a controlled test course, and objective data were collected from each snowmobile during the subjective testing. Additional subjective evaluation was performed on a snowmobile trail, utilizing a regimented operation scheme and a limited number of drivers. The following conclusions were drawn from the testing results:

- The drivers could not easily discern which fuel the snowmobiles were using during the subjective evaluation on the controlled test course.
- E0 and E15 were evaluated similarly by the riders while some machines seemed to run better on E0 than E15 and vice versa according to driver comments.
- For the objective evaluation on the snowmobile trail, the engines had higher cylinder head temperatures and EGTs when running on E15 compared to E0. An average increase in cylinder head temperature of 2%–8% was noted and 2%–11% for the EGT.

Emissions and Durability

The purpose of this test series was to measure the emissions and performance of the snowmobiles over the useful life of the vehicles (5,000 miles). Measurements included regulated and non-regulated emissions, engine speed, engine power, EGT, muffler exit temperature, and fuel flow. The following conclusions were drawn based on the data collected:

- There were no fuel-related engine failures on E0 or E15.
- Brake power increased an average of 0%–3%, and brake specific fuel consumption (BSFC) decreased an average of 0%–3% at mode 1 (100% of rated speed and torque) due to additional oxygen content in the combustion chamber from E15. However, in general

BSFC increased 2% for modes 2, 3, and 4 due to the reduced energy content of E15 compared to E0.

- Exhaust gas temperature increased with E15 by approximately 3% at mode 1 and approximately 1.5% at modes 2 through 4 due to a less fuel-rich (but still fuel-rich of the stoichiometric ratio) air/fuel mixture compared to E0. Factory-installed EGT sensors were present on two of the four engines tested, which had a limited effect on compensating for the fuel oxygenation. While operating on the E15 durability fuel, one sample experienced damage to the muffler packing material after exposure to higher exhaust temperatures than were seen with the E15 certification fuel or either E0 fuels. The higher exhaust temperatures and damage are assumed to result from a repeatable, secondary combustion event in the exhaust system, due to the less fuel-rich operation, differing octane rating, and differing vapor pressure. Engine emissions and power were essentially unchanged but the muffler was considered to have failed.
- Consistent with air/fuel mixtures closer to stoichiometric conditions, CO emissions were reduced on average by 37% with E15 compared to E0. Only minor changes in HC emissions were noted for all engines.
- Non-regulated emissions such as 1,3-butadiene tended to decrease by 20% with the addition of E15. For engine #4, there was an inconsistent trend of increasing and decreasing 1,3-butadiene emissions over the five modes. Formaldehyde emissions increased consistently for E15 fuel by 35%.

Conclusions and Recommendations

Occasional misfueling of snowmobiles with E15 is not likely to cause noticeable or immediate problems for consumers. E15 is not approved for snowmobile use, and issues recorded during this study support the U.S. Environmental Protection Agency's decision to not approve E15 for snowmobiles. These vehicles do not have the same sophisticated control systems as modern automobiles and do not compensate for the additional oxygen content of the E15 fuel. Long-term effects of sustained usage of E15 were not studied as part of this effort. Materials compatibility was not part of the study. One thing to note from this study was increased exhaust temperatures with E15 under certain conditions. This is believed to be primarily due to the engine operating closer to stoichiometric conditions. Increased exhaust temperatures are of concern to manufacturers because some parts in the engine and exhaust could be temperature sensitive.

Recommendations for future research include more studies on long-term durability with an increased sample size that represents a larger percentage of the legacy fleet. In addition, more work with the engine oil to determine if there is any effect and correlation on lubricity and ethanol content should be conducted.

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Introduction

Test Program Overview

The objective of this study was to evaluate the effects of ethanol blended in gasoline at up to 15 volume percent (vol%) (E15) on current product and legacy snowmobile engines and vehicles. Three test scenarios were conducted to evaluate the impact of E15, including:

- Cold-start performance and emissions
- On-snow vehicle driveability
- Laboratory exhaust emissions over the useful life of the engine.

Standard test protocols currently in use by the snowmobile industry were employed. A conventional (E0) gasoline and a gasoline splash-blended with E98 to form E15 were used as the test fuels. Octane was identified as one of the key parameters for snowmobile engine durability; as such, the octane level of both test fuels was maintained at the minimum required level for the particular engine.

Approach

Cold-start performance and emissions were investigated at temperatures from -6.7°C (20°F) to -28.9°C (-20°F). The evaluation included start-up engine emissions concentrations, time to start or number of pulls to start, engine speed, and exhaust gas temperature (EGT). A series of three evaluations at each temperature for each fuel were conducted over a three-minute interval.

On-snow vehicle driveability was analyzed using four sets of evaluations. Subjective evaluation was conducted on a controlled test course, using a jury of eight experienced drivers. Objective data were collected from each snowmobile during the subjective testing, using high-speed data acquisition and sensors installed on the vehicles. An additional subjective evaluation was performed on a snowmobile trail in the Upper Peninsula of Michigan, utilizing a regimented operation scheme and a limited number of drivers. Objective data were collected from each snowmobile during the subjective, on-trail testing as well.

Engine durability and emissions testing was conducted on an engine dynamometer with each engine mounted in its original equipment manufacturer (OEM) chassis. Emissions tests were conducted with the dynamometer connected directly to the engine crankshaft while durability testing utilized the clutches and jackshaft, with the dynamometer attached to the jackshaft. Emissions tests were conducted using the standard five-mode cycle per Code of Federal Regulations (CFR) Title 40, Part 1051 requirements. Durability testing was performed using a modified, six-mode cycle developed specifically for this program, in cooperation with all four vehicle manufacturers.

Scope of Work

Engines

Eight engines (four engine pairs) were specified for evaluation in this test program. These engines were chosen by the National Renewable Energy Laboratory's (NREL's) Technical Monitor in consultation with ISMA (International Snowmobile Manufacturer's Association) and represented current and legacy product that may exhibit sensitivity to increased ethanol blended in gasoline. Two-stroke and four-stroke engines, including both fan and liquid cooled, were included in this study. Mixture preparation technologies included carburetors, port-fuel injection, and direct fuel injection. Two of the engines required a minimum fuel anti-knock index (AKI) of 87, and two required a minimum AKI of 91. Three of the engines tested were factory calibrated for E10, not E0. Only one engine was factory calibrated for E0, and then E10 is checked to ensure no operational issues exist. Engines were tested in pairs; one of each pair on E0 fuel and the other on E15. Engines to perform this testing were donated to the subcontractor by the relevant OEMs. End-user engine calibration changes due to ethanol content were conducted per OEM instructions. OEM-supplied electrical resistors, specifically for E0 and E10 fuel, were installed when the engine/vehicle was operating on E0 and E15 fuel, respectively.

Vehicles

Four snowmobile vehicles were utilized for the cold-start and on-snow driveability evaluations. These snowmobiles were chosen by the NREL Technical Monitor in consultation with ISMA and represented current and legacy product that may exhibit sensitivity to increased ethanol blended in gasoline. These snowmobiles corresponded directly to the engines specified earlier.

Fuels

Fuel formulations were agreed upon in consultation with NREL, ISMA, and the subcontractor. Splash-blending was used to make the E15 fuel formulations. For the cold-start, driveability, and laboratory durability testing, gasoline with zero ethanol content (E0) was splash-blended with E98. Control over specific fuel properties was required based on the specific sensitivities of snowmobile equipment. Because snowmobiles use high power density engines calibrated to run close to the detonation limit, octane of the test fuels was controlled for the cold-start, driveability and laboratory durability testing. The minimum octane requirement for each manufacturer was matched for these blends.

The laboratory emissions test fuels consisted of E0 (Indolene) and E15 that was formulated by splash-blending Indolene with E98 ethanol. This resulted in an elevated octane number compared to Indolene for the E15 emissions certification fuel. This elevated octane number helps suppress detonation, which would be more prevalent as a result of fuel oxygenation and a leaner air/fuel mixture. Table 1 shows the actual octane number of each of the test fuels, as it relates to the test and vehicle/engine. The complete fuel data analysis is included in Appendix A.

Table 1: Test Fuel Utilization and Octane

Fuel	Test	Vehicles/Engines	Octane: (R+M)/2
E0, 87 octane	Cold-start, Driveability, Lab Durability	2, 3	88.7
E15, 87 octane	Cold-start, Driveability, Lab Durability	2, 3	89.6
E0, 91 octane	Cold-start, Driveability, Lab Durability	1, 4	91.6
E15, 91 octane	Cold-start, Driveability, Lab Durability	1, 4	92.4
E0 cert. fuel	Lab Emissions	All	92.7
E15 cert. fuel	Lab Emissions	All	96.1

Cold-Start Performance

The purpose of this test series was to assess the cold-start emissions and performance of the four snowmobiles on E0 and E15 fuel. The temperatures investigated included -6.7°C (20°F), -17.8°C (0°F), and -28.9°C (-20°F). The evaluation included time to start or number of pulls to start, engine speed, EGT, and start-up engine emissions concentrations. A series of three evaluations at each temperature for each fuel was conducted over a three-minute interval.

Upon completing one series of evaluations at a specified temperature, the four snowmobiles were removed from the cold-start facility, allowed to warm up at idle, and then operated in a controlled area to properly heat the spark plug and crankcase in preparation for the next cold-start evaluation. The clean-out procedure utilized in this testing was sufficient due to the observed repeatability of the performance and emissions data.

When a particular fuel was completed, the fuel tank was drained and then the snowmobile was operated at idle until it ran out of fuel to ensure a minimal amount of residual fuel in the system. The snowmobiles were then refueled and operated in the control area to properly condition the engine and fuel system before the snowmobiles were cold soaked.

The cold-start test facility was capable of providing an environment down to -30°C and had the capacity to cold-soak all four snowmobiles simultaneously. The snowmobile and fuel were required to reach the set point temperature before the cold-start test was performed. This was monitored using the instrumentation installed on each snowmobile, specifically coolant temperature.

The raw exhaust emissions were measured using a Sensors Inc. Semtech-DS portable emissions analyzer. The analyzer measured carbon dioxide (CO_2)), carbon monoxide (CO), nitrogen oxide (NO), hydrocarbons (HC), and oxygen (O_2) concentrations in the raw exhaust. Analyzer measurement ranges and accuracies are shown in Table 2.

Table 2: Semtech-DS Analyzer Measurement Range and Accuracy

Exhaust Constituent	Measurement Technique	Measurement Range	Accuracy
CO_2	Non-dispersive infrared	0%–20%	±3% of reading or ±0.1%, whichever is greater
CO	Non-dispersive infrared	0%–8%	±3% of reading or 50 ppm, whichever is greater
NO	Non-dispersive ultraviolet	0–3,000 ppm	±2% of measurement, or 2% of point
HC	Flame ionization detector	0–40,000 ppm C	±2% of reading or ±100 ppm C, whichever is greater
O_2	Electro-chemical	0%–25%	±1% oxygen

C = Carbon atoms
ppm = parts per million

A schematic diagram of the cold-start test facility is shown in Figure 1 with the close proximity of the emissions analyzer to the test vehicles.

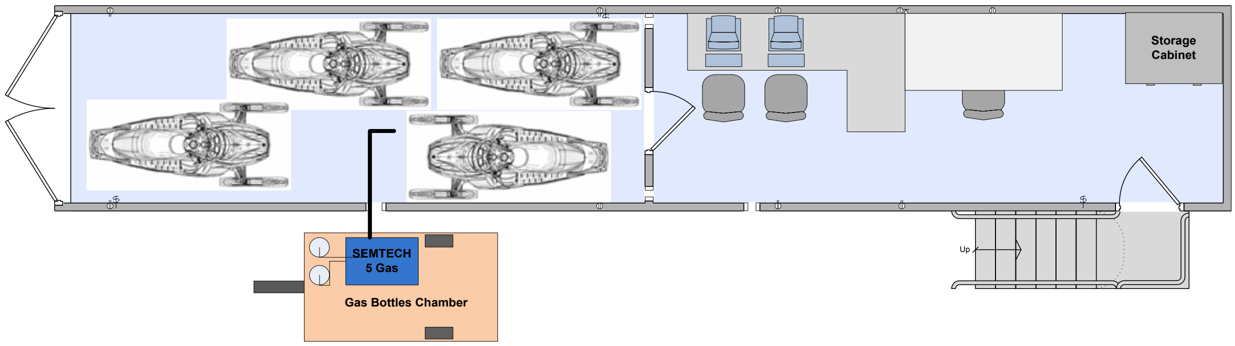

Figure 1: Cold-start test facility schematic

An additional, external heated filter was utilized between the snowmobile exhaust sample point and the heated line of the analyzer, to reduce HC hang-up in the sample line. A zero and span of the analyzer were performed before every evaluation. The zero was performed using ambient air, and the span gas concentrations utilized are shown in Table 3.

Table 3: Semtech-DS Span Gas Concentrations

CO_2	16.5%
CO	6.13%
NO	2,103 ppm
HC	3,013 ppm C3

C3 = propane

The engine speed and several temperatures were measured using an AiM EVO system. Engine speed was measured using the engine tachometer signal wire on vehicles #2 and #3. A non-contact optical pick-up was used to measure primary clutch speed on vehicles #1 and #4. Temperatures were measured with 0.125-in.-diameter, ungrounded, K-type thermocouples.

Test Matrix

A total of 18 valid tests were conducted on each snowmobile with the two different fuels and three different temperatures, as outlined in Table 4. Three different tests at each temperature and fuel combination were performed to determine the repeatability of the procedure and make sure that the order of starting the snowmobiles did not affect the emissions. A different snowmobile was started first each time a test was conducted inside the cold-start test facility. The error bars represent the maximum and minimum values recorded for the three tests.

Table 4: Test Matrix of Cold-start Evaluation

Fuel/Temperature	-6.7°C (20°F)	-17.8°C (0°F)	-28.9°C (-20°F)
E0	Cold-start 1	Cold-start 1	Cold-start 1
	Cold-start 2	Cold-start 2	Cold-start 2
	Cold-start 3	Cold-start 3	Cold-start 3
E15	Cold-start 1	Cold-start 1	Cold-start 1
	Cold-start 2	Cold-start 2	Cold-start 2
	Cold-start 3	Cold-start 3	Cold-start 3

Test Validity with Repeatability

A total of 202 individual cold-start tests were conducted to acquire the 72 tests used for this analysis. To reduce time and cost, most of the tests were run with all four snowmobiles at once. However, several tests were conducted with only one or two snowmobiles being retested because of issues with previous tests. An example of the three tests and an average to show repeatability for CO emissions is shown in Figure 2 at -28.9°C and for E15 fuel. Figure 3 is a plot of three individual tests of the engine speed at -28.9°C for E15 fuel. The data acquisition system for the temperatures and engine speed started recording the data for each test when the engine speed exceeded 500 RPM, so time aligning was not necessary.

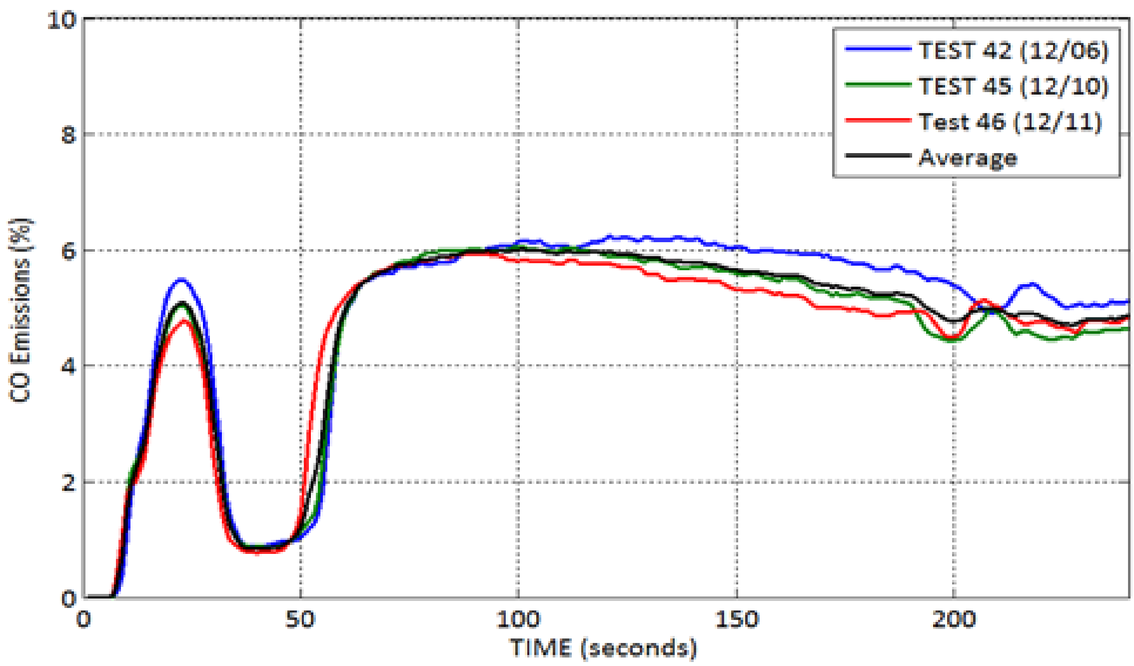

Figure 2: CO emissions concentrations showing test-to-test repeatability

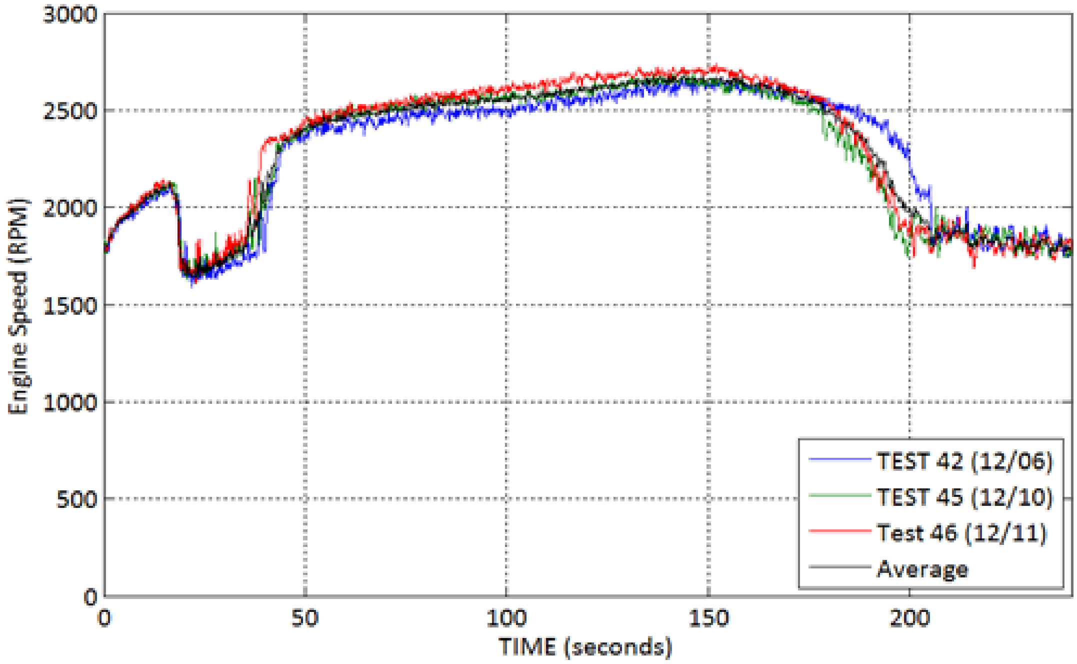

Figure 3: Engine speed showing test-to-test repeatability

Vehicle #1

The pulls-to-start data for vehicle #1 are shown in Figure 4. There was a consistent increase in the number of pulls-to-start when operating on E15 fuel, regardless of the ambient temperature. The average increase was less than one pull in all cases with the variability exceeding the average values.

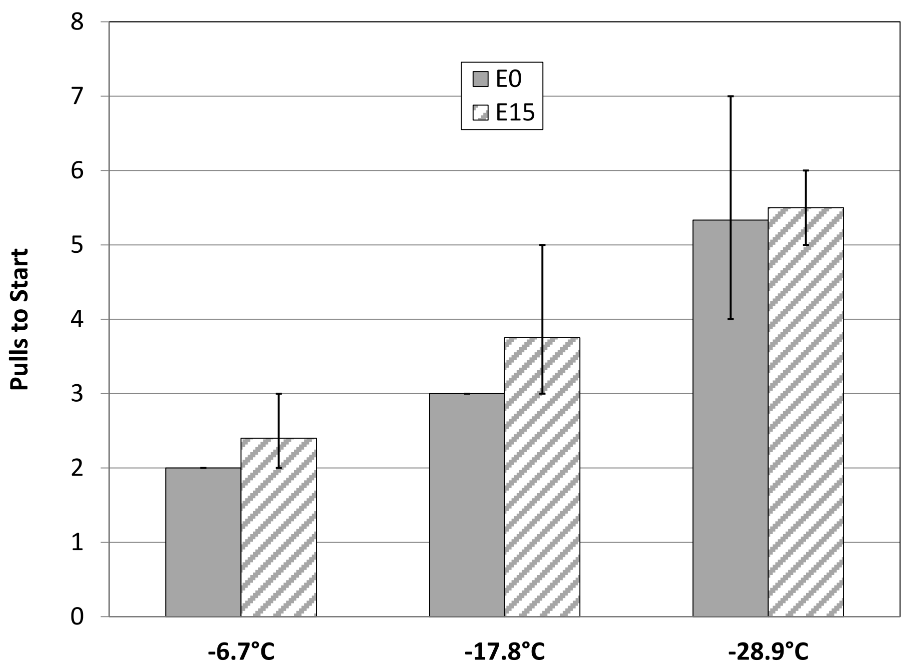

Figure 4: Pulls-to-start for E0 and E15 fuel: Vehicle #1

The CO_2 and CO emissions, Figure 5, show very little effect at -6.7°C and -28.9°C. A reduction in CO_2 emissions and a corresponding increase in CO emissions occurred at -17.8°C. No HC emissions are shown for this snowmobile because the concentration at idle exceeded the analyzer measurement range.

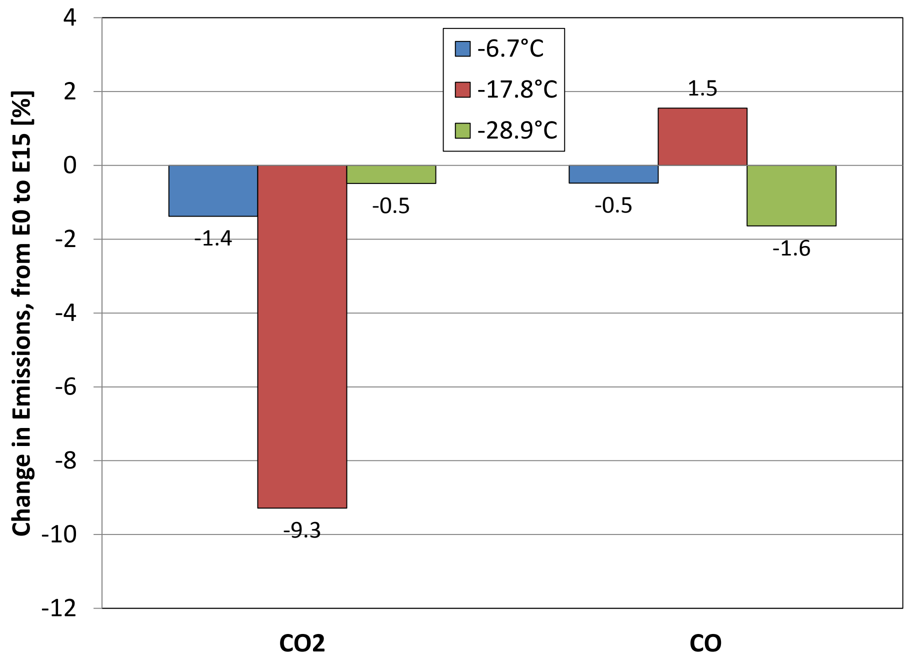

Figure 5: CO_2 and CO emissions percent change from E0 to E15: Vehicle #1

As shown in Figure 6, engine speed increased and EGT decreased as ambient temperature decreased, regardless of the fuel. E15 caused engine speed to decrease at each temperature, compared to E0 along with a reduction in EGT as well. The lower energy density of E15 would be expected to lower the engine idle speed. The higher latent heat of vaporization would be expected to lower combustion temperature at idle.

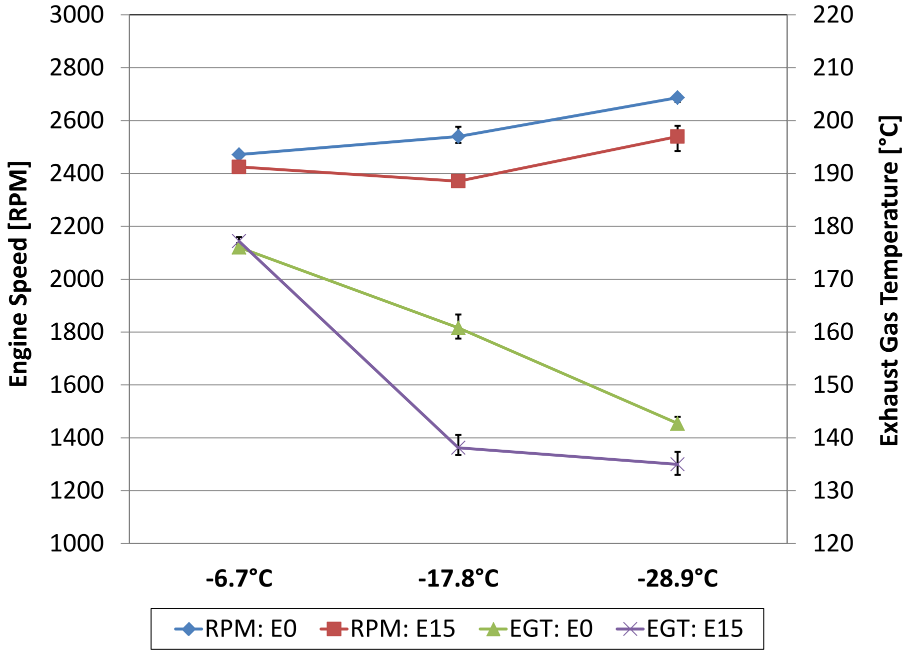

Figure 6: Engine speed and exhaust gas temperature: Vehicle #1

Engine speed was not significantly impacted by the change in temperature or fuel type for vehicle #1. A slight reduction in engine speed was noted for E15 at -17.8°C and -28.9°C, but almost no difference in speed was noted at -6.7°C. The EGT showed almost no difference at -6.7°C and a reduction for E15 at both -17.8°C and -28.9°C.

Vehicle #2

The starting procedure for vehicle #2 required considerable iteration to produce consistent results due to a manual enrichment circuit on this particular snowmobile. A method for determining when to turn the choke off was developed that worked for both E0 and E15 fuel. The procedure involved setting a fixed time of full choke with E0 that produced a robust start and then ensured the engine remained idling for the duration of the test (three minutes). For -6.7°C and -28.9°C, a second application of choke was required to keep the engine running for the full three minutes. A second application of choke for -17.8°C was not required. Once an acceptable start procedure was developed for E0, it was then tested with E15 to ensure the engine would remain running for three minutes.

Figure 7 shows the impact of E15 on the number of pulls required to start vehicle #2. For the -6.7°C and -28.9°C conditions, an average increase was noted, yet at -17.8°C, a slight reduction in the average number of pulls occurred for E15 fuel. Only at -28.9°C did a difference greater than one pull exist between E0 and E15.

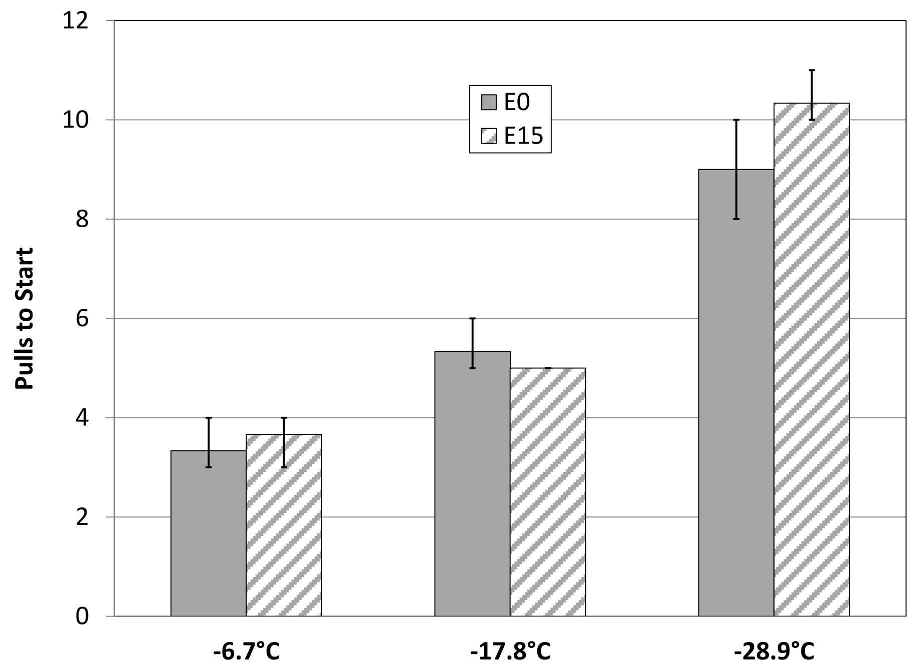

Figure 7: Pulls-to-start for E0 and E15 fuel: Vehicle #2

An increase in CO_2 emissions and a reduction in CO emissions were noted at -6.7°C when switching from E0 to E15, as shown in Figure 8. For all temperatures, CO emissions decreased at startup when operating with E15 fuel. HC emissions are not reported for this snowmobile because the concentrations exceeded the analyzer range. It should be noted that during one test, the HC concentration dropped below the maximum analyzer value briefly when operating on E15 fuel with a temperature of -6.7°C.

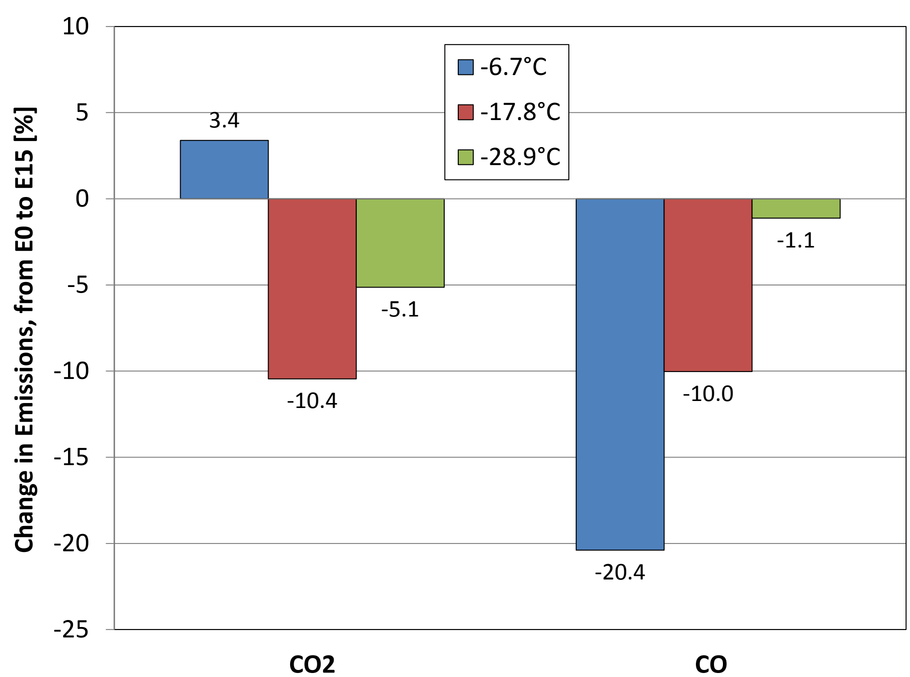

Figure 8: CO_2 and CO emissions percent change: Vehicle #2

Engine idle speed increased with decreasing ambient temperature regardless of the fuel, as shown in Figure 9. E0 resulted in a higher average idle speed compared to E15 with up to a 12% reduction for E15 at -17.8°C.

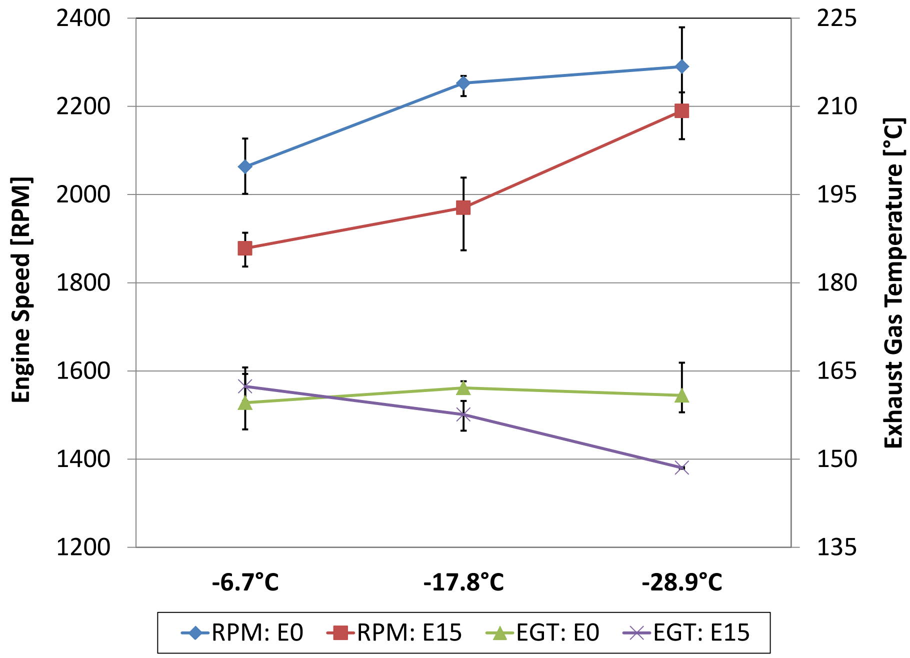

Figure 9: Engine speed and exhaust gas temperature: Vehicle #2

Engine speed dropped consistently for all ambient test conditions when operating with E15 fuel. The average reduction in engine speed ranged from 100 to 200 RPM. EGT tended to decrease for E15 as the ambient temperature was reduced. A significant quantity of fuel is required to ensure a consistent start at -28.9°C, and the evaporative cooling effect of E15 may have caused the decreased EGTs.

Vehicle #3

The time-to-start was recorded for vehicle #3 because it was an electric start model. A general trend of increasing start time with reduced ambient temperature was observed. With E15 fuel, a significant increase in the time-to-start was noted for the -28.9°C ambient condition and a modest increase in the start time for the -6.7°C condition, as shown in Figure 10.

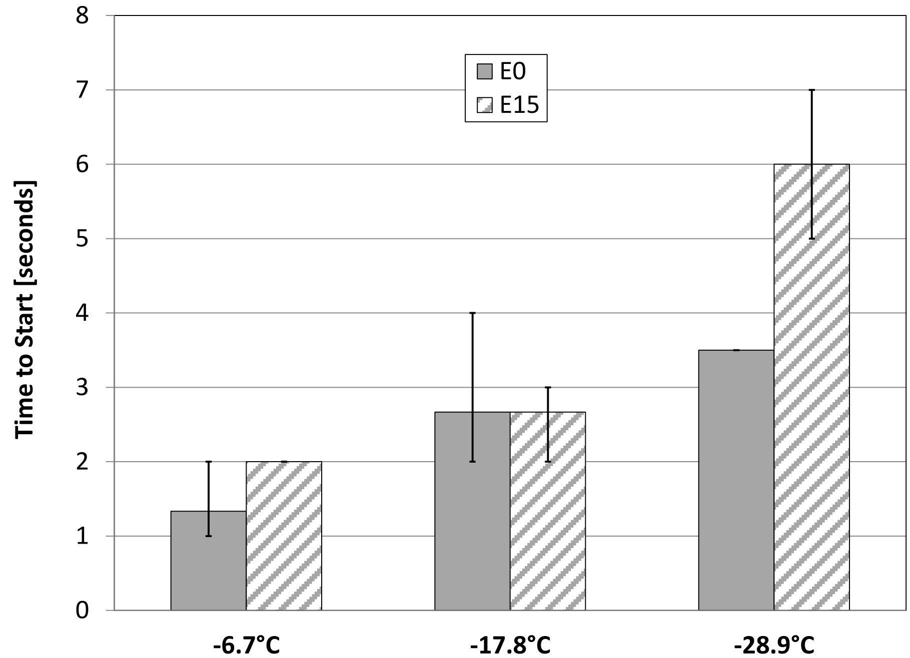

Figure 10: Time-to-start for E0 and E15 fuel: Vehicle #3

As shown in Figure 11, the changes in CO_2, CO, and HC emissions are consistent with a less fuel-rich (still fuel-rich of the stoichiometric ratio) air/fuel mixture as a result of the oxygenated fuel. This particular snowmobile engine design produced HC emissions levels within the analyzer range and thus the data were able to be analyzed. The idle control strategy (engine speed target) was able to compensate for the reduced energy content of E15 by opening the throttle plates and injecting more fuel. This resulted in a leaner air/fuel mixture at cold-start idle.

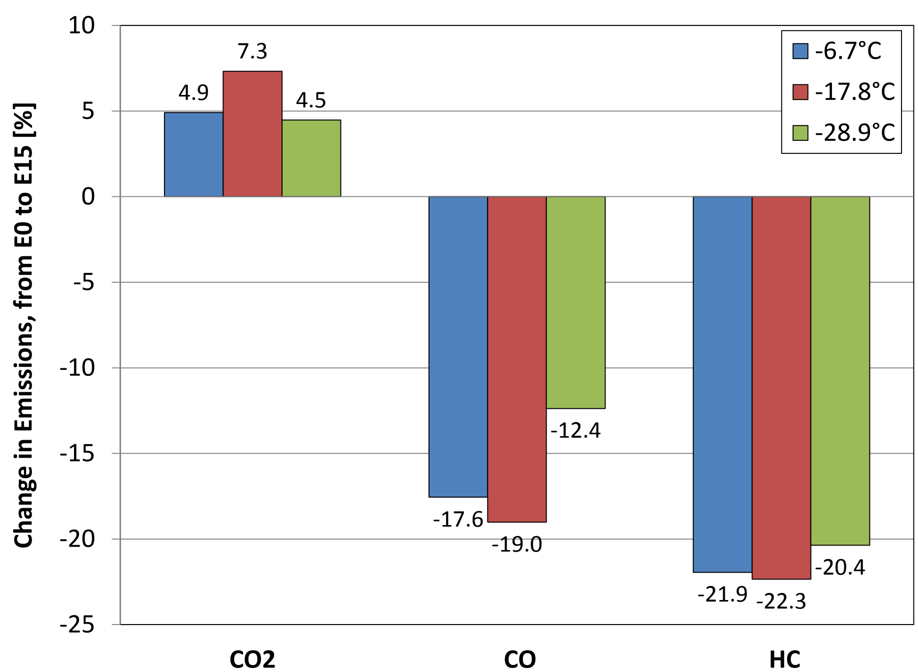

Figure 11: CO_2, CO, and HC emissions percent change: Vehicle #3

As shown in Figure 12, as the ambient temperature was reduced, the idle speed increased for both E0 and E15 fuel. As noted earlier, almost no difference in idle speed was noted between the E0 and E15 fuels. All changes in engine speed with E15 were less than 1%. The EGT was slightly higher for E15 fuel, regardless of ambient temperature. The EGT increased by approximately 1.5% over the three ambient temperatures, with diminishing differences as the temperature was reduced.

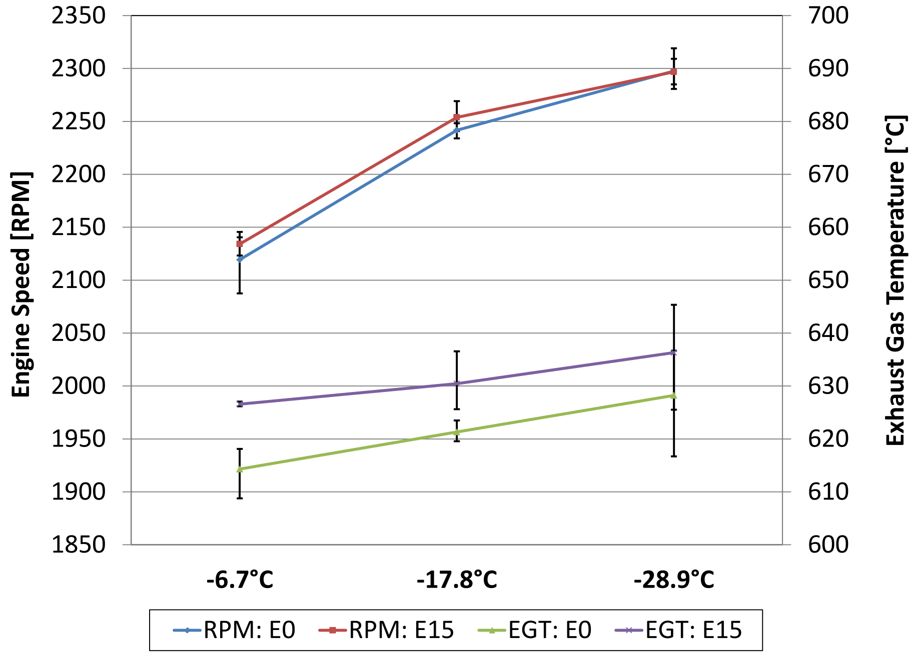

Figure 12: Engine speed and EGT: Vehicle #3

Vehicle #4

There was no change in the pulls-to-start for vehicle #4 when operating with E15 fuel for -6.7°C and -28.9°C conditions, as shown in Figure 13. An increase in the pulls-to-start at -17.8°C was noted, but the difference was within the test-to-test variability.

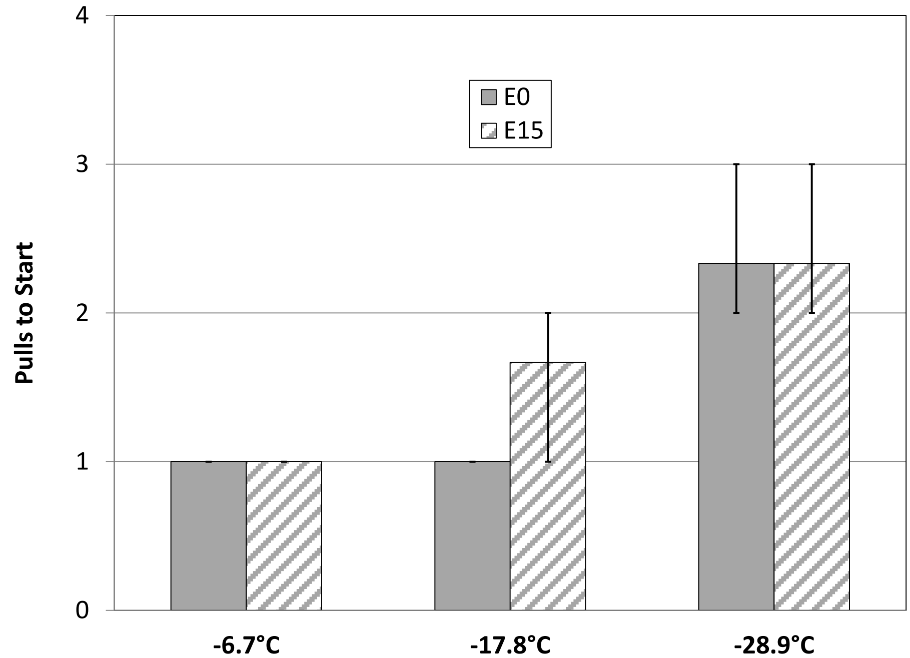

Figure 13: Pulls-to-start for E0 and E15 fuel: Vehicle #4

For vehicle #4, E15 tended to decrease CO_2 emissions and produced variable results associated with CO, as shown in Figure 14. Over a 30% reduction in CO emissions was measured at -17.8°C on E15.

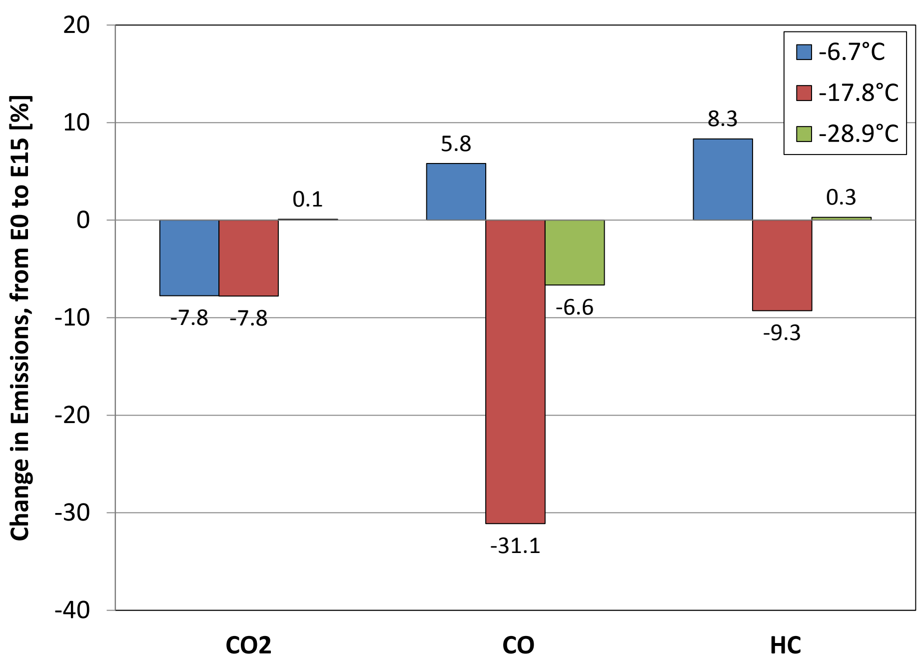

Figure 14: CO_2, CO, and HC emissions percent change: Vehicle #4

This particular snowmobile engine design produced HC emissions levels within the analyzer range, and thus the data were able to be analyzed. A simultaneous reduction in all three emissions was recorded for the -17.8°C ambient condition on E15. At -28.9°C, no change in CO_2 was noted, and there was a 6.6% reduction in CO.

A slight increase in engine idle speed was noted for both fuels as the ambient temperature decreased, as shown in Figure 15. No significant changes in engine speed were noted for E15 fuel. There was a consistent drop in EGT for E15 at all ambient temperatures. The largest drop in EGT occurred at -17.8°C, corresponding to the largest reduction in CO and slight increase in engine speed. The EGT reduction is likely caused by the higher latent heat of vaporization of E15.

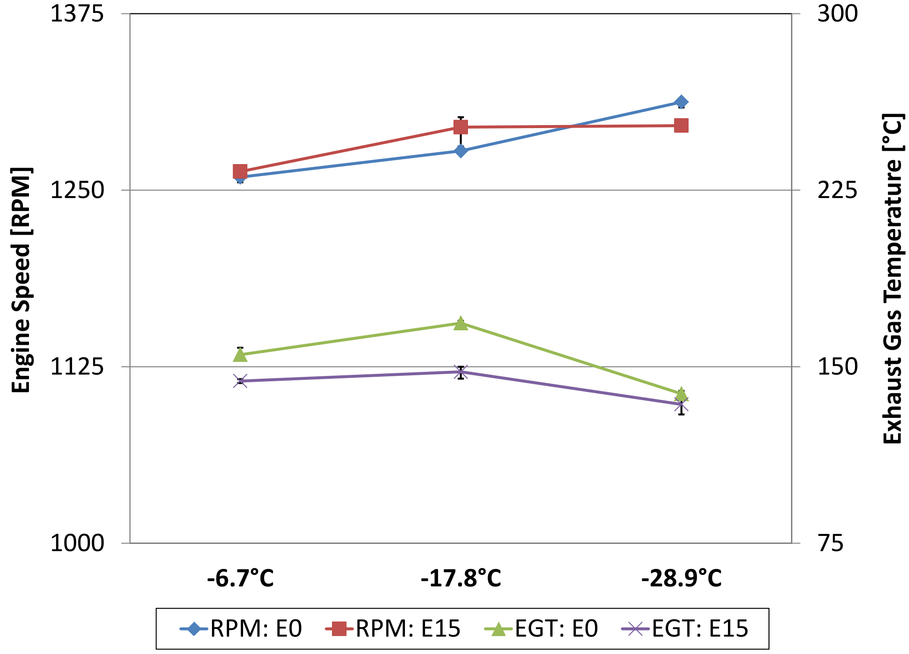

Figure 15: Engine speed and EGT: Vehicle #4

Vehicle Driveability

Snowmobile driveability while operating on E0 or E15 fuel was analyzed using four sets of evaluations. Subjective evaluation was conducted on a controlled test course using a jury of eight experienced drivers. Objective data were collected from each snowmobile during the subjective testing, using high-speed data acquisition and sensors installed on the vehicles. An additional subjective evaluation was performed on a snowmobile trail in the Upper Peninsula of Michigan, utilizing a regimented operation scheme and a limited number of drivers. Objective data were collected from each snowmobile during the subjective on-trail testing as well.

Subjective Evaluation on Test Course

The four snowmobiles were subjectively evaluated on E0 and E15 using a jury of eight experienced snowmobile riders. The snowmobiles were operated on a groomed, snow-covered test course with speeds ranging from 25 to 50 mph (Figure 16). As can be seen in the figure, this course consisted of straight stretches and both left and right hand maneuvers. Speed limit signs were used to produce repeatable data among the riders.

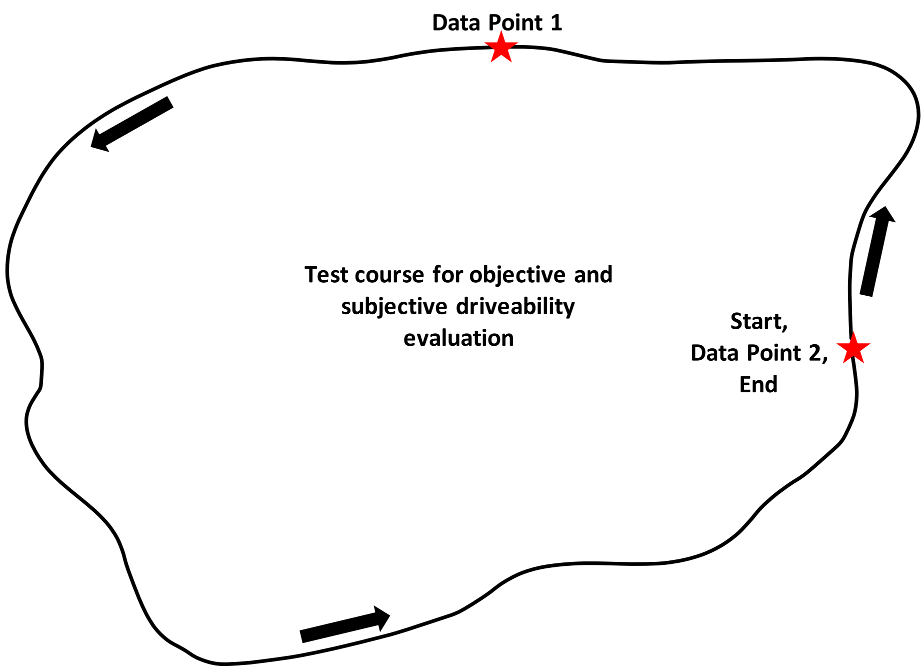

Figure 16: Subjective driveability test course

Each rider operated the snowmobiles around the test course for two complete laps for each fuel. The first lap required the riders to stop at Data Point 1 and provide their initial feedback on the snowmobile operation. The riders proceeded to Data Point 2, where they again provided their feedback on the snowmobile operation. The riders then operated the snowmobile for one complete lap around the test course where final operational feedback was recorded.

Riders were not aware of the fuel blend during the testing. Vehicle #2 and vehicle #3 were initially fueled with E0, and vehicle #1 and vehicle #4 were initially fueled with E15. Upon completing the first round of testing, the fuel tanks were drained of fuel, the sleds run dry and then refilled with the other fuel (either E0 or E15). All testing was completed within an eight-hour day. Ambient temperature varied less than 6°C throughout the day of testing on the course.

At each of the data points, the riders were asked to evaluate the performance of the snowmobiles based on the following criteria:

1. Misfire (YES/NO, How Many?)
2. Detonation (YES/NO, How Many?)
3. Engine Stumble (YES/NO, Rating 1–10, 10 severe)
4. Engine Surging (YES/NO, Rating 1–10, 10 severe)
5. Smoothness of Acceleration (1–10, 10 good)
6. Overall Impression of Engine Calibration (1–10, 10 good)
7. Other Comments.

The following conclusions are based on the feedback provided by the riders.

Vehicle #1

Rider comments included that more engine surging was identified with E15 fuel as compared to E0 for vehicle #1. General comments were noted that vehicle #1 felt as though it had more power on E0 compared to E15.

The average differences between the numeric ratings of "Smoothness of Acceleration" and "Overall Impression of Engine Calibration" were:

- Acceleration: E15 ranked 0.54 point higher on a 1–10 scale.
- Engine Calibration: E15 ranked 0.33 point higher on a 1–0 scale.

The numerical rankings and rider comments appear to be in conflict as E15 ranked higher in the numeric evaluations but the comments suggested that E0 had more power and E15 had some engine surging.

Vehicle #2

No significant differences in comments were noted but the riders did believe that Fuel #2 was E0 based on their impressions when it actually was E15. This fact was discovered when talking to the riders after testing, and many were fairly confident they knew which fuel was E15. The differences they sensed could have been present because vehicle #2 was calibrated richer than the other engines. E15 would have effectively leaned out the calibration and improved operation, not degraded it for this particular application and test condition. It is important to note that the change from E0 to E15 in the particular model did make a notable difference to a majority of the riders.

The average differences between the numeric ratings of "Smoothness of Acceleration" and "Overall Impression of Engine Calibration" were:

- Acceleration: E0 ranked 0.54 point higher on a 1–10 scale.

- Engine Calibration: E0 ranked 0.375 point higher on a 1–10 scale.

The riders did identify more instances of both stumble and surging on E0 than on E15. The numerical rankings and rider comments appear to be in conflict as the riders listed more issues with E0 than with E15 in the comments but rated E0 as better in terms of acceleration and engine calibration.

Vehicle #3

Rider comments included that more engine surging and stumble were identified with E0 in vehicle #3 compared to E15. A slight trend toward more positive comments was noted for E15.

The calculated differences between the numeric ratings of "Smoothness of Acceleration" and "Overall Impression of Engine Calibration" were:

- Acceleration: E0 ranked 0.385 point higher on a 1–10 scale.
- Engine calibration: E0 ranked 0.104 point higher on a 1–10 scale.

It appears E0 and E15 are comparable in vehicle #3 from a subjective perspective. While E0 had a slightly better numeric evaluation for acceleration and engine calibration, there were a few negative comments concerning E0 surging and stumble.

Vehicle #4

Rider comments included that more engine surging was identified with E15 fuel in vehicle #4 compared to E0.

The calculated differences between the numeric ratings of "Smoothness of Acceleration" and "Overall Impression of Engine Calibration" were:

- Acceleration: E15 ranked 0.125 point higher on a 1–10 scale.
- Engine calibration: E15 ranked 0.04 point higher on a 1–10 scale.

It appears E0 and E15 are comparable in vehicle #4 from a subjective perspective. Very little to no differences in the performance of E0 and E15 were noted, while there were more "surging" comments for E15 than E0. However, the numeric rankings did not identify a major issue with surging or poor performance.

Summary: Subjective Evaluation on Test Course

The conclusion from the subjective testing appears to be that it was difficult for the riders to discern which fuel actually performed better around this particular test course. For vehicle #1 and vehicle #4, there were comments about engine surging on the E15 fuel. For vehicle #3, engine surging and stumble were noted for the E0 fuel. Written comments often were not reflected in the numeric scores given for each snowmobile.

Objective Evaluation on Test Course

The objective evaluation on the test course consisted of automated data collection during the subjective evaluation from the eight drivers. The data sets are broken up into three sections, due to the requirement that the drivers needed to stop at two locations around the test track. Therefore, short, medium, and long lap averages for E0 and E15 have been analyzed. Each snowmobile was instrumented with an AiM EVO data acquisition system to collect the following parameters:

- Ambient temperature
- Engine speed
- Belt speed
- Jackshaft speed
- Vehicle speed (global positioning system [GPS] based)
- Distance traveled (GPS based)
- Air inlet temperature (fan-cooled model only)
- Air outlet temperature (fan-cooled model only)
- Coolant in temperature (liquid-cooled models only)
- Coolant out temperature (liquid-cooled models only)
- Cylinder head temperature
- Cylinder head acceleration
- EGT.

Data Validation

The first analysis done on each of the sets of runs for each snowmobile was to verify that the length of the time acquired for each dataset was as consistent as possible as well as to verify that parameters such as engine speed, track speed, vehicle speed, and fore/aft acceleration rates were similar for both fuels for each snowmobile.

Because the actual length of time required for each snowmobile to travel the distance between feedback stations and for the full lap was slightly different, the first processing done on the data was to expand/contract each individual run in time such that they had an equivalent scaled lap time. It should be noted that in nearly all cases the amount of time scaling required was less than 5% of the average lap time. It was felt that this was a surprising level of consistency when it is considered that eight different drivers were involved. This time scaling was done to allow an easy to interpret overlay of the averaged E0 runs and the averaged E15 runs for plotting purposes. Under no conditions was any vertical (amplitude) scaling applied to any of the data. All plots were generated in this fashion.

Figure 17 through Figure 20 show examples of each of the aforementioned parameters overlaid for E0 and E15 runs. Note the consistency in the data once the time scales have been matched.

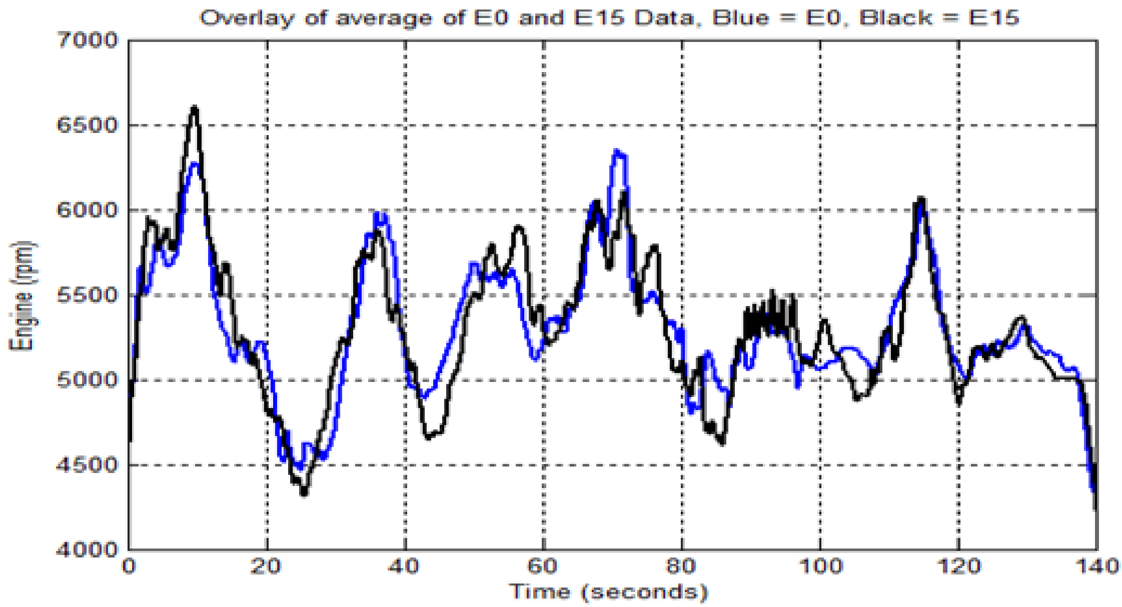

Figure 17: Example of engine speed (RPM) repeatability after averaging and time scaling

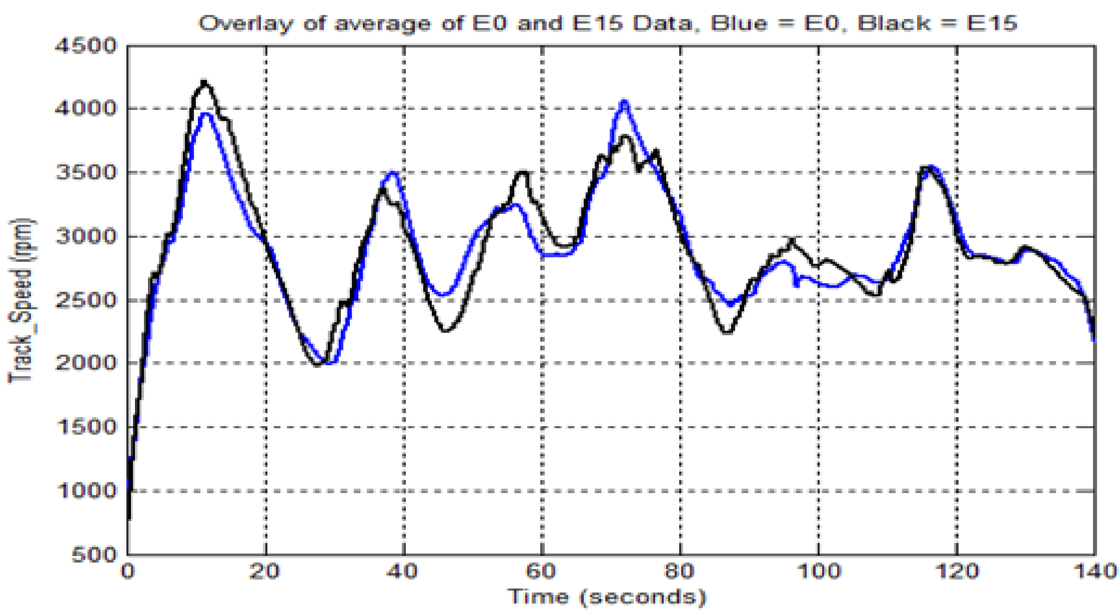

Figure 18: Example of track speed (RPM) repeatability after averaging and scaling

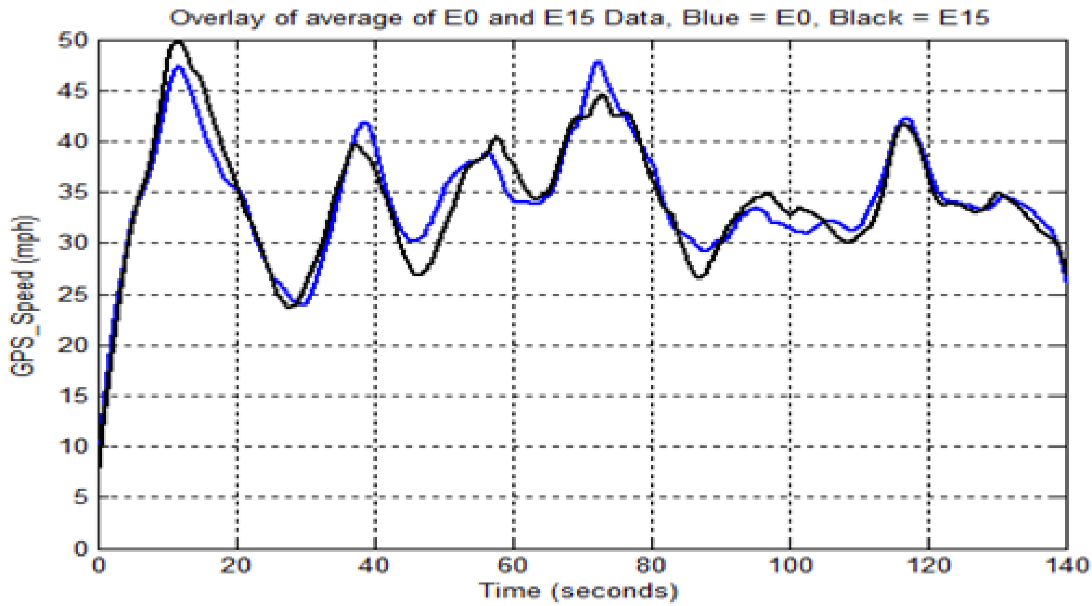

Figure 19: Example of GPS-measured vehicle speed repeatability after averaging and time scaling

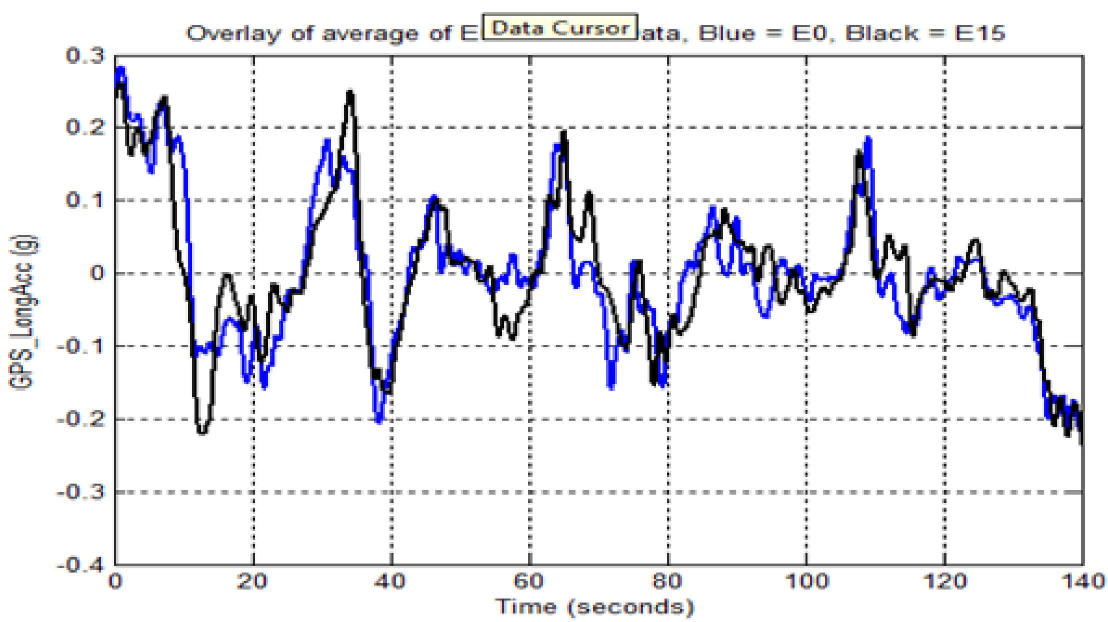

Figure 20: Example of GPS-measured longitudinal acceleration repeatability after averaging and time scaling

Vehicle #1

After verifying repeatability as shown above, various other engine performance parameters were evaluated from the objective lap data. Figure 21 shows the averaged and time-scaled power take-off (PTO) side EGT for vehicle #1 for the mid-length lap data collected. It can be seen that while there is some difference in temperatures and a similar difference in the magneto (MAG) side EGT exists as well, the temperatures do follow the same general profile. Not knowing what temperatures the engine is designed to operate with, it is not possible to comment on whether the temperatures are higher than recommended.

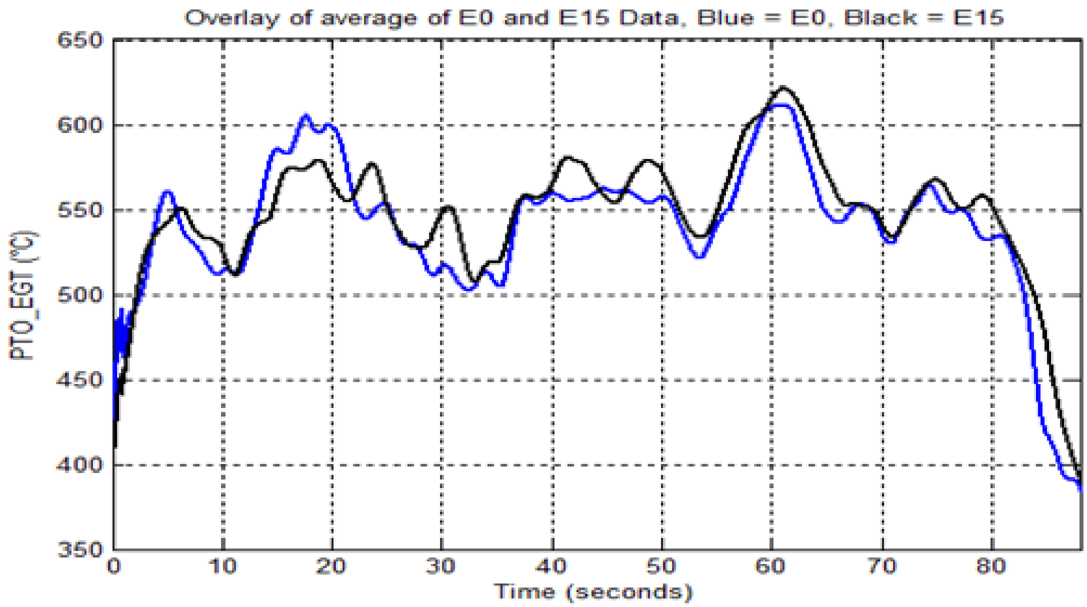

Figure 21: Comparison of PTO EGT for the middle length laps: Vehicle #1

An example MAG side head temperature is shown in Figure 22 for the middle length laps.

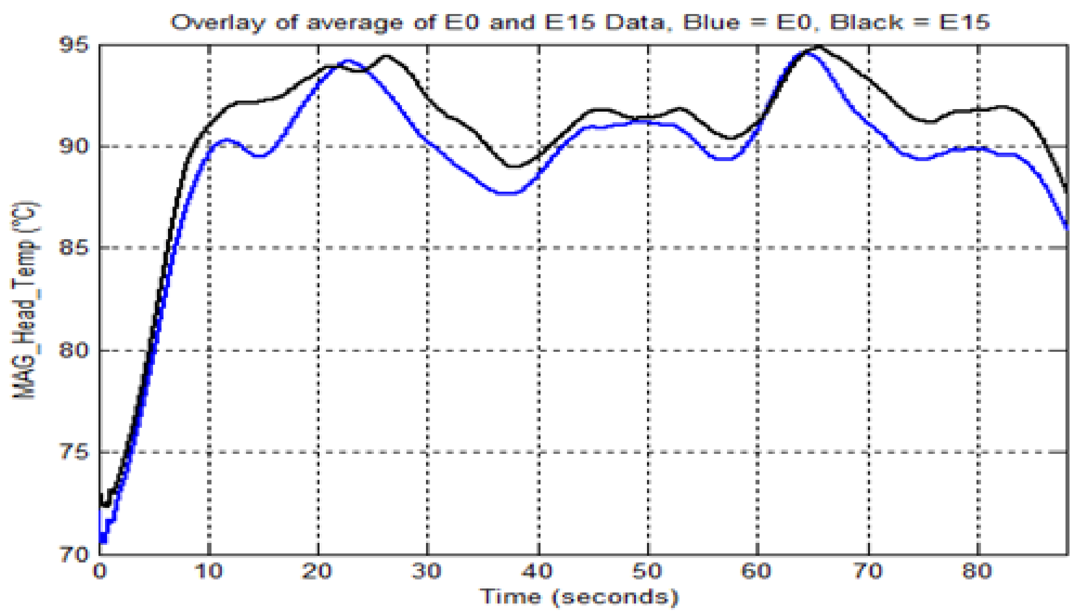

Figure 22: Comparison of MAG head temperatures for the middle length laps: Vehicle #1

It is apparent that the E15 fuel leads to slightly higher head temperatures. The same trend was seen in the PTO side head temperature and for all of the lap lengths. Note that while all of these temperatures tend to be higher on E15, the difference is only a couple of degrees.

Vehicle #2

Vehicle #2 data show consistent increases in both EGTs and head temperatures in all cases when using E15 as compared to using E0. Figure 23 and Figure 24 show the MAG and PTO head temperatures for the middle length laps.

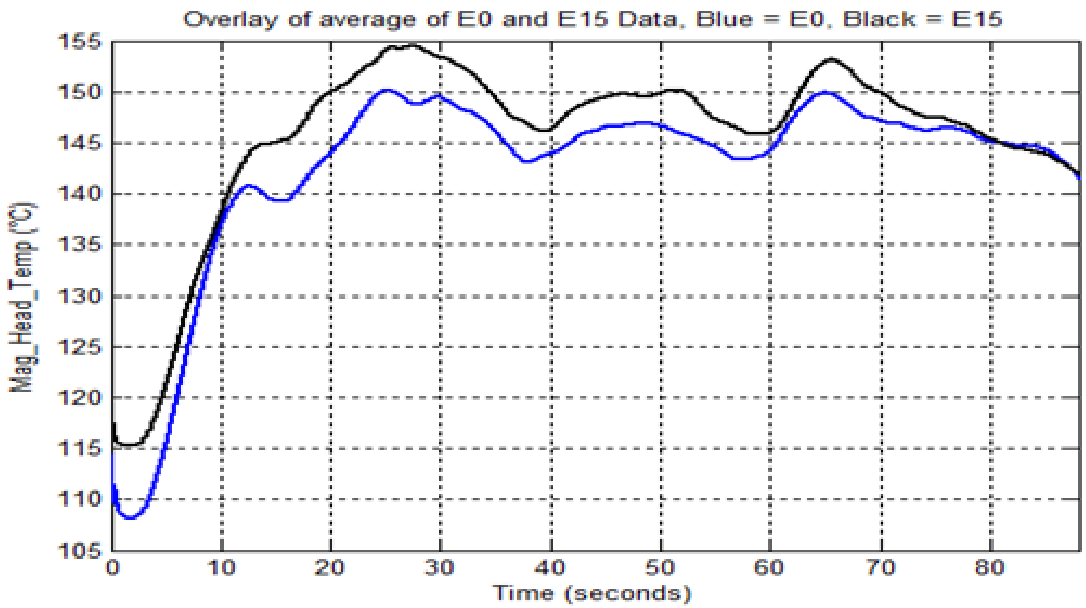

Figure 23: Comparison of MAG head temperatures for the middle length laps: Vehicle #2

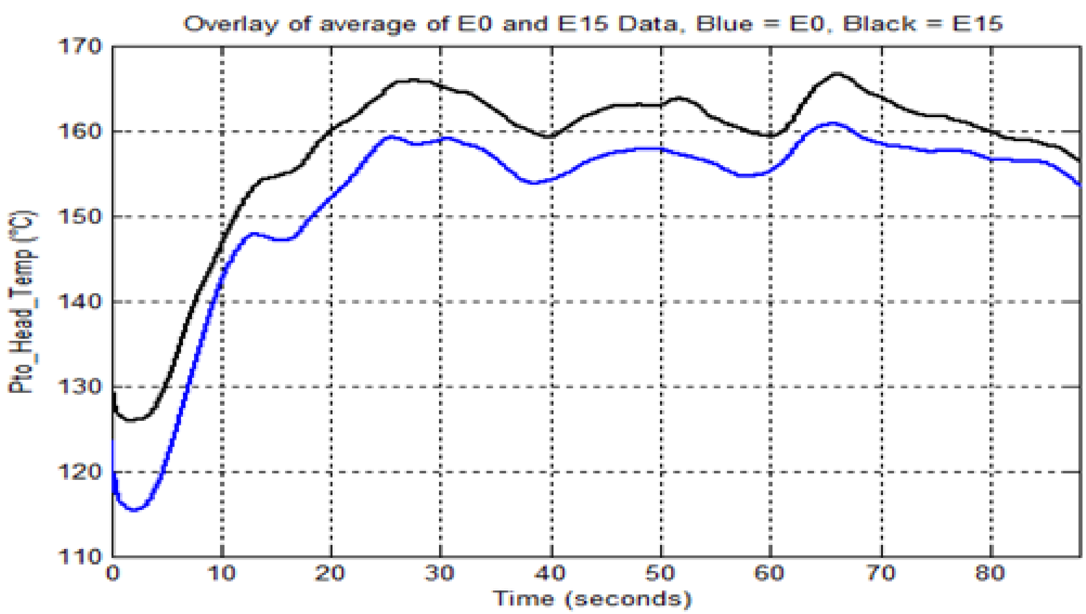

Figure 24: Comparison of PTO head temperatures for the middle length laps: Vehicle #2

While both the MAG and PTO head temperatures increased with E15, the differences were less than 5°C and get less as the lap nears its end. The temperature changes shown in these plots are larger than that measured in either the short laps or the long laps.

Figure 25 and Figure 26 show that there is up to approximately a 40°C difference in EGT, with E15 being higher in most conditions. Again, not knowing the maximum allowable design temperature for this engine, it is not known whether the increase in temperatures is enough to significantly impact engine life or emissions.

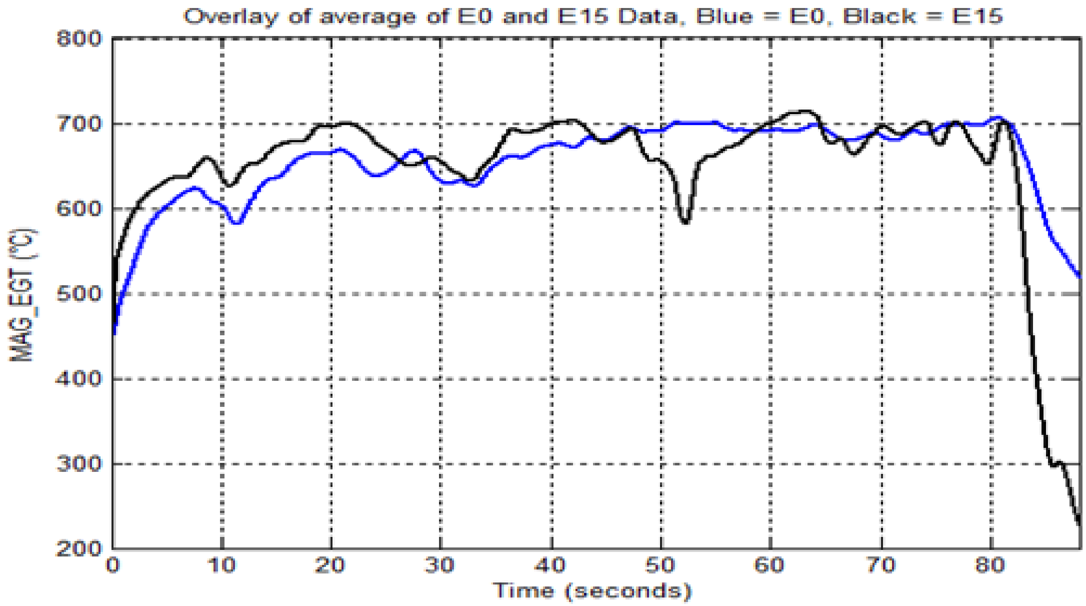

Figure 25: Comparison of MAG EGTs for the middle length laps: Vehicle #2

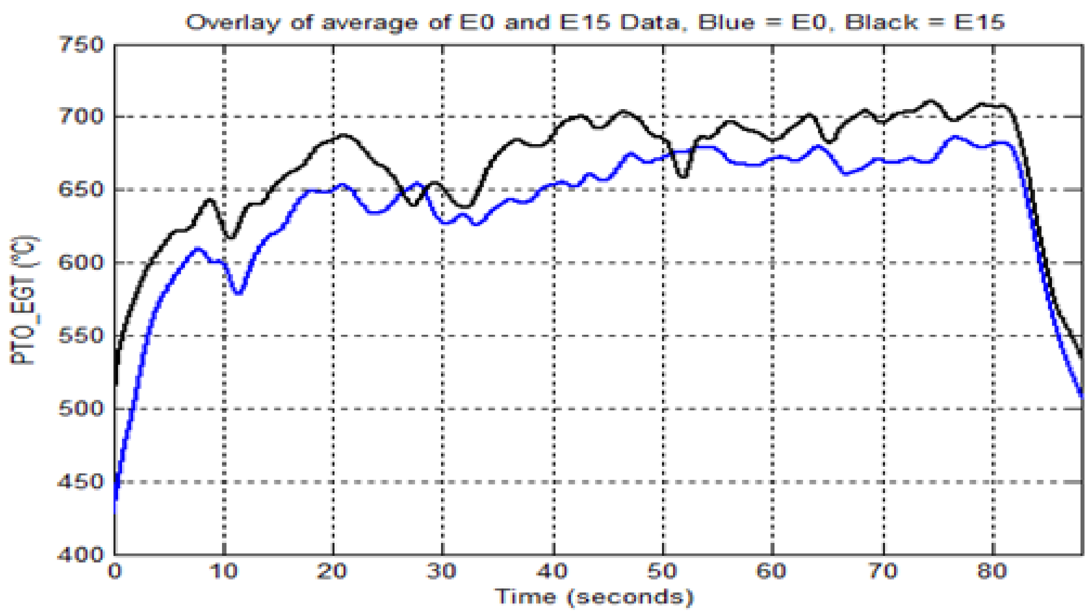

Figure 26: Comparison of the PTO EGTs for the middle length laps: Vehicle #2

Vehicle #3

The measured EGT temperatures on both the MAG and the PTO cylinders were much closer in Vehicle #3 than in the other vehicles, as shown in Figure 27 and Figure 28.

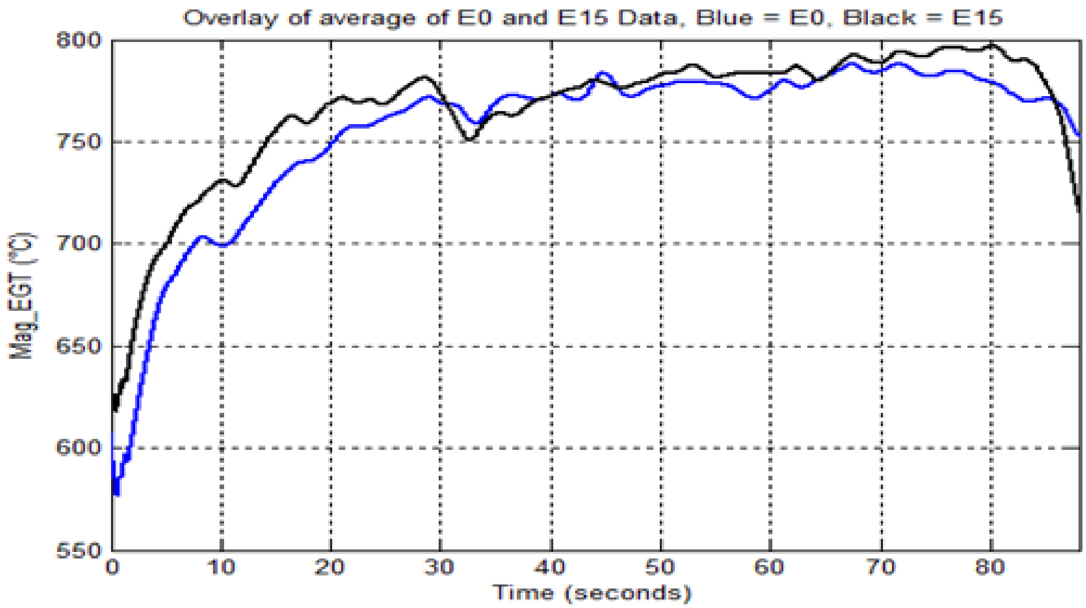

Figure 27: Comparison of MAG EGTs for the middle length laps: Vehicle #3

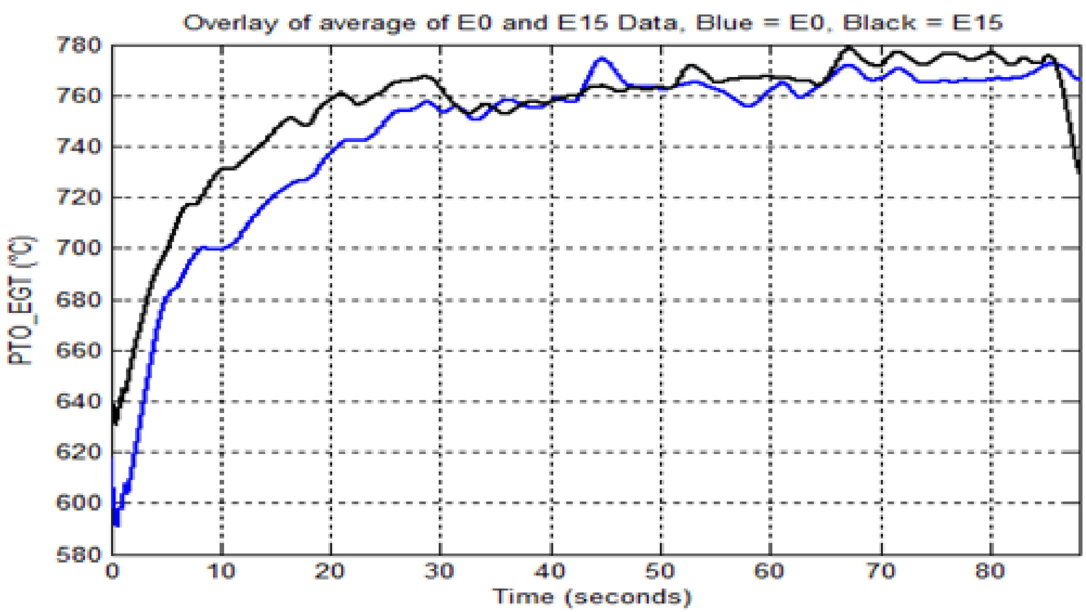

Figure 28: Comparison of PTO EGTs for the middle length laps: Vehicle #3

The area in the data where there is a larger temperature difference is at the start of the data; the operating condition during this phase of the data collection was an acceleration event. This implies that under acceleration there is a significant temperature difference, with E15 being higher.

Vehicle #4

Vehicle #4 showed a different trend than the other three engines in that, in most cases, the E0 temperatures for the head temperatures were higher than the E15 temperatures. Figure 29 shows these trends very clearly.

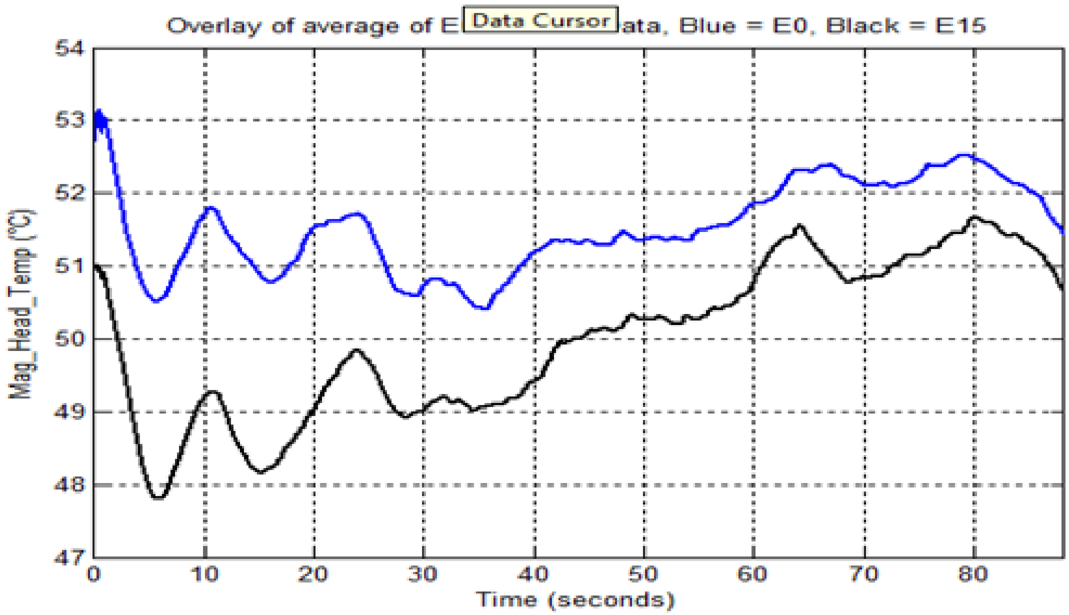

Figure 29: Comparison of MAG head temperatures from middle length laps: Vehicle #4

Figure 30 and Figure 31 show EGT temperature comparisons with conflicting results. The MAG side EGT had very similar temperatures across the entire trace while the PTO side EGT showed significantly higher temperatures on E15 than on E0.

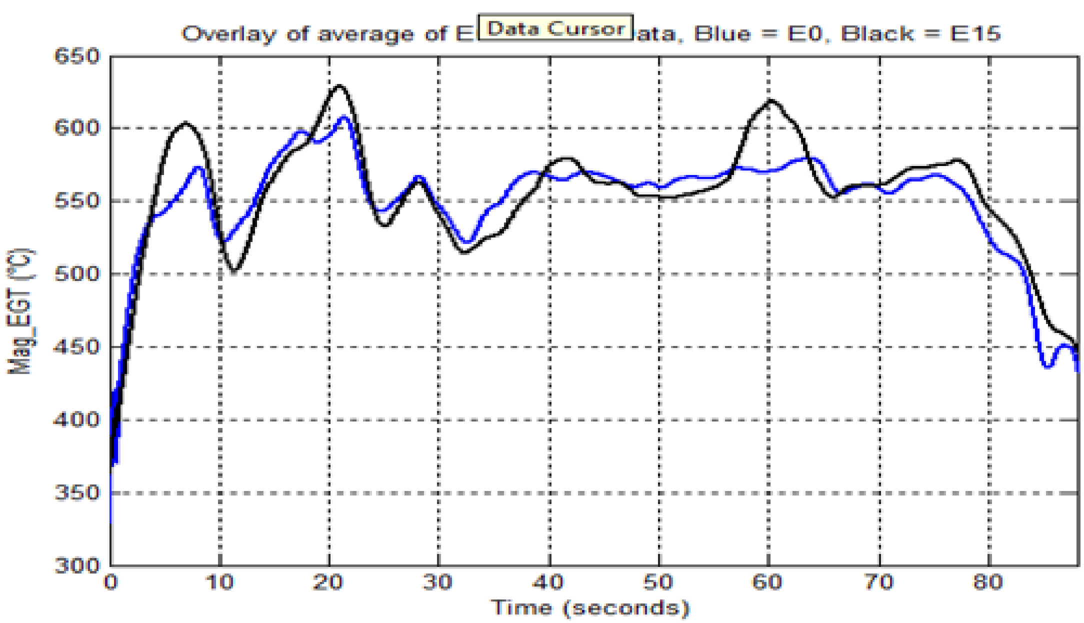

Figure 30: Comparison of the MAG EGTs for the middle length laps: Vehicle #4

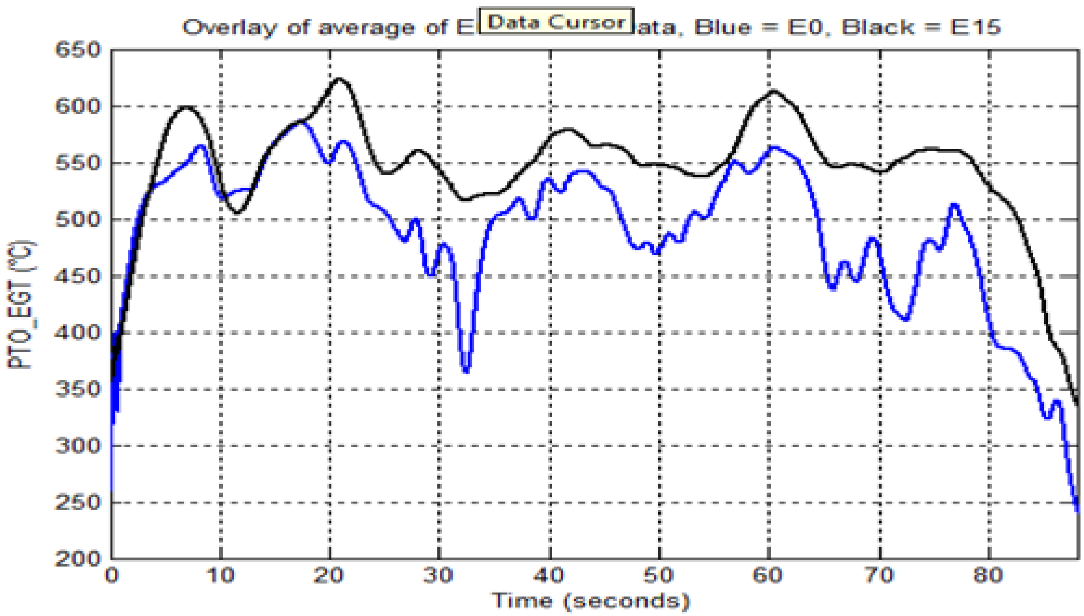

Figure 31: Comparison of the PTO EGTs for the middle length laps: Vehicle #4

Summary: Objective Evaluation on Test Course

Three of the snowmobiles had higher EGTs on E15 than on E0. It is not known whether the temperature differences were large enough to result in reduced engine durability. In general, head temperatures also increased when running on E15. The forth snowmobile had EGTs that were higher on E15 than on E0; however, the head temperatures on this snowmobile were generally higher on E0 than on E15. It is believed that in nearly all cases with the four snowmobiles tested the changes in head and EGTs can be attributed to the engines operating with a less-fuel-rich (still fuel-rich of the stoichiometric ratio) air/fuel ratio on E15 than on E0.

Subjective Evaluation on Snowmobile Trail

The subjective evaluation on the snowmobile trail utilized an acceleration test from zero mph vehicle speed, up to a pre-determined speed, and then a deceleration back to zero. This was completed for 10–15 cycles, and then the rider would stop the snowmobile and provide comments on vehicle operation such as smoothness of acceleration, hesitation, stumble, etc. Upon completing the first set of data, the peak speed was increased and the testing resumed. A test matrix for the 0-X-0 testing is shown in Table 5.

Table 5: 0-X-0 Test Matrix

Vehicle #2	Vehicle #1	Vehicle #4	Vehicle #3
0-20-0	0-20-0	0-20-0	0-20-0
0-30-0	0-30-0	0-30-0	0-30-0
0-40-0	0-40-0	0-40-0	0-40-0
0-50-0	0-50-0	0-50-0	0-50-0
0-60-0	0-60-0	0-60-0	0-60-0

Vehicle #2	Vehicle #1	Vehicle #4	Vehicle #3
0-70-0	0-70-0	0-70-0	0-70-0
	0-80-0	0-80-0	0-80-0

In addition to the tests shown in Table 5, there was an additional set of tests with non-zero initial vehicle speeds. The testing was accomplished with roll-in speeds of 15 mph, 20 mph, and 30 mph that resulted in constant accelerations and decelerations as opposed to the start-stop testing of the 0-X-0 tests.

The subjective evaluation of the riders during the 0-X-0 and roll-in testing resulted in one comment. The riders did comment that vehicle #3 stumbled or hiccupped on launch at the higher speed 0-X-0 tests on E15. None of the other snowmobiles had any significant issues noted.

Objective Evaluation on Snowmobile Trail

The objective evaluation on the snowmobile trail utilized the acceleration tests from the subjective on-trail testing and the same AiM EVO data acquisition system and sensors used for the lap testing.

The first steps in the objective data evaluation were the identical data processing as in the lap testing. The data were first time-scaled then averaged; again, no amplitude scaling was done on any data.

Data Validation

Figure 32 through Figure 35 show examples of the same validation process used in the lap data. The figures show examples of engine speed (RPM), track speed (RPM), GPS vehicle speed, and fore/aft acceleration. The figures show very good repeatability of the runs, indicating that the drivers and the runs were both repeatable.

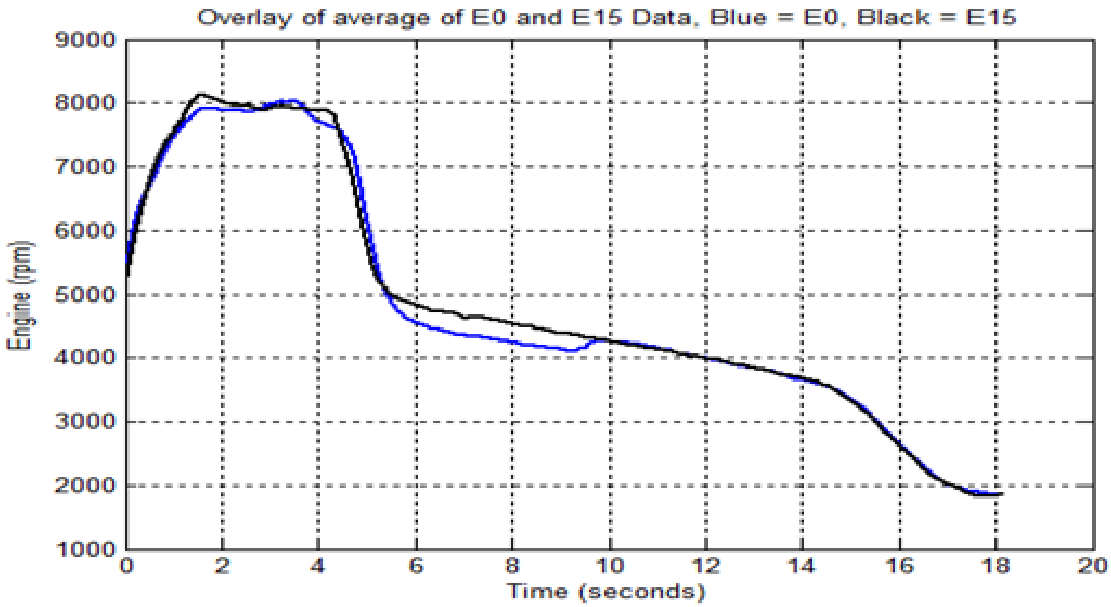

Figure 32: Comparison of engine speed (RPM) for 0-60-0 tests: Vehicle #1

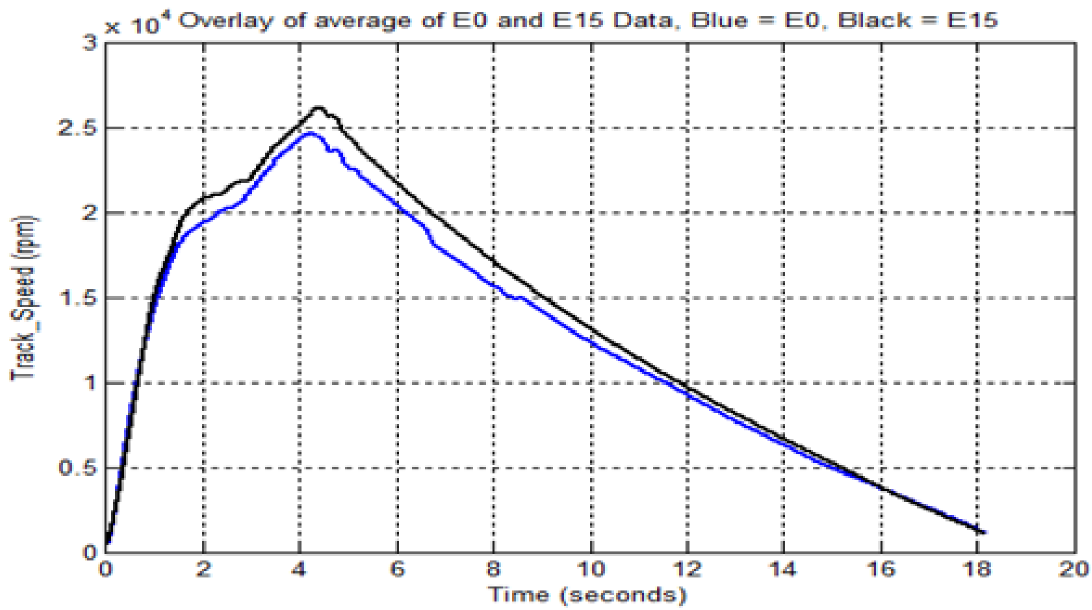

Figure 33: Comparison of track speed (RPM) for 0-60-0 tests: Vehicle #1

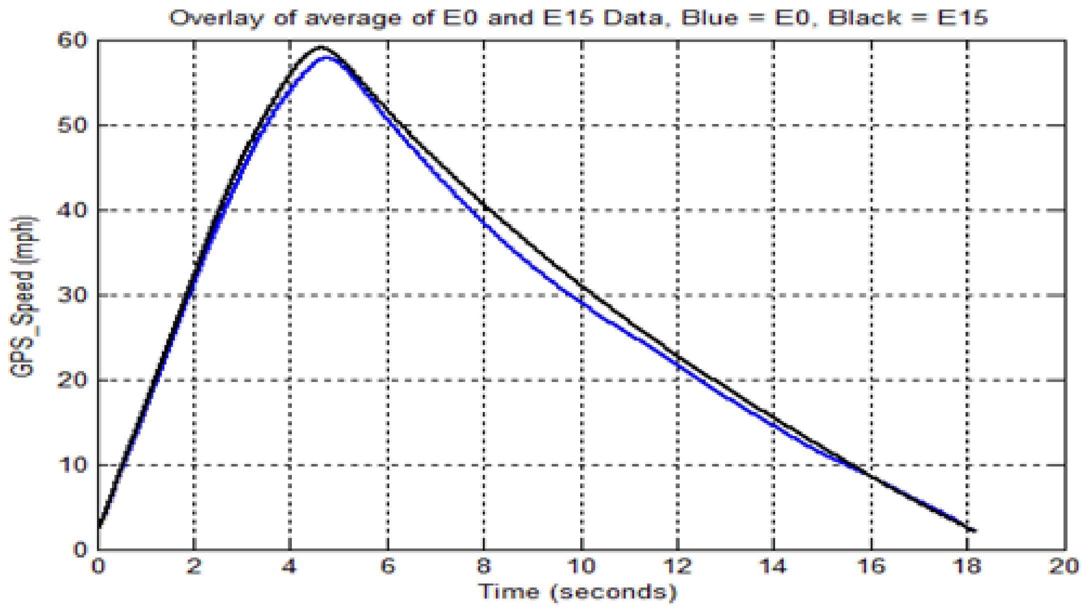

Figure 34: Comparison of GPS speed of 0-60-0 tests: Vehicle #1

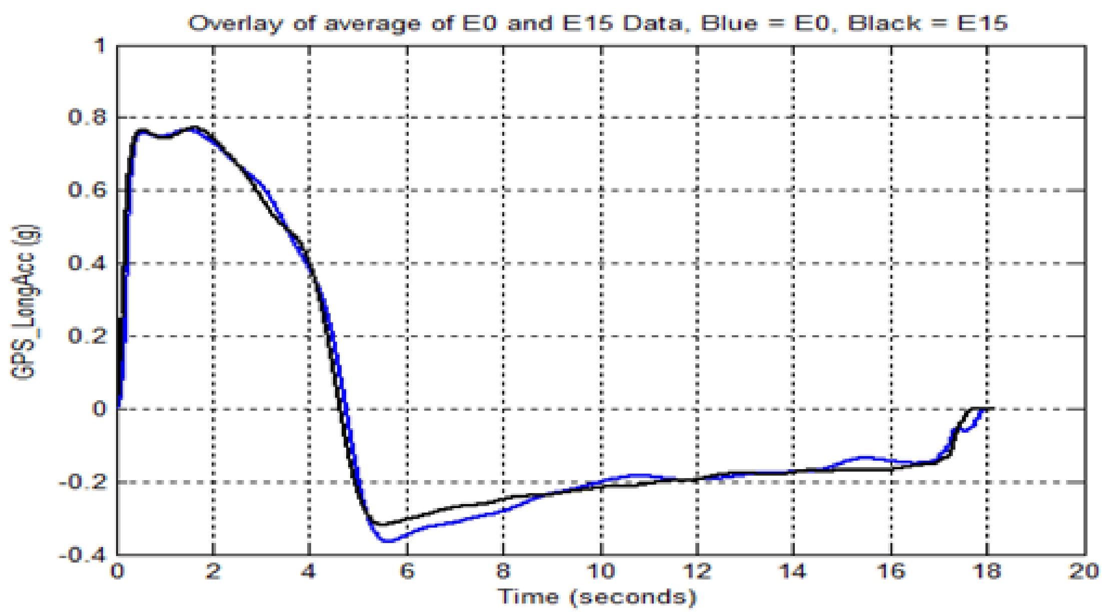

Figure 35: Comparison of GPS longitudinal acceleration for 0-60-0 tests: Vehicle #1

Due to the very large volume of data acquired during the 0-X-0 and roll-in testing, the data were processed the same way as in the lap testing but are presented in a different manner. The plots for the 0-X-0 and roll-in data show percent differences in the temperatures instead of actual temperatures.

Vehicle #1

Figure 36 shows the PTO head temperature percent differences between E0 and E15 for vehicle #1. Across the bottom of the plot are the different test conditions. The y-axis values are positive if the E15 temperature was higher than the E0 temperature. It is clear that in all cases for this vehicle, E15 resulted in higher measured temperatures than E0. The MAG side head temperature showed very similar trends.

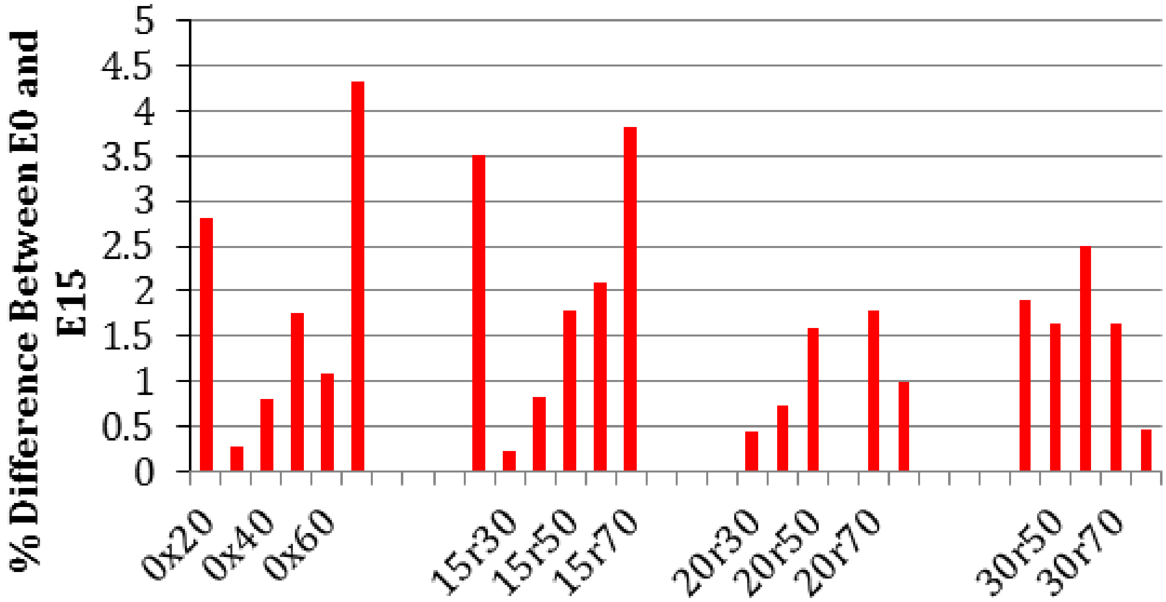

Figure 36: Percent difference in PTO head temperature: Vehicle #1

The MAG side EGT percent differences are shown in Figure 37. Again, it can be seen that E15 results in higher EGTs than E0. The PTO side EGTs showed very similar trends though slightly lower percentage differences.

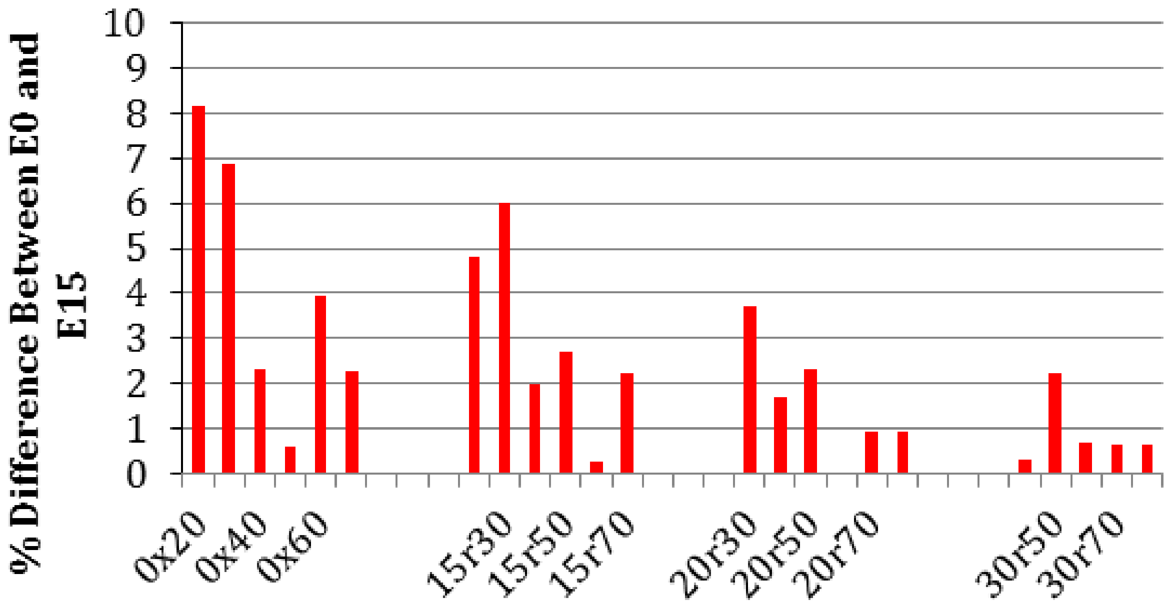

Figure 37: Percent difference in MAG EGTs: Vehicle #1

Vehicle #2

The MAG side head temperatures for vehicle #2 are shown in Figure 38. Again, it can be seen that E15 results in higher temperatures than E0. The PTO side head temperatures exhibited similar trends though slightly smaller percentage differences.

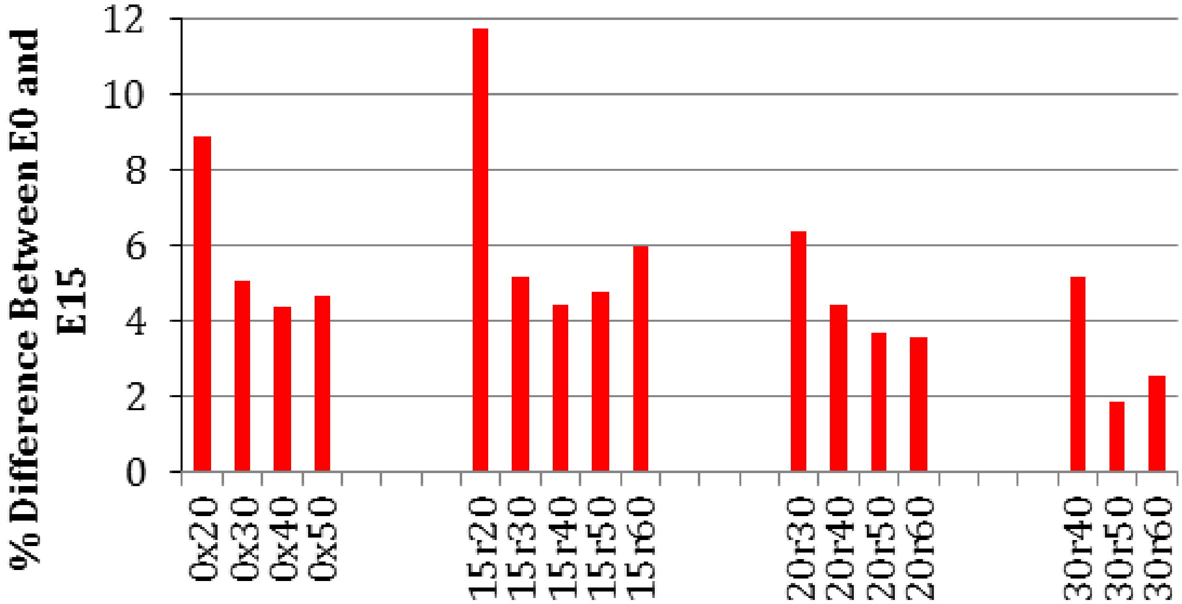

Figure 38: Percent differences in MAG side head temperatures: Vehicle #2

Figure 39 shows the percentage differences in the PTO side EGTs when running E15 vs. E0. The MAG side EGTs are very similar. All results indicate an increase in EGT with E15.

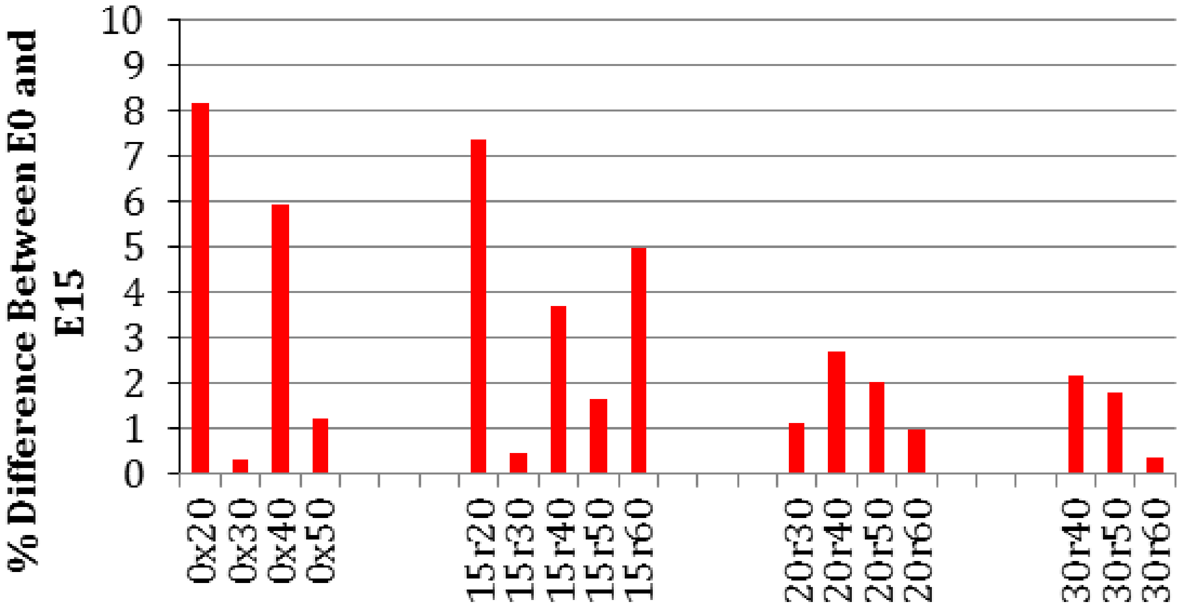

Figure 39: Percent differences for PTO side EGTs: Vehicle #2

Vehicle #3

Figure 40 shows the percentage differences in the PTO side EGTs for vehicle #3. It can be observed that there is a very consistent increase in temperatures when operating on E15 vs. operating on E0. The MAG side EGTs showed consistent increases as well, but of a smaller amplitude.

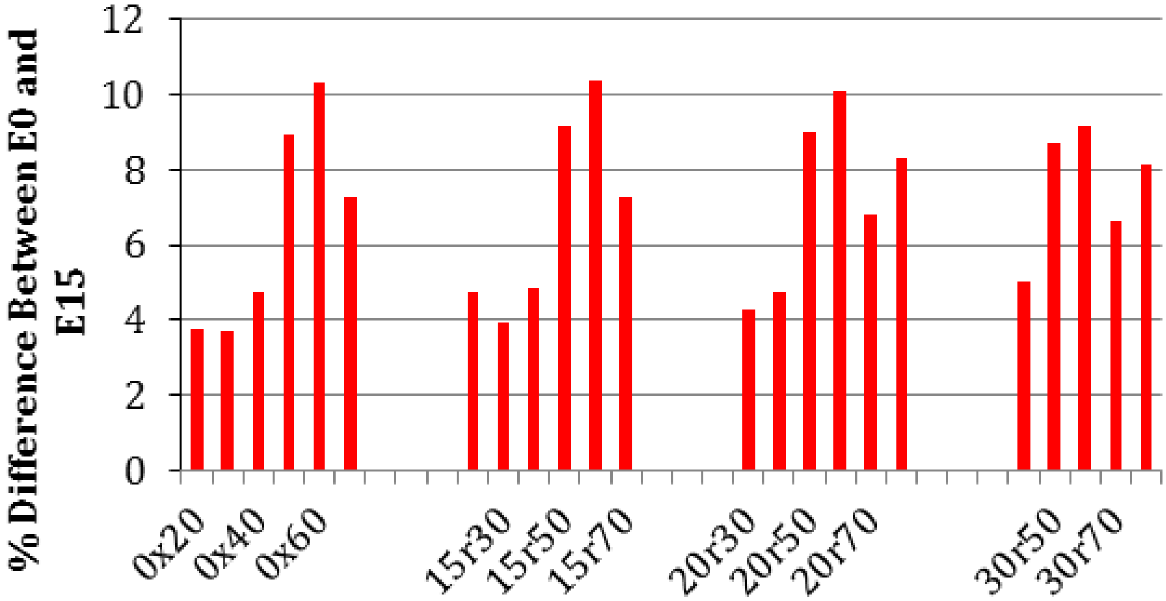

Figure 40: Percent differences for PTO side EGTs: Vehicle #3

Vehicle #4

The MAG side head temperatures for vehicle #4 are shown in Figure 41. Note that the percentage increases for this engine show a very consistent pattern in the plot with the largest difference being at the lowest test speeds, the differences increasing through the mid test speeds, and finally dropping off at the highest test speed. The PTO side head temps also increased on E15 but did not show as uniform a pattern relative to test speeds.

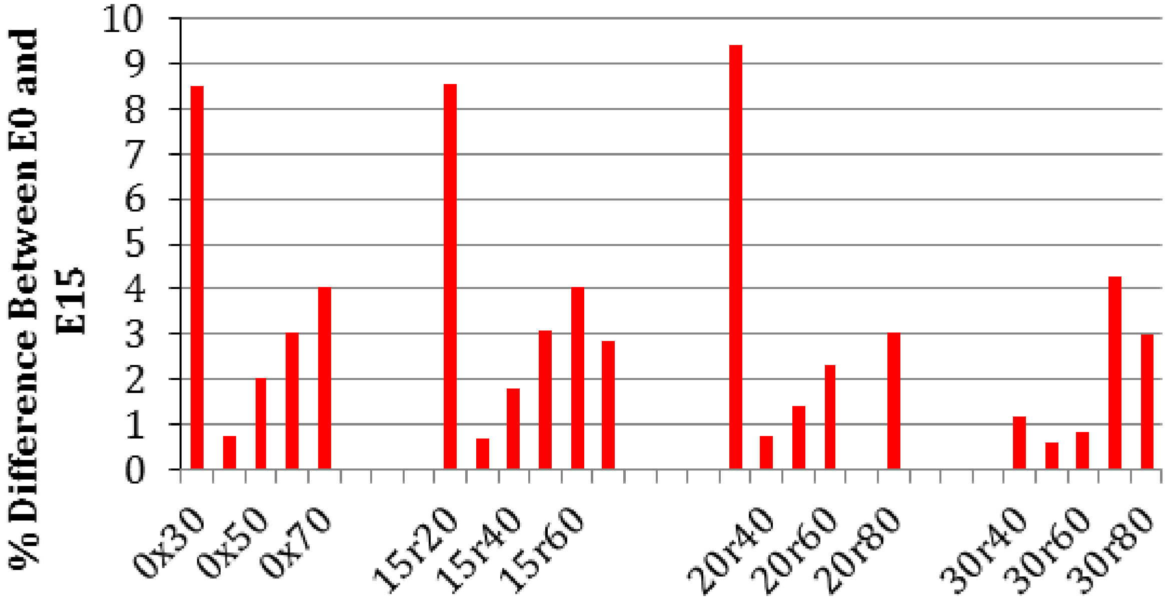

Figure 41: Percent differences for MAG side head temperatures: Vehicle #4

Figure 42 shows the percentage differences for the PTO side EGTs for vehicle #4. The MAG side EGTs show an increase in temperature when using E15.

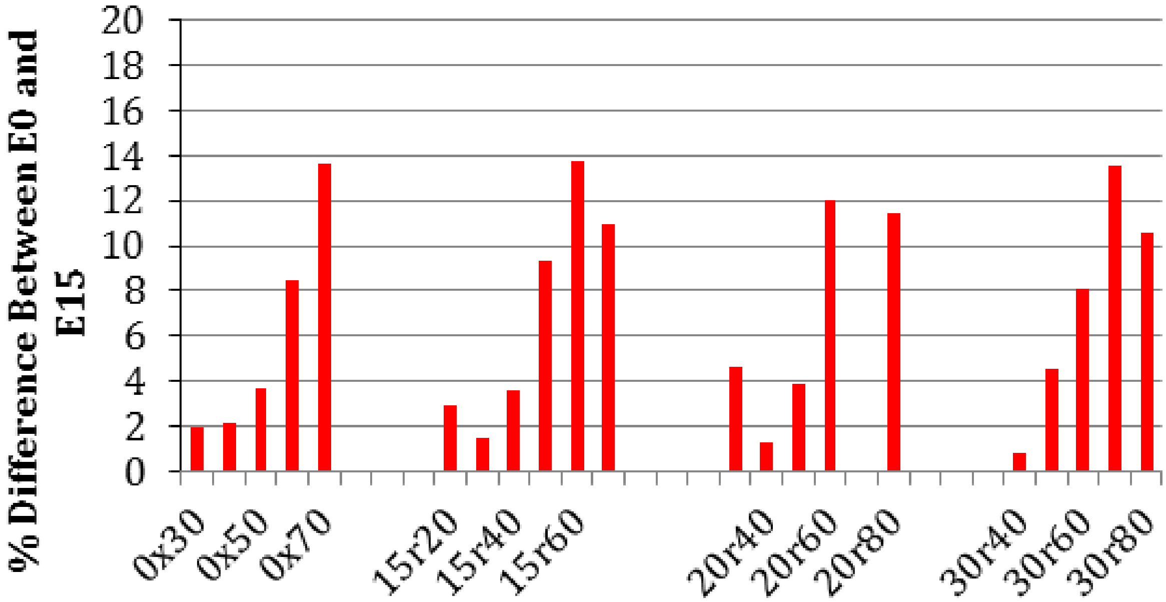

Figure 42: Percent differences for PTO side EGTs: Vehicle #4

Overall Driveability Conclusions

The overall conclusions that can be drawn from the driveability study include the following main points.

- The drivers could not easily discern which fuel the snowmobiles were using in any test conditions but did notice a few engine calibration issues in the form of engine hiccups or stumbles.
- E0 and E15 were very similar to the riders while some machines seemed to run better on E0 than E15 and vice versa according to comments during the lap testing.
- More calibration issues (engine stumbling) were identified in 0x0 testing than lap testing.
- In nearly all cases, the engines had higher head temperatures and EGTs when running on E15 than on E0.
- Temperatures varied more in the 0x0 testing than the laps; some increases were significant.
- Temperature change between E0 and E15 was dependent on engine calibration scheme.
- The most significant temperature increases happened in nearly all cases on all of the snowmobiles when the engines accelerated more rapidly. This is evident in the lap testing as well as both the 0-X-0 and roll-in tests.
- No engine failures occurred on either fuel for all the driveability analyses.
- The limited number of snowmobiles tested produced inconclusive results from the driveability analyses.

Engine Emissions and Durability Testing

The purpose of this test series was to measure the emissions and performance of four snowmobiles on E0 (Indolene) and E15 fuel over the useful life of the vehicles (5,000 miles). Critical measurements included regulated and non-regulated emissions, engine speed, engine power, EGT, muffler exit temperature, fuel flow, and combustion parameters. All emissions test points were performed in triplicate and averaged.

The raw exhaust emissions were measured using an AVL SESAM emissions bench that contained a Fourier transform infrared spectrometer along with an integrated flame ionization detector and oxygen analyzer. The emissions bench measured all regulated components, including CO and HC, as well as many unregulated components such as 1,3-butadiene and formaldehyde.

Emissions tests were conducted using the standard five-mode cycle per Code of Federal Regulations Title 40, Part 1051 (40 CFR 1051) requirements. This test sequence is shown in Table 6, where the engine was held at the test point for three minutes to stabilize the temperatures and then run an additional two minutes to collect the data.

Table 6: Five-mode Emissions Cycle

Mode No.	Engine Speed (%)[a]	Engine Torque (%)[b]	Time in Mode (minutes)	Weighting Factor
1	100	100	5	0.12
2	85	51	5	0.27
3	75	33	5	0.25
4	65	19	5	0.31
5	Idle	0	5	0.05

[a] Percent speed is percent of maximum test speed.
[b] Percent torque is percent of maximum torque at maximum test speed.

Prior to durability and emissions testing, all engines underwent a standard break-in procedure per each manufacturer’s recommendation. This break-in procedure was conducted using E0 retail-grade fuel. Following break-in, each pair of engines underwent a beginning-of-life (BOL) emissions test using certification-grade E0 (Indolene) fuel with testing protocols in accordance with 40 CFR Parts 1051 and 1065 requirements. Following the BOL emissions evaluation, the E15-dedicated engine underwent emissions testing using the E15 certification fuel. Middle-of-life (MOL) and end-of-life emissions tests were conducted in the same manner. For the MOL and end-of-life tests, however, the E15-dedicated engine was first tested on the E15 certification fuel followed by the E0 (Indolene) certification fuel. To maintain consistency among the E15 emissions tests, adequate certification E15 fuel was splash-blended at one time and used for all E15 certification emissions tests. All emissions testing throughout the program were performed in triplicate.

Following the successful completion of the BOL emissions test, each engine pair underwent durability testing using a six-mode test cycle developed specifically for this program. The six-mode cycle was conducted recursively up to an estimated mileage accumulation of 8,000 km

(5,000 miles). The durability cycle consisted of six vehicle speed/engine speed points that simulated real-world operation of each snowmobile and was developed in cooperation with all four vehicle manufacturers. The vehicle speed was controlled by the dynamometer, and the engine speed was controlled by the throttle position. The six points of the durability cycle are shown in Table 7, along with the time in each mode.

Table 7: Six-mode Durability Test Cycle

Mode	Vehicle Speed (%)	Target Engine Speed (%)	Time in each mode (seconds)
1	100	100	20
2	70	85	40
3	50	75	60
4	40	70	140
5	25	60	100
6	0	Idle	40

A sample of the six-mode test cycle is shown in Figure 43. The test cycle uses a high output mode followed by a low output mode to help cool the clutches and extend drive belt life.

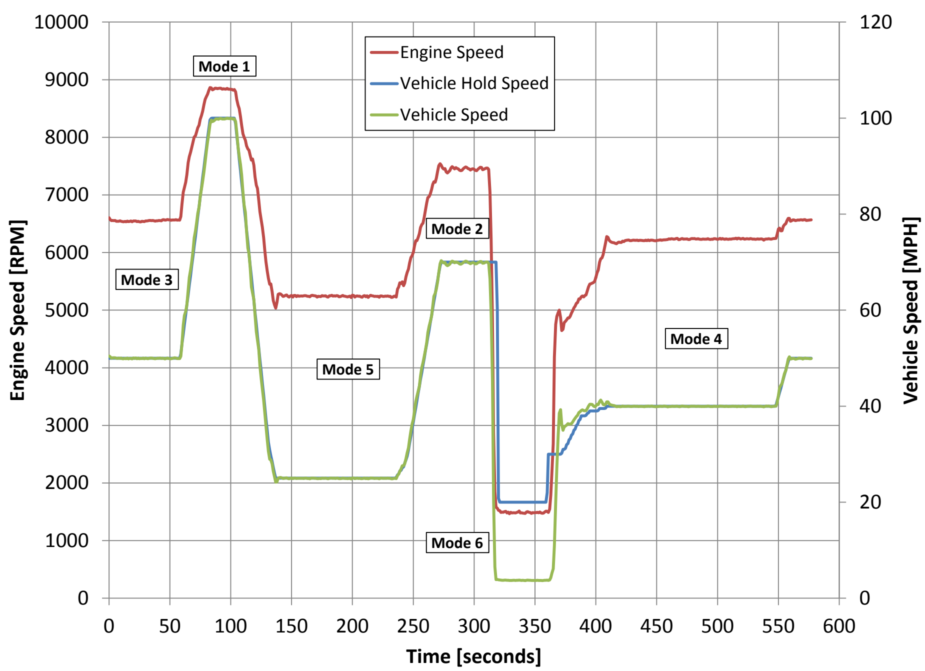

Figure 43: Engine speed, vehicle hold speed, and actual vehicle speed for the six-mode durability cycle

The manufacturers' recommended services intervals for lubricants, spark plugs, and belts were followed throughout the testing. Engine condition was continuously monitored during durability testing to evaluate any degradation in performance. Measurements included:

- Engine speed
- Engine torque
- Ambient air temperature
- Intake manifold temperature
- Mid-pipe temperature (not engine #3)
- EGT
- Muffler exit temperature
- Cylinder head temperature (not engine #3)
- Fuel supply temperature and pressure
- Fuel return temperature (engines #1 and #4 only)
- Operating time
- Mileage accumulation.

For each engine, the first four figures present the changes from E0 to E15 for brake specific fuel consumption (BSFC), engine power, EGT, and muffler exit temperature. Within each bar graph, the E0 (Indolene) data point is shown in text form around the zero line of the bar charts. The next two figures show specific CO and HC emissions (grams per kilowatt-hour [g/kW-hr]) for the E0 engine, the E15 engine on E0 fuel (Indolene), and the E15 engine on E15 fuel. The error bars represent the maximum and minimum values obtained during the triplicate testing. Finally, two figures show the percent changes from E0 to E15 for 1,3-butadiene (C_4H_6) and formaldehyde (CH_2O) emissions. 1,3-Butadiene is listed as a known carcinogen by the U.S. Environmental Protection Agency [1]. Acute low exposures may cause irritation to the eyes, throat, nose, and lungs. Acute high exposures may cause damage to the central nervous system or cause symptoms such as distorted blurred vision, vertigo, general tiredness, decreased blood pressure, headache, nausea, decreased pulse rate, and fainting [2]. Formaldehyde was described by the U.S. National Toxicology Program as "known to be a human carcinogen." At concentrations as low as 0.2 part per million (ppm) in air, formaldehyde can cause watery eyes and irritated mucous membranes [3]. It results from the incomplete combustion of a hydrocarbon fuel.

Engine #1

The E0-designated engine failed shortly after completing the MOL emissions point. The failure was not related to the fuel. The E15-designated engine failed during BOL E0 fuel baseline emissions testing. Therefore, no emissions or durability data is available for engine #1. Perhaps something unidentified but related to this engine and test cycle may have been inappropriate and contributed to the failure.

Engine #2

Fuel Consumption and Power

The effect of E15 on BSFC is shown in Figure 44 for engine #2. E15 increased BSFC at the BOL stage compared to E0, but reduced BSFC as the engine aged.

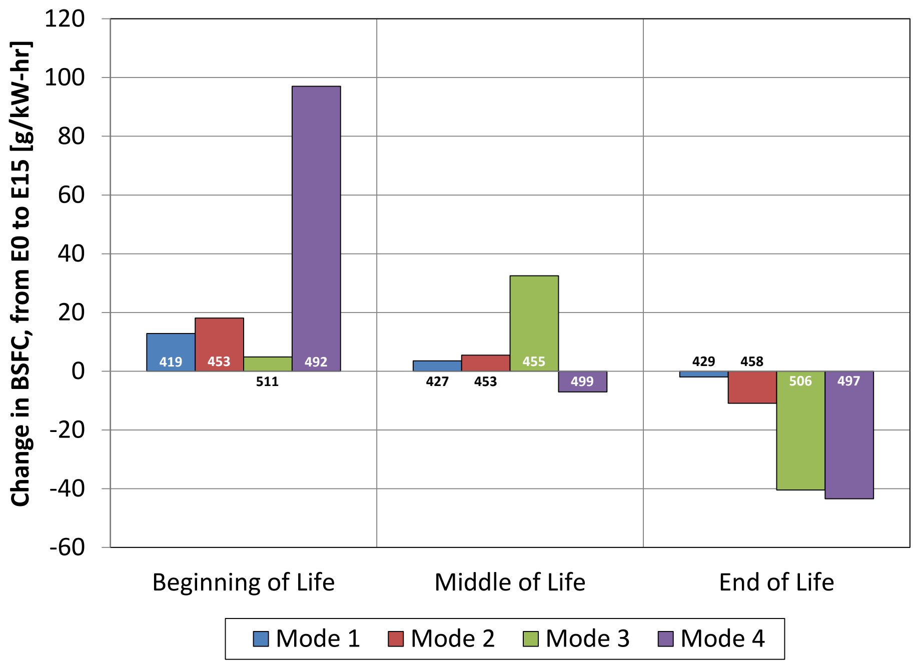

Figure 44: Change in BSFC from E0 to E15: Engine #2

The power output changed less than 1 kW between E0 and E15 over all four test modes, as shown in Figure 45.

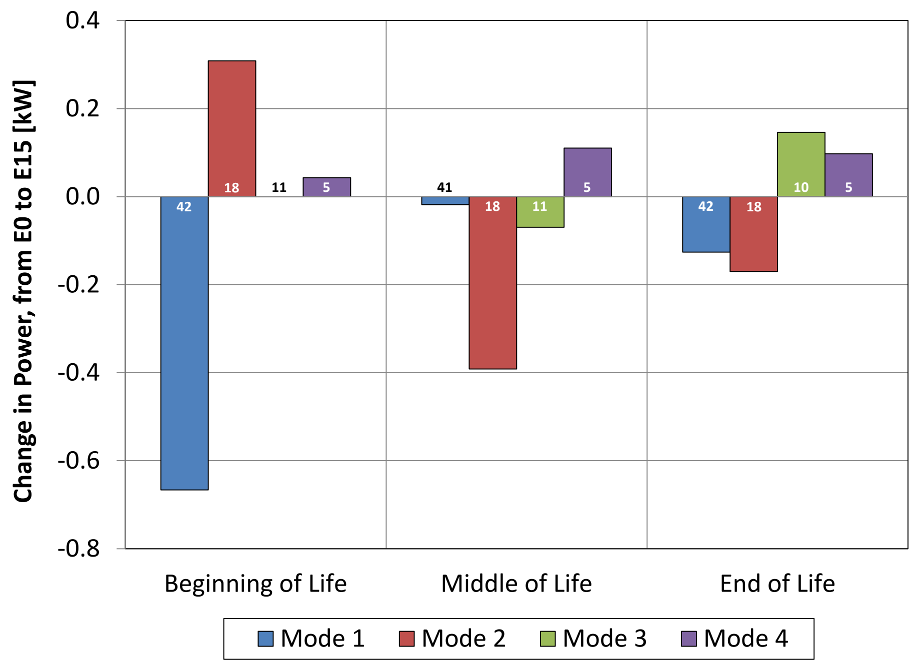

Figure 45: Change in power (kW) from E0 to E15: Engine #2

Exhaust Temperatures

E15 caused the EGT to increase, especially when the engine was new (Figure 46). As the engine aged, the impact of E15 on EGTs appeared to lessen, consistent with the decrease in BSFC.

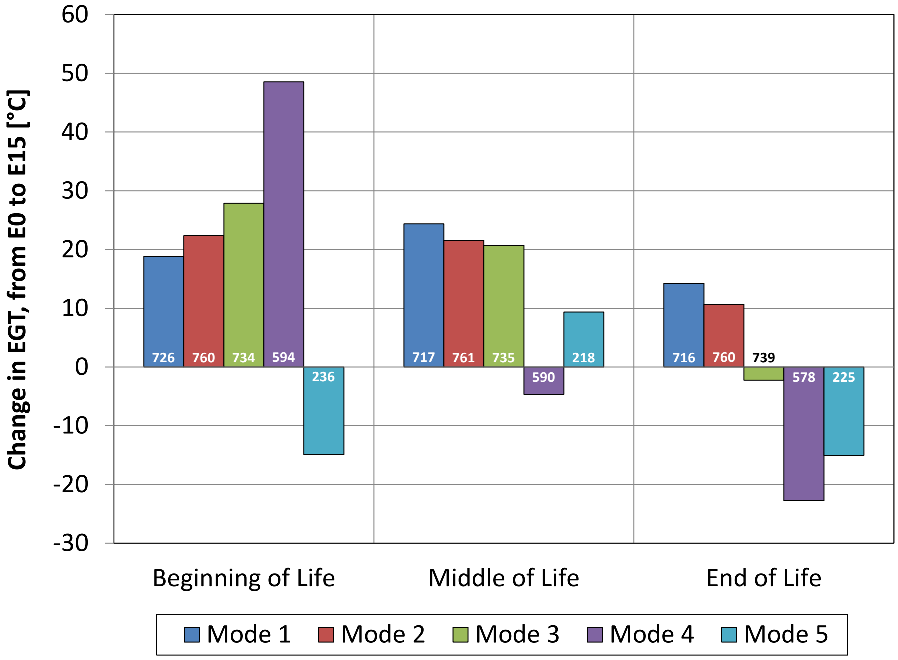

Figure 46: Change in EGT from E0 to E15: Engine #2

The changes noted in EGT directly affected the muffler exit temperature, as shown in Figure 47. Only during the durability testing for this engine on E15 did a blue exhaust flame appear at the muffler exit approximately 10–15 seconds into mode 1 operation. Muffler exit temperatures exceeded 800°C during this secondary combustion event. The fuel for durability testing was 90 AKI with a vapor pressure of 11 pounds per square inch gauge. During emissions testing, the splash-blended E15 certification fuel had an AKI of 96 and a vapor pressure of 9.55 pounds per square inch gauge. The secondary combustion event never occurred with the E15 certification fuel blend at mode 1. Combustion of the unburned fuel in the exhaust can occur when a critical ignition temperature is reached. The combination of the lower AKI of the E15 durability blend compared to the E15 certification blend and higher vapor pressure of the E15 durability fuel perhaps led to the increased temperature and thus combustion in the exhaust system. At the end of the 5,000-mile durability test, the baffling inside the muffler was significantly damaged due to excessive temperature, as shown in Figure 48.

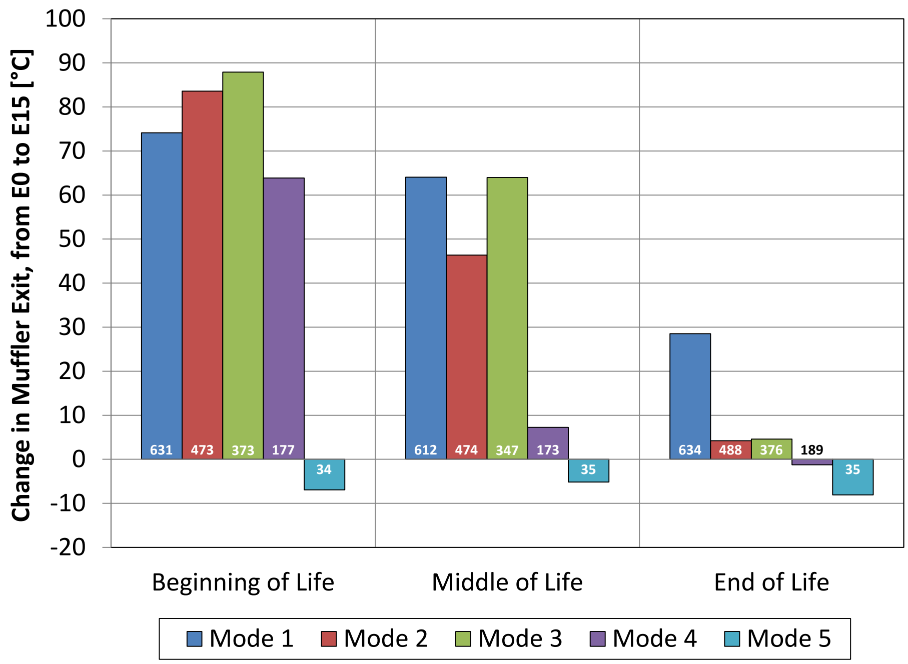

Figure 47: Change in muffler exit temperature from E0 to E15: Engine #2

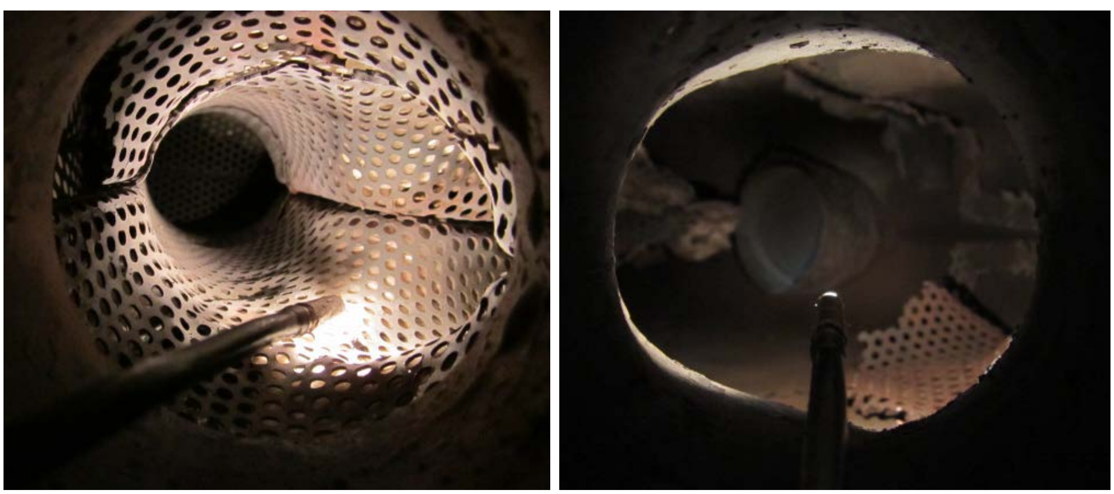

Figure 48: E0 muffler (left) and E15 muffler (right) after 5,000 miles: Engine #2
(Photo credit: Scott Miers, Michigan Technological University)

The manufacturer of engine #2 stated that all of its products undergo extensive durability and calibration testing to determine the appropriate operating ranges for its engines and their sub-systems. Any changes to these components or their operating ranges can increase the chances of engine and sub-system failure or deterioration, in particular the exhaust system. The OEM does not endorse any deviation from these operating ranges and considers a 25°C change a significant increase.

Regulated Emissions

As expected, E15 caused the normally fuel-rich air/fuel charge to operate closer to the stoichiometric ratio, leading to a reduction in CO emissions, as shown in Figure 49. No compensation for the fuel oxygenation was available for this engine.

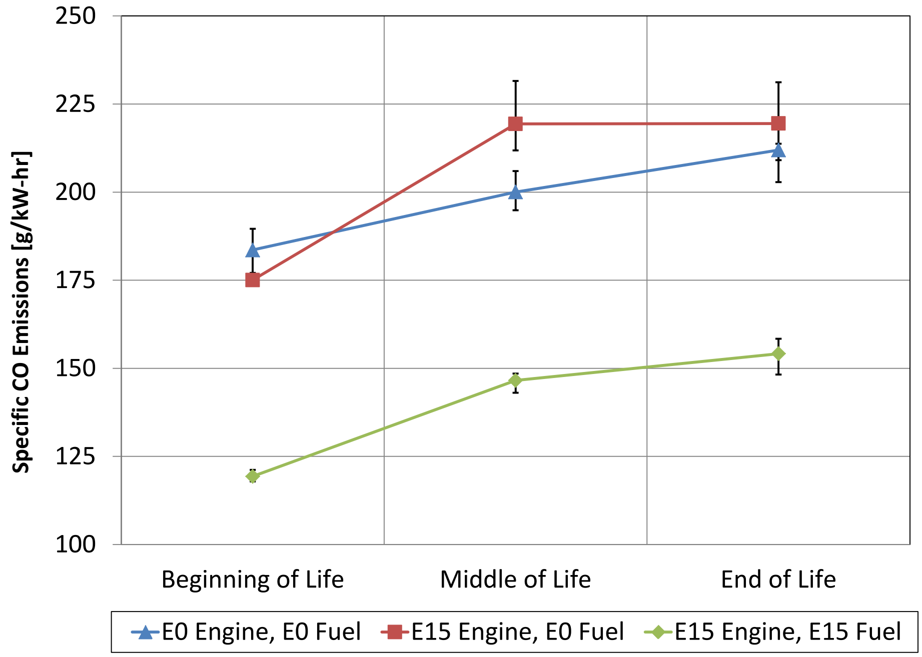

Figure 49: Specific CO emissions: Engine #2

HC emissions, Figure 50, were slightly reduced with E15 fuel. The largest reduction occurred at the end-of-life stage. Note the range of data at each point (error bars) almost overlap for each stage of life, regardless of the fuel.

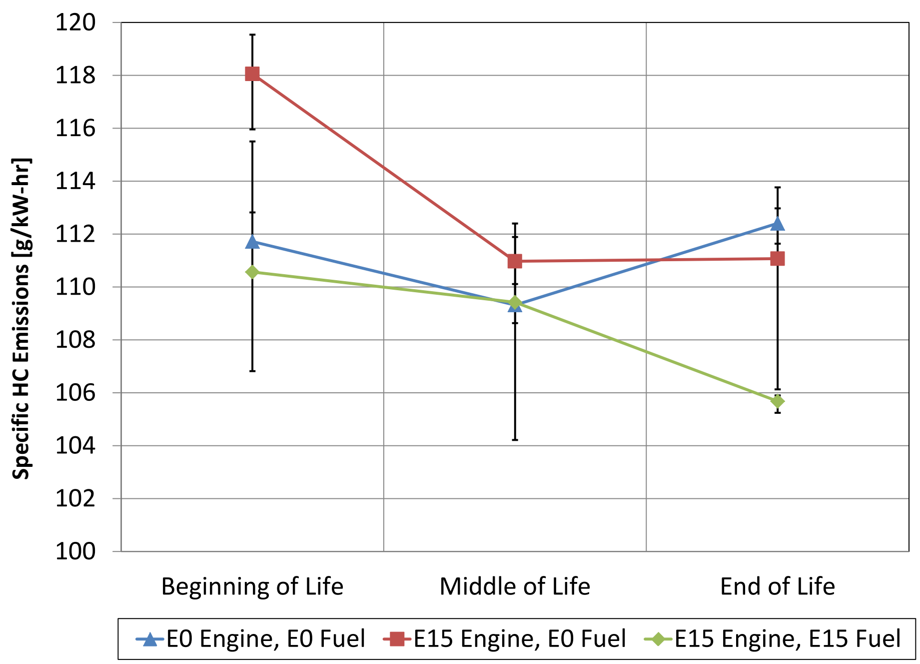

Figure 50: Specific HC emissions: Engine #2

Non-regulated Emissions

Figure 51 shows the change in 1,3-butadiene emissions for the E15 fuel. Significant reductions were noted for E15, caused by a less fuel-rich mixture (still fuel-rich of the stoichiometric ratio). 1,3-Butadiene is a product of incomplete combustion, and air/fuel mixtures closer to stoichiometric conditions would have less unburned product.

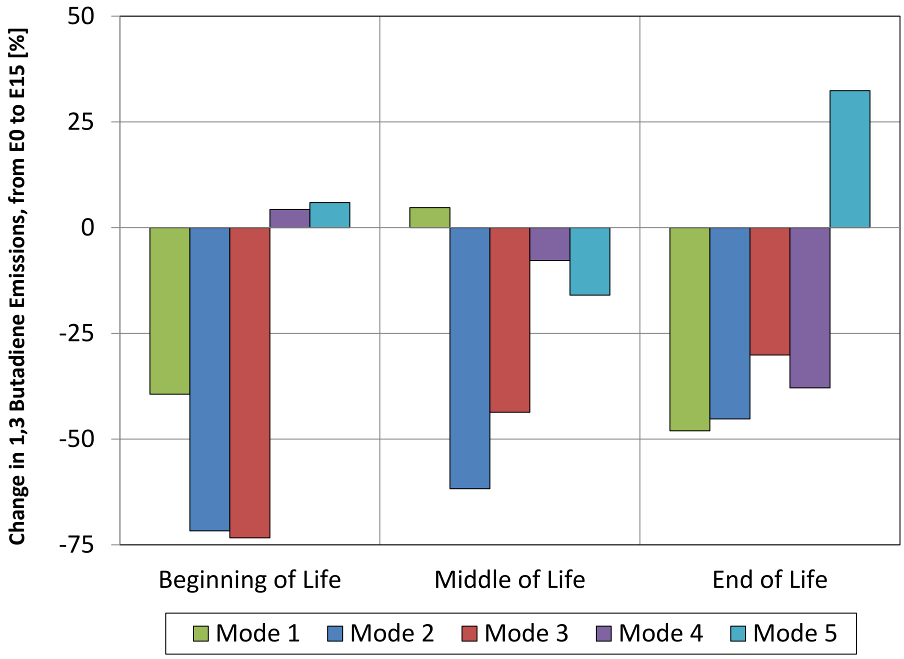

Figure 51: 1,3-Butadiene emissions % change from E0 to E15: Engine #2

As shown in Figure 52, formaldehyde emissions increased significantly for engine #2 when operating on E15 fuel. In some cases, the concentration of formaldehyde almost doubled when operating on E15. Because formaldehyde is an oxygenated hydrocarbon, higher oxygen concentrations typically will lead to more formaldehyde in the exhaust.

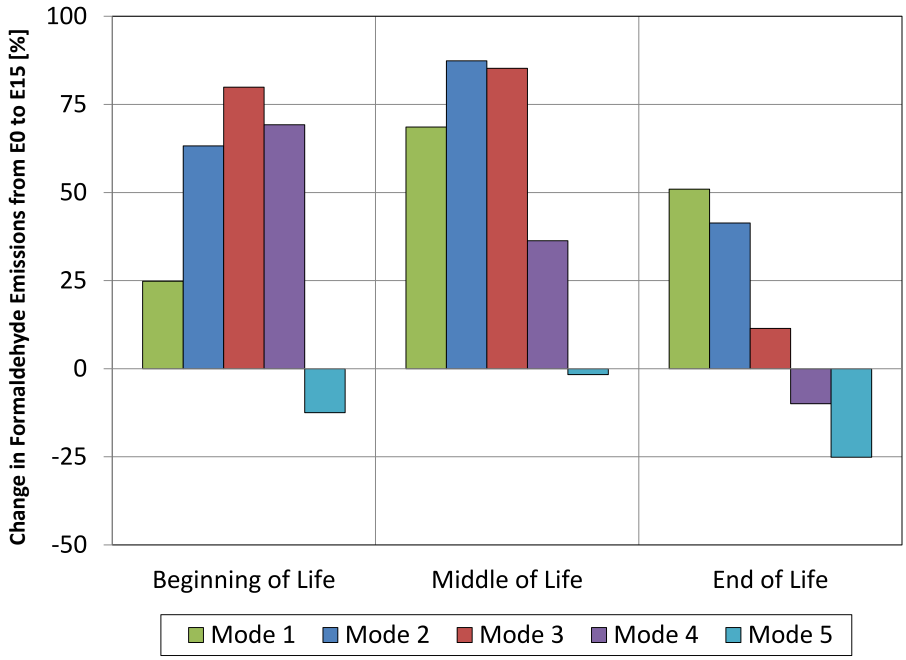

Figure 52: Formaldehyde emissions % change from E0 to E15: Engine #2

Engine #3

After completing both the E0 and E15 engines, the OEM disassembled and inspected several components. They found that the cam profile was worn beyond the wear limit for the E15 engine. The abnormal wear may have been caused by fuel dilution during startup, but the root cause is unknown.

Fuel Consumption and Power

The effect of E15 on BSFC is shown in Figure 53 for engine #3. At mode 1, BSFC was reduced with E15 due to a power increase, shown in Figure 54. At modes 3 and 4, BSFC increased with E15. The addition of E15 at mode 1 provides the oxygenate necessary to burn additional excess fuel, which results in a power increase. The power output for modes 2–4 were the same for the two fuels, and thus the lower energy content of E15 increased the BSFC at modes 3 and 4. The reduction in BSFC at mode 2 for BOL and MOL is significant and may have been a result of fuel cooling from E15, which improved the thermal efficiency.

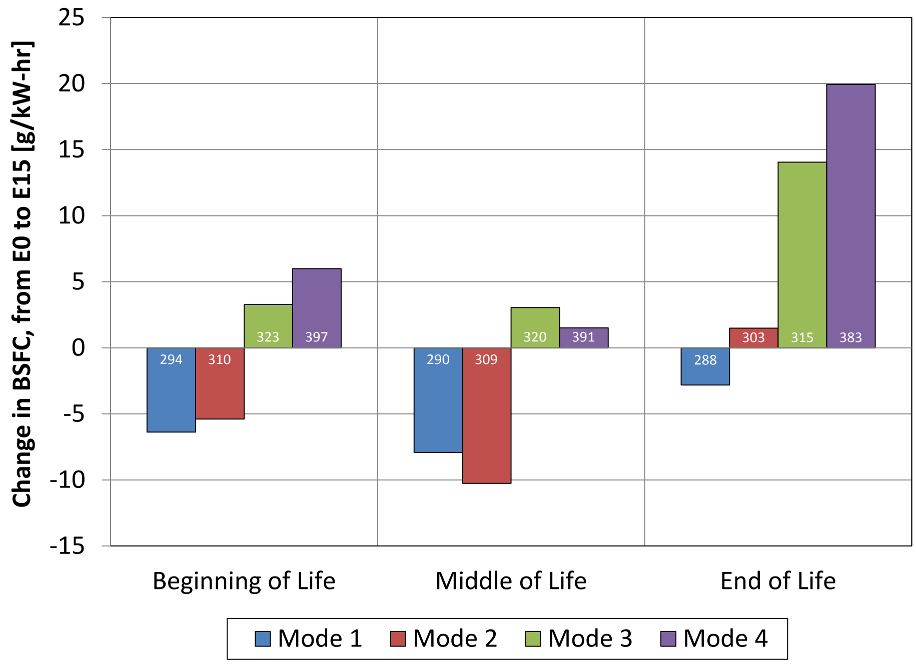

Figure 53: Change in BSFC from E0 to E15: Engine #3

As stated earlier, power increased at mode 1 for E15, as shown in Figure 54, due to additional oxygen being available for combustion. The differences in power output for Modes 2–4 are test-to-test variations.

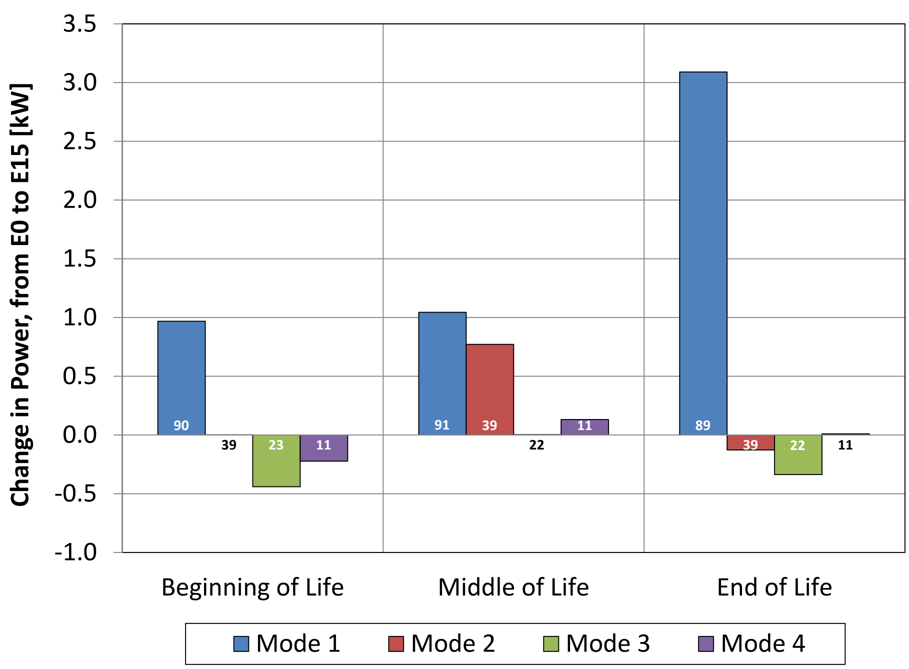

Figure 54: Change in power (kW) from E0 to E15: Engine #3

Exhaust Temperatures

EGT increased consistently with E15 fuel, regardless of engine miles. Figure 55 shows that EGTs increased from 18 to almost 80 degrees, depending on the mode. E15 produced a less fuel-rich (still fuel-rich of the stoichiometric ratio) air/fuel ratio, thus increasing combustion temperature and ultimately the EGT.

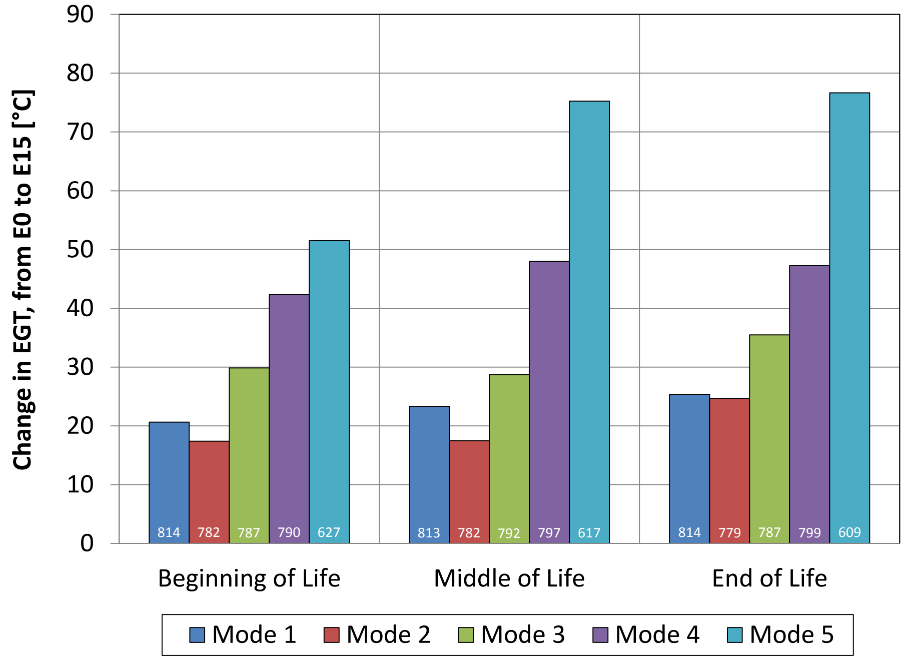

Figure 55: Change in EGT from E0 to E15: Engine #3

The muffler exit temperature, Figure 56, follows the same trend as the EGT plot. Increases in muffler exit temperature ranged from 15 to almost 40 degrees.

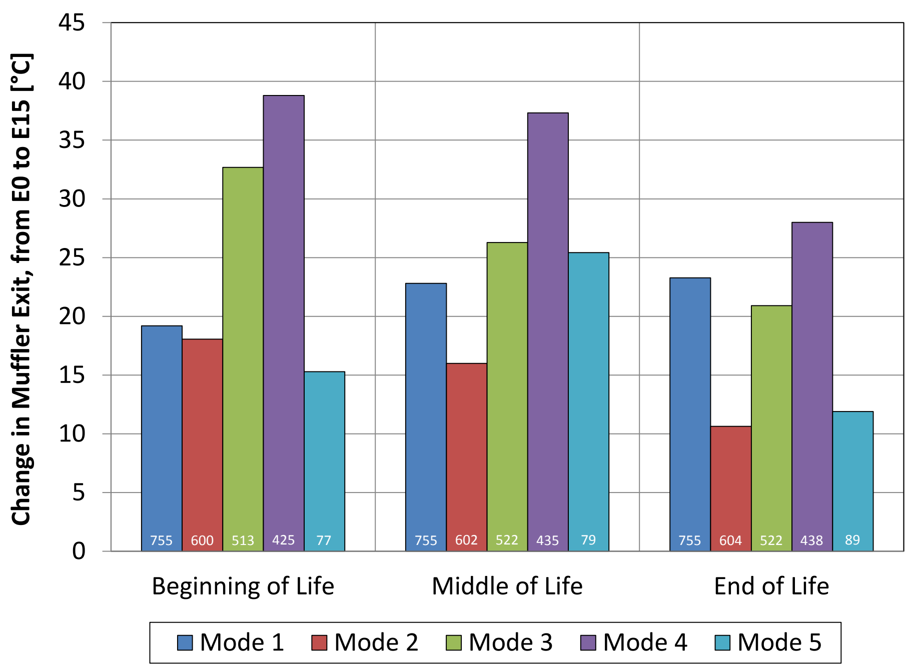

Figure 56: Change in muffler exit temperature from E0 to E15: Engine #3

Regulated Emissions

CO emissions, shown in Figure 57, were reduced significantly with the addition of E15. The less fuel-rich (still fuel-rich of the stoichiometric ratio) air/fuel mixture provided additional oxygen to oxidize CO to CO_2 and thus reduce the concentration of CO in the exhaust.

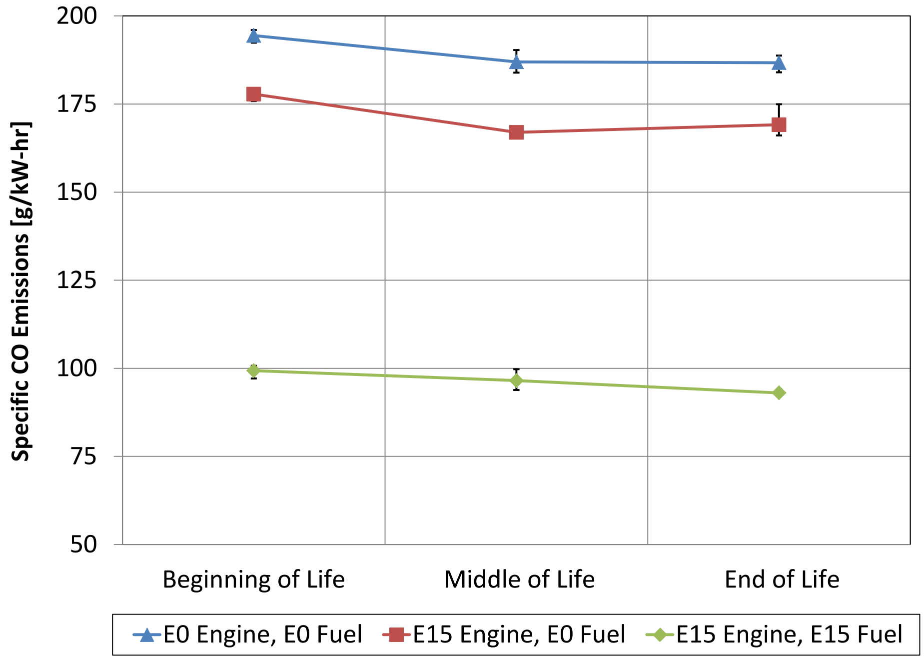

Figure 57: Specific CO emissions: Engine #3

This particular engine did produce lower HC emissions when operating on E15 due to the less fuel-rich (still fuel-rich of the stoichiometric ratio) air/fuel ratio, leading to reduced unburned fuel in the exhaust.

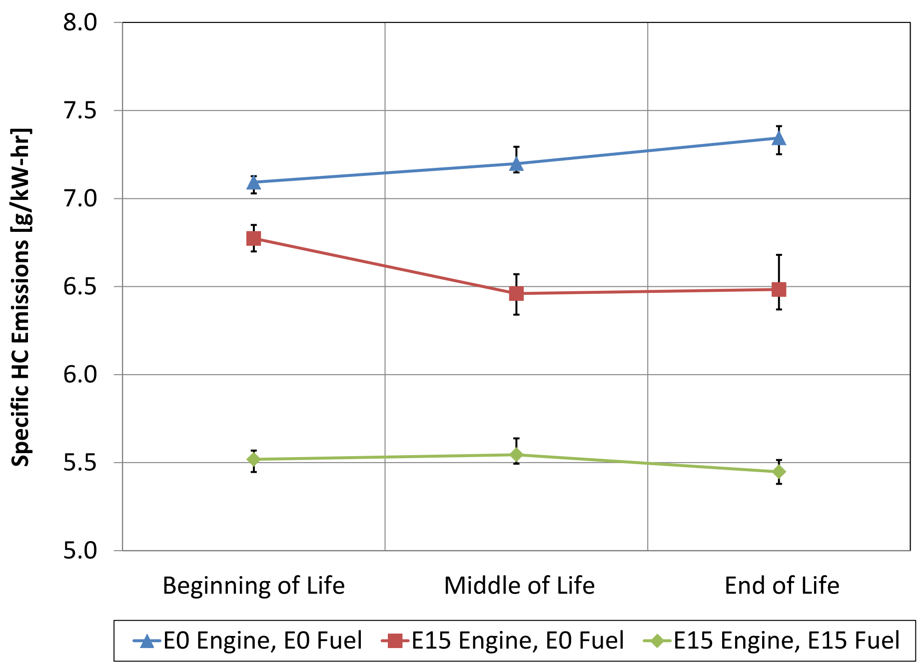

Figure 58: Specific HC emissions: Engine #3

Non-regulated Emissions

Overall, 1,3-butadiene emissions were reduced with E15, as shown in Figure 59. The slight increase (less than 1 ppm) in 1,3-butadiene at BOL is within the measurement accuracy of the analyzer. All levels are low across the life of the engine (less than 20 ppm).

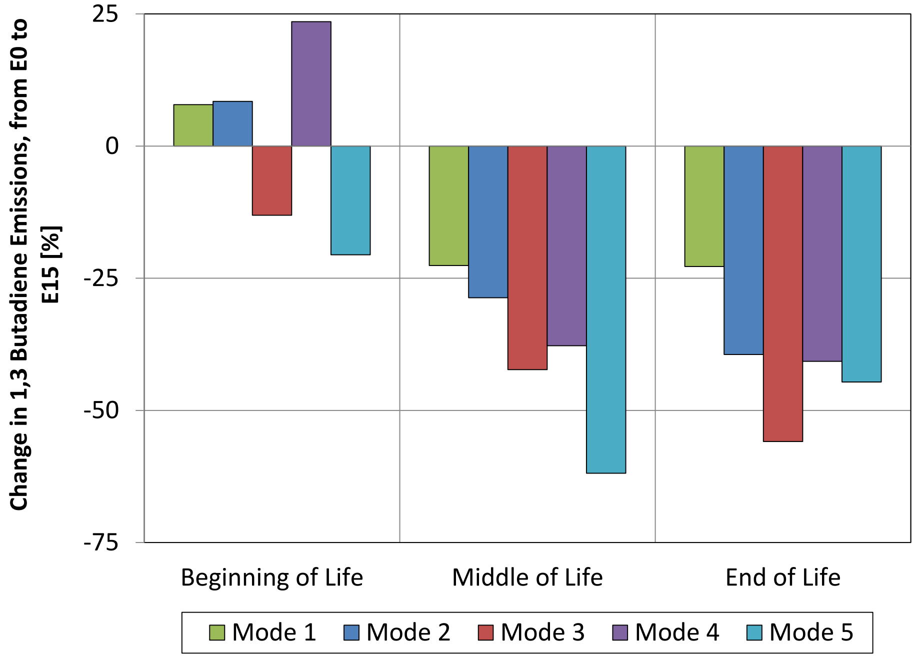

Figure 59: 1,3-Butadiene emissions percent change from E0 to E15: Engine #3

The addition of oxygen to the fuel (E15) caused formaldehyde emissions to increase, as shown in Figure 60. Levels were highest at mode 2, where the exhaust temperatures were lowest.

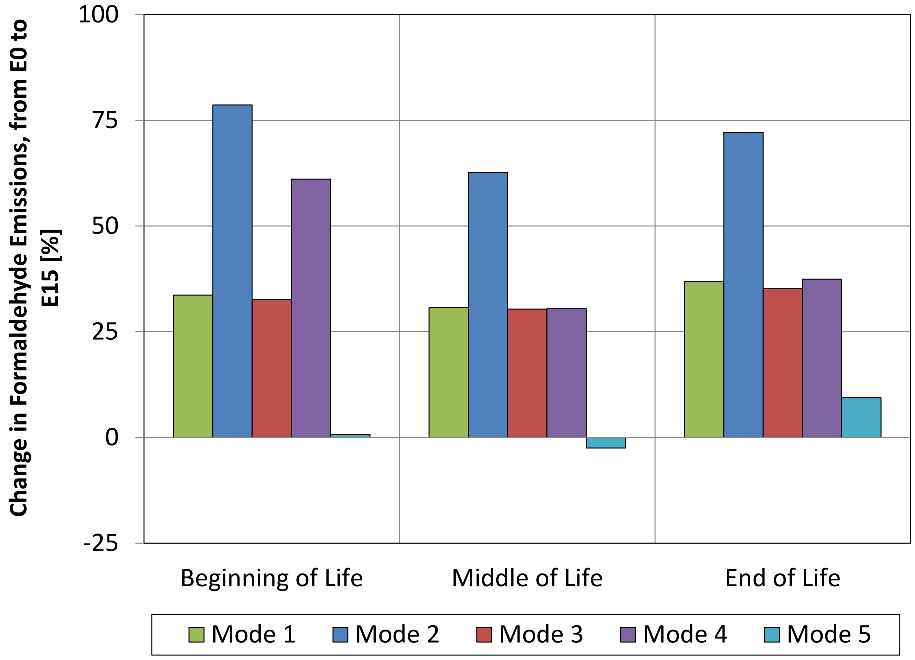

Figure 60: Formaldehyde emissions percent change, from E0 to E15: Engine #3

Engine #4

The E0 engine failed approximately 3,500 miles into the durability test. Therefore, only BOL and MOL data are presented for this engine. According to the manufacturer, the engine failure was not fuel related.

Fuel Consumption and Power

The effect of E15 on BSFC is shown in Figure 61 for engine #4. BSFC decreased at mode 1 due to an increase in power, as shown in Figure 62. It increased at modes 2–4 due to an increase in fuel flow, to maintain the same power with E0.

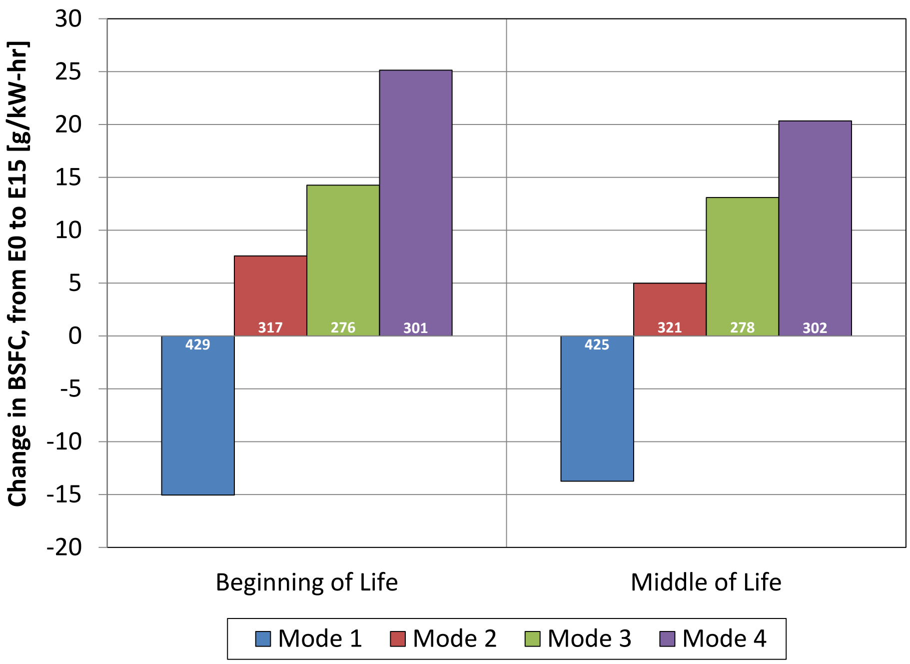

Figure 61: Change in BSFC from E0 to E15: Engine #4

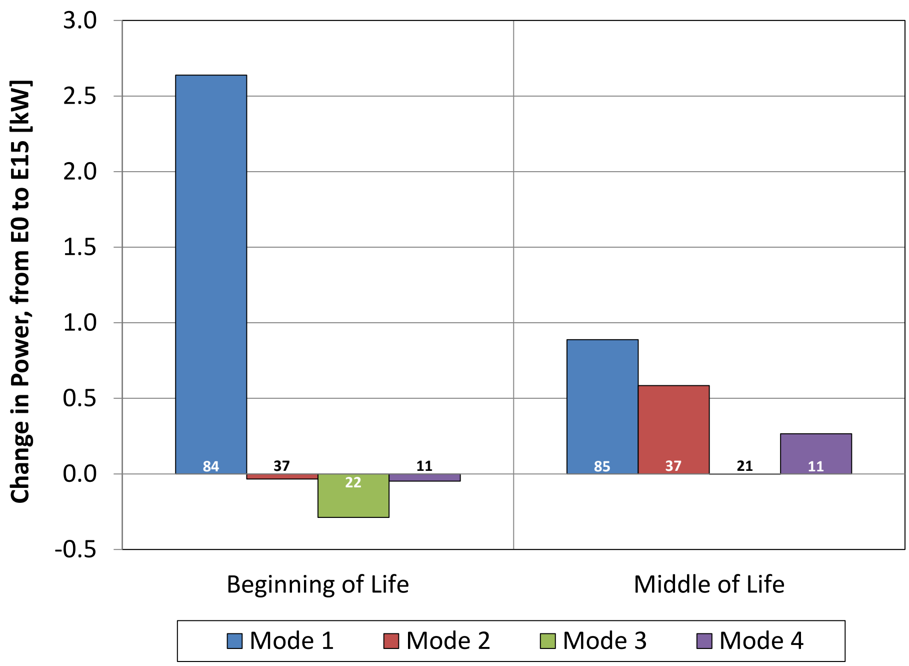

Figure 62: Change in power (kW) from E0 to E15: Engine #4

Exhaust Temperatures

The EGT, shown in Figure 63, increased at mode 1 due to a less fuel-rich (still fuel-rich of the stoichiometric ratio) mixture caused by E15. A measureable decrease in EGT at modes 3–5 are a result of in-cylinder fuel cooling (direct injection) from the higher latent heat of vaporization of E15.

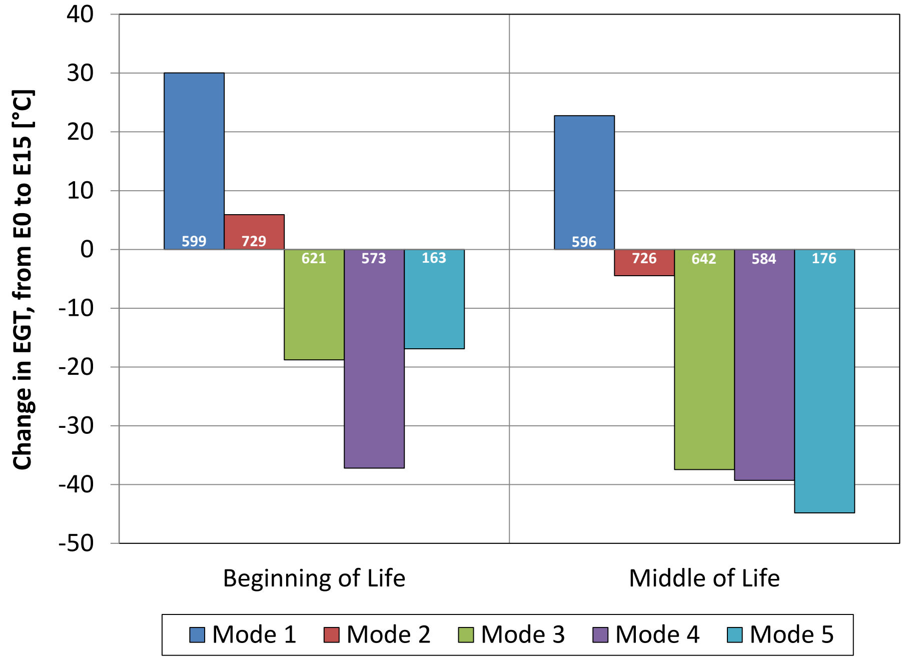

Figure 63: Change in EGT from E0 to E15: Engine #4

The muffler exit temperature, shown in Figure 64, followed the overall trend in EGT. A maximum increase in muffler exit temperature of over 50 degrees was recorded at mode 1, MOL. According to the manufacturer, the maximum permissible muffler inlet temperature is 680°C. If the inlet temperature rises above 710°C, the muffler could be damaged from a post-combustion event.

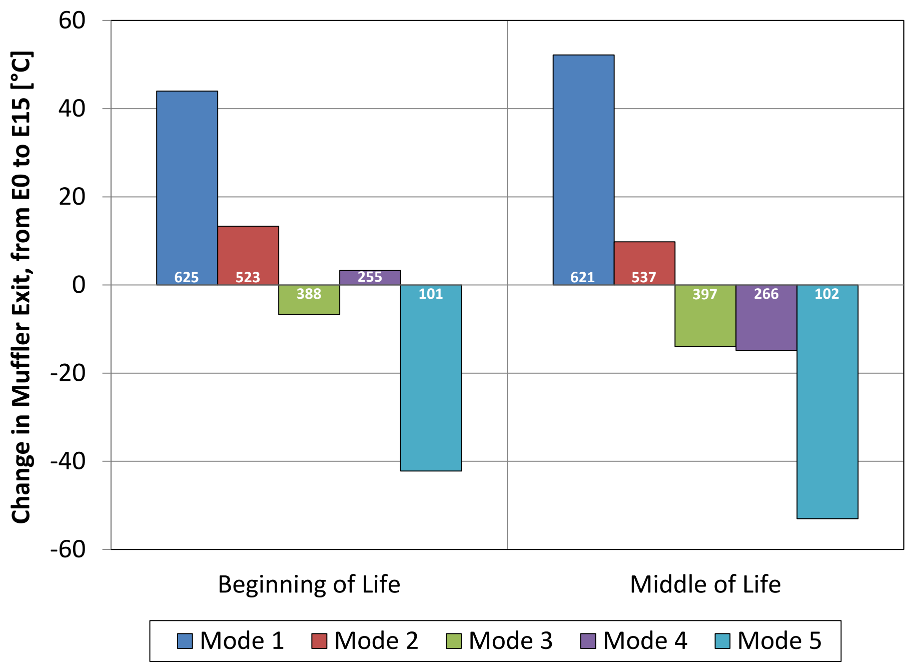

Figure 64: Change in muffler exit temperature from E0 to E15: Engine #4

Regulated Emissions

The enleanment caused by E15 reduced the carbon monoxide emissions, as shown in Figure 65. Note that the air/fuel ratio is still fuel-rich of the stoichiometric ratio.

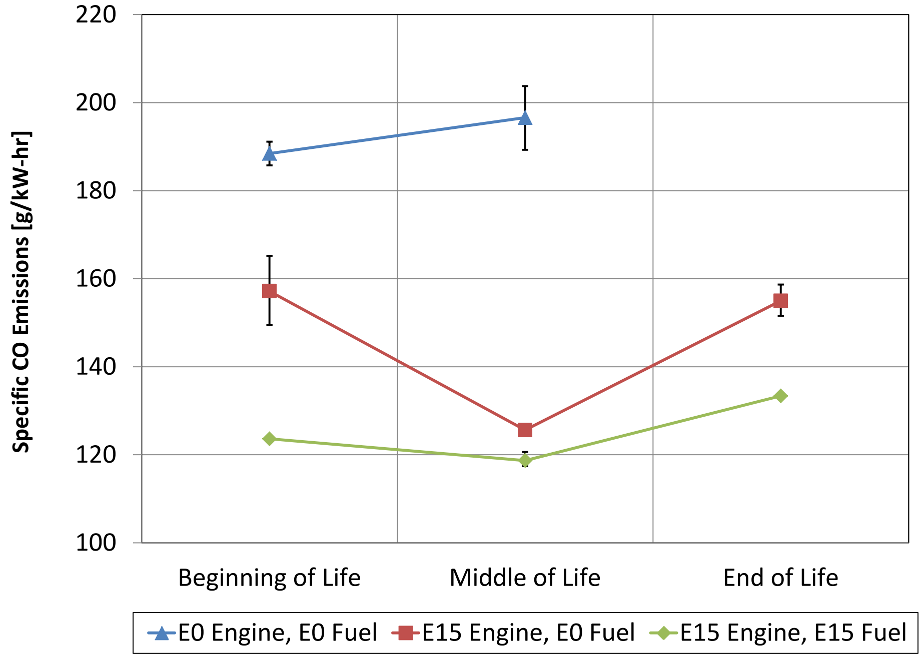

Figure 65: Specific CO emissions: Engine #4

Only a slight difference in hydrocarbon emissions was noted between E0 and E15, as shown in Figure 66 for engine #4.

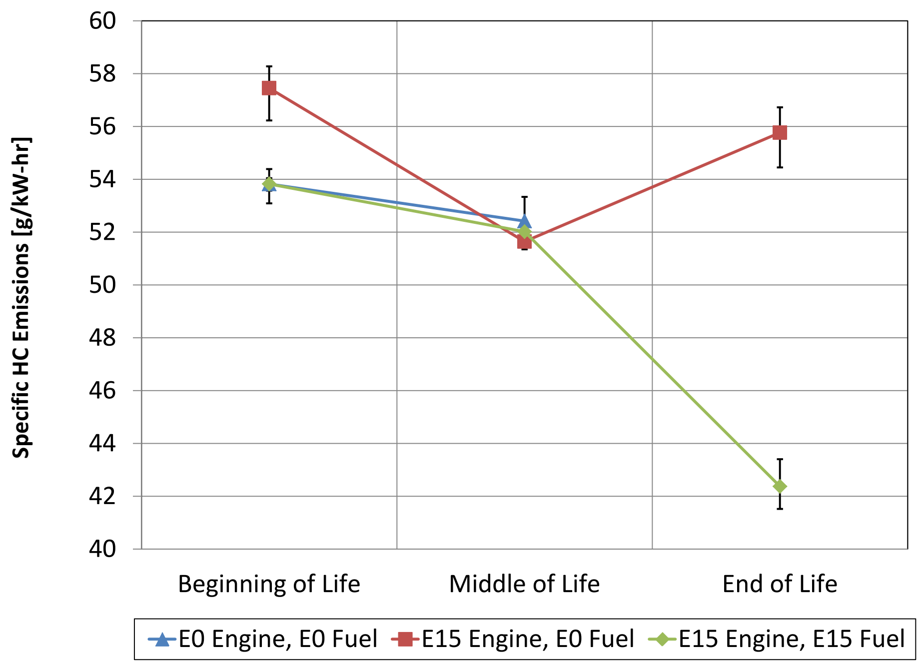

Figure 66: Specific HC emissions: Engine #4

Non-regulated Emissions

1,3-Butadiene emissions, shown in Figure 67, showed an increase at mode 1 and a decrease at mode 2 for engine #4. An increase at mode 3 and decreases at modes 4 and 5 were also noted.

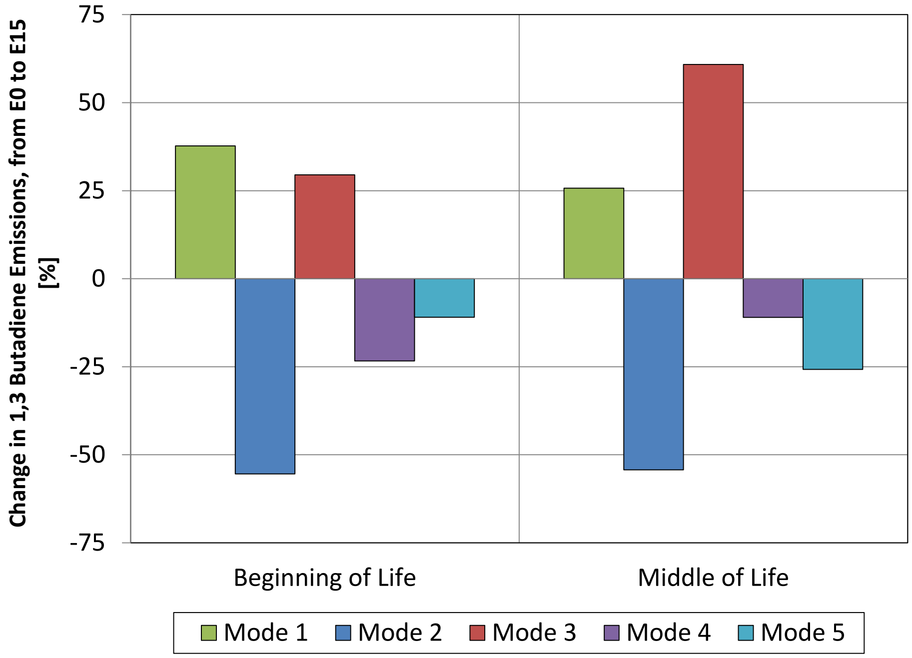

Figure 67: 1,3-Butadiene emissions percent change from E0 to E15: Engine #4

Formaldehyde emissions consistently increased with E15, as shown in Figure 68. The levels more than doubled at mode 1 for this engine, while almost no effect was measured at the lower power modes.

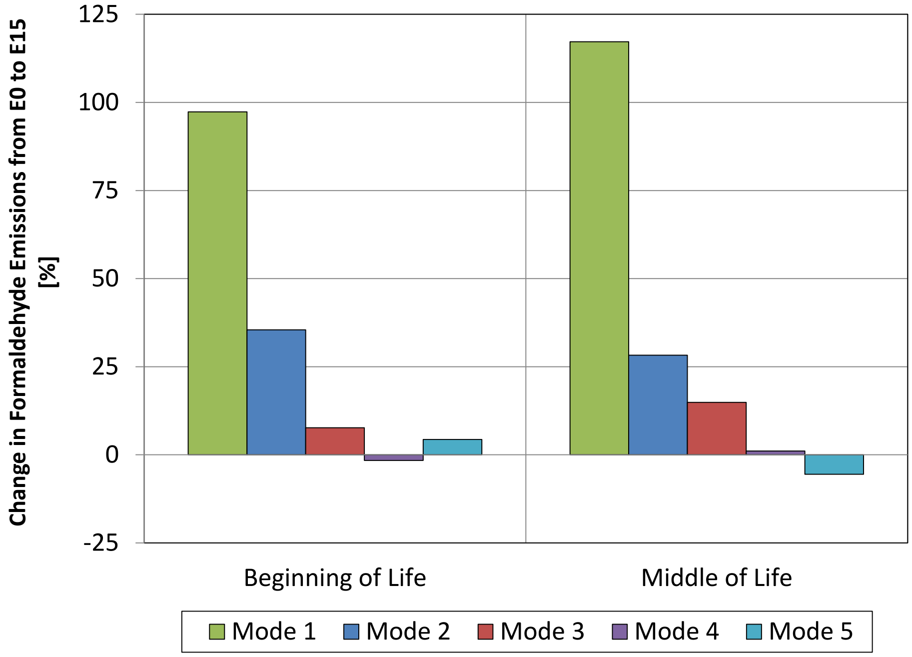

Figure 68: Formaldehyde emissions percent change from E0 to E15: Engine #4

Summary of Results

Objective

E15 can be used in model year 2001 and newer light-duty motor vehicles yet is not approved for use in snowmobiles or off-highway vehicles of any kind. The objective of this study was to evaluate the effects of E15 on current product and legacy snowmobile engines and vehicles that could occur due to misfueling by the vehicle owner. Three test scenarios were conducted to evaluate the impact of E15, including cold-start performance and emissions, on-snow vehicle driveability, and laboratory exhaust emissions over the useful life of the engine.

A limited number of snowmobile engines were evaluated for this test program, and thus the results are not statistically significant. However, the broad range of engine and mixture preparation technology, combined with the various test scenarios provides preliminary information to assess potential issues with E15 use in snowmobiles. Note that all of the engines tested were calibrated on E10 fuel or at a minimum checked for proper operation on E10, prior to production. Legacy vehicles (10 years and older), typically calibrated using E0, would experience greater changes than those noted in this report when operating on E15.

Cold-Start

Cold-start tests were performed at -6.7°C (20°F), -17.8°C (0°F), and -28.9°C (-20°F). The evaluation included time to start or number of pulls to start, engine speed, EGT, and start-up engine emissions concentrations. A series of three evaluations at each temperature for each fuel were conducted over a three-minute interval. The following observations were drawn from the testing:

- Statistically significant differences in starting times were not observed for most vehicles. For those vehicles that experienced an increase in starting time, the higher latent heat of vaporization for ethanol may have reduced fuel evaporation in the combustion chamber, degrading cold-start performance.
- CO emissions decreased 10%–20% for two of the vehicles tested, increased for one of the vehicles by 6% at -6.7°C (20°F) yet reduced 30% at -17.8°C (0°F), and remained the same for the fourth vehicle.
- Of the two engines that were able to be measured for HC emissions, E15 tended to reduce HC concentrations at cold-start by up to 20% for one of the vehicles. HC emissions increased by 8% at -6.7°C (20°F) and decreased by 9% at -17.8°C (0°F) for the other vehicle. HC emissions could not be measured for the two remaining engines because concentrations were outside the analyzer range.
- E15 caused engine idle speed to reduce by 5%–10% on average, for those vehicles that did not control to a target RPM. The lower energy density of E15 may have led to reduced idle speed.

Driveability

Snowmobile driveability was analyzed using a subjective evaluation on a controlled test course, and objective data were collected from each snowmobile during the subjective testing. Additional subjective evaluation was performed on a snowmobile trail, utilizing a regimented operation scheme and a limited number of drivers. The following conclusions were drawn from the testing results:

- The drivers could not easily discern which fuel the snowmobiles were using during the subjective evaluation on the controlled test course.
- E0 and E15 were evaluated similarly by the riders while some machines seemed to run better on E0 than E15 and vice versa according to driver comments.
- For the objective evaluation on the snowmobile trail, the engines had higher cylinder head temperatures and EGTs when running on E15 compared to E0. An average increase in cylinder head temperature of 2%–8% was noted and 2%–11% for the EGT.

Emissions and Durability

The purpose of this test series was to measure the emissions and performance of the snowmobiles, over the useful life of the vehicles (5,000 miles). Measurements included regulated and non-regulated emissions, engine speed, engine power, EGT, muffler exit temperature, and fuel flow. The following conclusions were drawn based on the data collected:

- There were no fuel-related engine failures on E0 or E15.
- Brake power increased an average of 0%–3%, and BSFC decreased an average of 0%–3% at mode 1 (100% of rated speed and torque) due to additional oxygen content in the combustion chamber from E15. However, in general BSFC increased 2% for modes 2, 3, and 4 due to the reduced energy content of E15 compared to E0.
- EGT increased with E15 by approximately 3% at mode 1 and approximately 1.5% at modes 2 through 4 due to a less fuel-rich (still fuel-rich of the stoichiometric ratio) air/fuel mixture compared to E0. Factory-installed EGT sensors existed on two of the four engines tested, which had a limited effect on compensating for the fuel oxygenation. While operating on the E15 durability fuel, one sample experienced damage to the muffler packing material after exposure to higher exhaust temperatures than were seen with the E15 certification fuel or either E0 fuels. The higher exhaust temperatures and damage are assumed to result from a repeatable, secondary combustion event in the exhaust system due to the less fuel-rich operation, differing octane rating, and differing vapor pressure. Engine emissions and power were essentially unchanged but the muffler was considered to have failed.
- Consistent with air/fuel mixtures closer to stoichiometric conditions, CO emissions were reduced on average by 37% with E15 compared to E0. Only minor changes in HC emissions were noted for all engines.
- Non-regulated emissions such as 1,3-butadiene tended to decrease by 20% with the addition of E15. For engine #4, there was an inconsistent trend of increasing and decreasing 1,3-butadiene emissions over the five modes. Formaldehyde emissions increased consistently for E15 fuel by 35%.

Conclusions and Recommendations

Occasional misfueling of snowmobiles with E15 is not likely to cause noticeable or immediate problems for consumers. E15 is not approved for snowmobile use, and issues recorded during this study support the U.S. Environmental Protection Agency's decision to not approve E15 for snowmobiles. These vehicles do not have the same sophisticated control systems as modern automobiles and do not compensate for the additional oxygen content of the E15 fuel. Long-term effects of sustained usage of E15 were not studied as part of this effort. Materials compatibility was not part of the study. One thing to note from this study was increased exhaust temperatures with E15 under certain conditions. This is believed to be primarily due to the engine operating closer to stoichiometric conditions. Increased exhaust temperatures are of concern to manufacturers because some parts in the engine and exhaust could be temperature sensitive.

Recommendations for future research include more studies on long-term durability with an increased sample size that represents a larger percentage of the legacy fleet. In addition, more work with the engine oil to determine if there is any effect and correlation on lubricity and ethanol content should be conducted.

References

1. Integrated Risk Information System. "1,3-Butadiene (CASRN 106-99-0)." U.S. Environmental Protection Agency. http://www.epa.gov/iris/subst/0139.htm
2. U.S. Department of Labor. "1,3-Butadiene." http://www.osha.gov/SLTC/butadiene/
3. U.S. Environmental Protection Agency. "An Introduction to Indoor Air Quality (IAQ): Formaldehyde." http://www.epa.gov/iaq/formaldehyde.html

Appendix A: Fuel Property Testing Results

			1051096	1051097	1051098	1051099	1051100	1051101
	ProjName		ODDB	ODDB	ODDB	ODDB	ODDB	ODDB
	ProjSeq		8277	8278	8279	8280	8281	8282
	SmplCode		E0 Cert	E0/87	E0/91	E15 Cert	E15/87	E15/91
D5191	DVPE	psi	9.02	11.43	12.77	9.55	11.00	12.02
D2699Mdp	RON	inch-lbs	96.7	93.5	97.3	102.4	94.4	98.3
D2700Mdp	MON	Inch-lbs	88.7	83.9	85.9	89.7	84.8	86.4
D4052s	API@60F		60.4	59.8	58.2	57.6	59.9	58.1
	SPGr@60F		0.7372	0.7398	0.7461	0.7482	0.7392	0.7463
	Dens@15C	grams/L	737.0	739.6	745.8	748.0	739.0	746.0
D5291 CH	Carbon	wt%	86.49	86.69	86.82	81.13	80.67	81.2
	Hydrogen	wt%	13.76	13.35	12.95	13.61	13.94	13.27
D5599	DIPEVol	Vol%	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	DIPEWt	Wt%	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	ETBEVol	Vol%	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	ETBEWt	Wt%	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	EtOHVol	Vol%	<0.1	<0.1	0.34	15.50	15.25	15.97
	EtOHWt	Wt%	<0.1	0.10	0.37	16.45	16.38	16.99
	iBAVol	Vol%	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	iBAWt	Wt%	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	iPAVol	Vol%	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	iPAWt	Wt%	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	MeOHVol	Vol%	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	MeOHWt	Wt%	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	MTBEVol	Vol%	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	MTBEWt	Wt%	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	nBAVol	Vol%	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	nBAWt	Wt%	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	nPAVol	Vol%	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	nPAWt	Wt%	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	sBAVol	Vol%	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	sBAWt	Wt%	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	TAMEVol	Vol%	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	TAMEWt	Wt%	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	tBAVol	Vol%	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	tBAWt	Wt%	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	tPAVol	Vol%	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	tPAWt	Wt%	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	TtlVol	Vol%	<0.1	<0.1	0.34	15.50	15.25	15.97
	TtlWt	Wt%	<0.1	<0.1	0.13	5.71	5.69	5.90
D86	IBP	deg F	95.0	76.8	80.4	92.1	89.5	83.2
	Evap_5	degF	107.6	95.9	90.5	112.2	105.7	99.9
	Evap_10	degF	123.0	109.7	105.1	121.6	114.9	112.4
	Evap_15	degF	133.2	120.9	117.6	128.6	121.6	121.0
	Evap_20	degF	143.1	132.5	130.6	134.7	127.2	128.8
	Evap_30	degF	166.7	158.6	164.8	147.1	138.4	143.8
	Evap_40	degF	197.3	186.1	198.2	157.5	147.9	153.6
	Evap_50	degF	220.0	211.2	222.1	164.3	155.6	160.2
	Evap_60	degF	230.7	232.7	239.3	222.2	162.0	176.4
	Evap_70	degF	241.4	253.9	256.8	242.8	231.5	241.9
	Evap_80	degF	261.9	279.6	280.9	266.5	265.5	269.8
	Evap_90	degF	313.7	312.8	312.7	318.4	310.0	307.9
	Evap_95	degF	335.3	340.0	334.9	333.4	348.4	334.1
	FBP	degF	361.8	390.3	375.8	353.4	393.7	381.8
	Recoverd	mL	96.5	97.4	96.1	97.4	97.1	97.0
	Residue	mL	0.7	0.6	1.0	1.0	1.1	0.7
	Loss	mL	2.8	2.0	2.9	1.6	1.8	2.3

Appendix B: Raw Emissions Data

Engine #2, E0 Engine, Indolene Fuel

Engine #2, Beginning of Life, E0, Indolene															Dry					
Mode	Engine Speed	Observed Torque		Observed Power		Fuel Flow	BSFC	Spark Plug Seat	EGT	Mid-Pipe	Muffler Exit	Intake Air	AFR	Lambda	HC	CO	CO2	O2	Specific Emissions (g/kW-hr)	
(-)	(RPM)	(ft-lb)	(Nm)	(HP)	(kW)	(kg/hr)	(g/kW-hr)	(°C)	(°C)	(°C)	(°C)	(°C)	(-)	(-)	(ppmC1)	(%)	(%)	(%)	HC	111.72
1	7001.1	42.20	57.40	56.26	42.08	17.56	418.63	200.3	726.4	712.9	631.2	22.0	12.3	0.8	43308.2	3.52	7.75	5.65	CO	183.59
2	5950.0	20.81	28.30	23.58	17.64	7.96	453.02	162.4	759.5	609.3	473.4	22.6	12.3	0.8	36499.8	3.64	8.54	4.83	CO2	807.11
3	5248.9	14.20	19.31	14.19	10.61	5.40	510.80	148.4	733.9	563.9	372.6	23.4	12.7	0.9	36332.5	2.69	9.08	5.01		
4	4548.7	8.02	10.91	6.95	5.20	2.55	492.19	126.5	593.8	380.3	177.2	22.5	13.6	0.9	27935.1	1.16	10.90	4.33		
5	1477.6	1.07	1.45	0.30	0.23	1.05	n/a	89.8	235.9	109.7	34.3	22.0	10.4	0.7	77875.3	4.98	3.15	10.53		

Engine #2, Middle of Life, E0, Indolene															Dry					
Mode	Engine Speed	Observed Torque		Observed Power		Fuel Flow	BSFC	Spark Plug Seat	EGT	Mid-Pipe	Muffler Exit	Intake Air	AFR	Lambda	HC	CO	CO2	O2	Specific Emissions (g/kW-hr)	
(-)	(RPM)	(ft-lb)	(Nm)	(HP)	(kW)	(kg/hr)	(g/kW-hr)	(°C)	(°C)	(°C)	(°C)	(°C)	(-)	(-)	(ppmC1)	(%)	(%)	(%)	HC	109.32
1	7002.6	41.18	56.00	54.91	41.07	17.46	426.56	181.0	717.3	693.9	611.8	25.6	11.9	0.8	45600.1	4.20	7.58	5.67	CO	200.05
2	5951.9	20.83	28.33	23.61	17.66	7.98	453.30	150.9	761.4	602.1	474.0	25.7	12.0	0.8	37357.1	4.13	8.43	4.81	CO2	768.43
3	5246.7	14.11	19.19	14.09	10.54	4.79	455.46	134.9	735.0	527.1	346.7	25.3	12.9	0.9	33750.3	2.52	9.40	4.66		
4	4549.5	8.04	10.94	6.97	5.21	2.59	498.66	121.3	589.7	375.4	172.7	24.9	13.4	0.9	28977.0	1.65	10.47	4.25		
5	1207.6	0.33	0.45	0.08	0.06	1.01	n/a	84.9	218.2	103.4	34.6	24.3	10.6	0.7	77263.6	4.88	2.29	11.20		

Engine #2, End of Life, E0, Indolene															Dry					
Mode	Engine Speed	Observed Torque		Observed Power		Fuel Flow	BSFC	Spark Plug Seat	EGT	Mid-Pipe	Muffler Exit	Intake Air	AFR	Lambda	HC	CO	CO2	O2	Specific Emissions (g/kW-hr)	
(-)	(RPM)	(ft-lb)	(Nm)	(HP)	(kW)	(kg/hr)	(g/kW-hr)	(°C)	(°C)	(°C)	(°C)	(°C)	(-)	(-)	(ppmC1)	(%)	(%)	(%)	HC	112.79
1	7000.8	41.63	56.61	55.49	41.51	17.80	430.43	179.7	716.3	706.0	634.4	25.9	12.0	0.8	45232.5	4.11	7.53	5.27	CO	211.04
2	5948.6	20.91	28.44	23.68	17.72	8.10	458.92	150.8	761.4	609.3	488.3	25.4	12.1	0.8	37220.9	4.18	8.38	4.30	CO2	781.65
3	5248.7	13.89	18.89	13.88	10.38	5.25	507.66	136.0	738.8	540.0	375.5	24.7	12.7	0.9	35864.1	2.96	8.98	4.66		
4	4548.5	7.94	10.80	6.88	5.14	2.56	498.93	121.0	579.1	374.5	188.0	23.7	13.4	0.9	27715.7	1.72	10.62	3.90		
5	1405.7	0.59	0.80	0.16	0.12	1.11	n/a	85.3	226.3	112.6	34.4	22.9	10.5	0.7	77210.8	4.98	2.80	10.79		

Engine #2, E15 Engine, E15 Fuel

Engine #2, Beginning of Life, E15, E15															DRY					
Mode	Engine Speed	Observed Torque		Observed Power		Fuel Flow	BSFC	Spark Plug Seat	EGT	Mid-Pipe	Muffler Exit	Intake Air	AFR	Lambda	HC	CO	CO2	O2	Specific Emissions (g/kW-hr)	
(-)	(RPM)	(ft-lb)	(Nm)	(HP)	(kW)	(kg/hr)	(g/kW-hr)	(°C)	(°C)	(°C)	(°C)	(°C)	(-)	(-)	(ppmC1)	(%)	(%)	(%)	HC	110.57
1	6999.4	41.54	56.50	55.37	41.41	17.81	431.45	204.8	745.2	747.3	705.3	16.3	12.0	0.9	37291.7	2.87	8.27	5.21	CO	119.33
2	5946.9	21.19	28.82	23.99	17.95	8.42	471.12	160.8	781.8	660.0	557.0	15.7	12.4	0.9	31084.9	2.18	8.95	4.60	CO2	913.51
3	5248.3	14.20	19.31	14.19	10.61	5.45	515.68	139.3	761.8	591.5	460.5	14.9	13.1	0.9	29049.9	0.94	9.63	5.10		
4	4548.4	8.09	11.00	7.00	5.24	3.07	589.25	116.8	642.4	439.6	241.0	14.0	13.2	1.0	29093.5	0.27	10.16	5.85		
5	1519.8	0.28	0.38	0.08	0.06	1.03	n/a	77.3	221.0	107.8	27.3	13.3	9.9	0.7	75661.4	4.36	4.48	10.30		

Engine #2, Middle of Life, E15, E15															DRY					
Mode	Engine Speed	Observed Torque		Observed Power		Fuel Flow	BSFC	Spark Plug Seat	EGT	Mid-Pipe	Muffler Exit	Intake Air	AFR	Lambda	HC	CO	CO2	O2	Specific Emissions (g/kW-hr)	
(-)	(RPM)	(ft-lb)	(Nm)	(HP)	(kW)	(kg/hr)	(g/kW-hr)	(°C)	(°C)	(°C)	(°C)	(°C)	(-)	(-)	(ppmC1)	(%)	(%)	(%)	HC	109.42
1	6995.9	41.20	56.03	54.88	41.05	17.60	430.08	192.0	741.7	730.1	675.8	29.3	11.7	0.8	40910.0	3.54	7.53	5.30	CO	146.56
2	5950.9	20.37	27.71	23.08	17.27	7.89	458.79	157.4	783.0	630.9	520.4	24.0	12.1	0.9	33775.4	2.87	8.65	4.38	CO2	812.85
3	5249.4	14.01	19.05	14.00	10.47	5.09	487.97	142.0	755.7	551.5	410.6	22.4	12.9	0.9	32184.7	1.56	9.76	4.61		
4	4547.6	8.21	11.17	7.11	5.32	2.61	491.64	124.2	585.1	373.7	179.9	20.3	14.1	1.0	27286.0	0.29	11.10	4.77		
5	1459.2	0.27	0.36	0.07	0.05	1.09	n/a	86.1	227.5	103.7	29.4	19.3	11.2	0.7	76701.1	4.84	4.15	10.43		

Engine #2, End of Life, E15, E15															DRY					
Mode	Engine Speed	Observed Torque		Observed Power		Fuel Flow	BSFC	Spark Plug Seat	EGT	Mid-Pipe	Muffler Exit	Intake Air	AFR	Lambda	HC	CO	CO2	O2	Specific Emissions (g/kW-hr)	
(-)	(RPM)	(ft-lb)	(Nm)	(HP)	(kW)	(kg/hr)	(g/kW-hr)	(°C)	(°C)	(°C)	(°C)	(°C)	(-)	(-)	(ppmC1)	(%)	(%)	(%)	HC	105.68
1	7003.0	41.60	56.57	55.46	41.49	17.65	426.93	193.2	730.0	720.2	662.2	27.2	11.7	0.9	43152.3	3.14	7.57	5.96	CO	154.15
2	5947.3	20.97	28.51	23.74	17.76	7.91	446.95	158.2	770.2	601.5	492.4	28.6	11.7	0.8	32523.9	3.42	8.36	4.96	CO2	771.27
3	5248.0	14.09	19.17	14.08	10.53	4.89	465.28	140.8	736.9	521.2	380.1	28.3	12.3	0.9	30848.0	2.08	9.45	4.90		
4	4548.3	8.17	11.11	7.08	5.29	2.40	453.98	123.3	555.7	336.3	188.1	26.4	13.1	1.0	23321.2	0.50	11.05	4.69		
5	1472.0	0.20	0.28	0.06	0.04	1.12	n/a	83.4	209.7	88.0	26.8	23.6	9.8	0.7	72958.9	3.32	2.24	13.69		

Engine #3, E0 Engine, Indolene Fuel

Engine #3, Beginning of Life, E0, Indolene													DRY					
Mode	Engine Speed	Observed Torque		Observed Power		Fuel Flow	BSFC	EGT	Muffler Exit	Intake Air	AFR	Lambda	HC	CO	CO2	O2	Specific Emissions (g/kW-hr)	
(-)	(RPM)	(ft-lb)	(Nm)	(HP)	(kW)	(kg/hr)	(g/kW-hr)	(°C)	(°C)	(°C)	(-)	(-)	(ppmC1)	(%)	(%)	(%)	HC	7.09
1	8752.9	71.85	97.72	119.75	89.57	26.24	293.82	813.8	754.9	21.3	11.9	0.8	3517.6	6.31	10.87	0.38	CO	194.44
2	7432.7	37.02	50.34	52.39	39.18	12.12	309.87	781.6	600.2	24.6	12.3	0.8	5036.7	5.28	11.23	0.82	CO2	676.82
3	6561.7	24.16	32.86	30.19	22.58	7.27	323.11	787.1	512.7	25.4	12.6	0.9	2669.3	4.37	11.92	0.49		
4	5687.9	14.10	19.18	15.28	11.43	4.52	396.69	789.5	425.4	25.6	12.9	0.9	3022.8	3.59	12.51	0.50		
5	1503.3	0.00	0.00	0.00	0.00	1.00	n/a	626.7	77.4	25.7	13.0	0.9	4158.5	3.28	12.40	0.87		

Engine #3, Middle of Life, E0, Indolene													DRY					
Mode	Engine Speed	Observed Torque		Observed Power		Fuel Flow	BSFC	EGT	Muffler Exit	Intake Air	AFR	Lambda	HC	CO	CO2	O2	Specific Emissions (g/kW-hr)	
(-)	(RPM)	(ft-lb)	(Nm)	(HP)	(kW)	(kg/hr)	(g/kW-hr)	(°C)	(°C)	(°C)	(-)	(-)	(ppmC1)	(%)	(%)	(%)	HC	7.20
1	8750.2	72.80	99.01	121.29	90.72	26.26	290.16	813.5	755.3	23.8	11.9	0.8	3672.2	6.19	10.76	0.29	CO	186.96
2	7437.9	36.60	49.78	51.84	38.77	11.94	308.91	782.1	602.4	25.4	12.3	0.8	5023.9	5.15	11.20	0.56	CO2	677.72
3	6563.0	23.92	32.53	29.89	22.36	7.13	320.09	791.7	522.0	24.6	12.8	0.9	2562.1	4.01	12.09	0.24		
4	5687.6	13.74	18.69	14.88	11.13	4.34	391.12	796.9	434.5	25.0	13.1	0.9	3206.8	3.15	12.72	0.29		
5	1500.9	1.45	1.97	0.41	0.31	1.04	n/a	616.5	79.4	26.0	12.7	0.9	4259.3	3.73	11.48	1.31		

Engine #3, End of Life, E0, Indolene													DRY					
Mode	Engine Speed	Observed Torque		Observed Power		Fuel Flow	BSFC	EGT	Muffler Exit	Intake Air	AFR	Lambda	HC	CO	CO2	O2	Specific Emissions (g/kW-hr)	
(-)	(RPM)	(ft-lb)	(Nm)	(HP)	(kW)	(kg/hr)	(g/kW-hr)	(°C)	(°C)	(°C)	(-)	(-)	(ppmC1)	(%)	(%)	(%)	HC	7.34
1	8748.3	71.52	97.27	119.13	89.11	25.63	288.24	814.3	754.5	22.7	12.0	0.8	3949.0	6.03	10.83	0.20	CO	186.74
2	7437.7	36.92	50.22	52.29	39.11	11.81	302.90	779.4	603.9	24.5	12.2	0.8	4941.6	5.32	11.07	0.37	CO2	663.44
3	6562.3	23.95	32.57	29.92	22.38	7.04	315.49	786.8	522.2	24.9	12.7	0.9	2760.9	4.28	11.83	0.11		
4	5688.6	13.76	18.72	14.91	11.15	4.25	382.73	799.3	438.0	24.3	13.1	0.9	3413.8	3.18	12.64	0.15		
5	1504.4	1.95	2.66	0.56	0.42	1.02	n/a	608.9	89.4	23.2	12.7	0.9	4634.4	3.80	11.65	0.85		

Engine #3, E15 Engine, E15 Fuel

Engine #3, Beginning of Life, E15, E15													DRY					
Mode	Engine Speed	Observed Torque		Observed Power		Fuel Flow	BSFC	EGT	Muffler Exit	Intake Air	AFR	Lambda	HC	CO	CO2	O2	Specific Emissions (g/kW-hr)	
(-)	(RPM)	(ft-lb)	(Nm)	(HP)	(kW)	(kg/hr)	(g/kW-hr)	(°C)	(°C)	(°C)	(-)	(-)	(ppmC1)	(%)	(%)	(%)	HC	5.52
1	8751.2	72.64	98.79	121.04	90.54	25.95	287.44	834.4	774.1	23.7	12.2	0.9	2775.1	3.82	12.41	0.15	CO	99.33
2	7437.6	36.99	50.31	52.39	39.18	11.89	304.48	799.0	618.2	21.7	12.6	0.9	4016.9	2.83	12.71	0.51	CO2	761.76
3	6562.6	23.69	32.21	29.60	22.14	7.20	326.39	816.9	545.4	22.4	13.0	0.9	1536.4	1.89	13.66	0.13		
4	5686.8	13.83	18.81	14.98	11.20	4.50	402.67	831.8	464.2	22.4	13.3	1.0	1812.3	0.96	14.32	0.16		
5	1500.6	1.55	2.10	0.44	0.33	1.14	n/a	678.2	92.6	21.1	13.1	1.0	2531.8	1.36	13.50	0.89		

Engine #3, Middle of Life, E15, E15													DRY				Specific Emissions (g/kW-hr)	
Mode	Engine Speed	Observed Torque		Observed Power		Fuel Flow	BSFC	EGT	Muffler Exit	Intake Air	AFR	Lambda	HC	CO	CO2	O2		
(-)	(RPM)	(ft-lb)	(Nm)	(HP)	(kW)	(kg/hr)	(g/kW-hr)	(°C)	(°C)	(°C)	(-)	(-)	(ppmC1)	(%)	(%)	(%)	HC	5.54
1	8749.2	73.65	100.16	122.69	91.77	25.84	282.24	836.8	778.1	24.7	12.3	0.9	2918.2	3.52	12.44	0.48	CO	96.50
2	7438.1	37.33	50.77	52.87	39.54	11.77	298.65	799.6	618.4	24.8	12.5	0.9	3905.6	2.84	12.60	0.79	CO2	749.25
3	6562.5	23.92	32.54	29.89	22.36	7.20	323.13	820.4	548.2	23.7	12.9	0.9	1685.1	2.07	13.37	0.41		
4	5688.0	13.90	18.91	15.06	11.26	4.41	392.63	844.9	471.8	23.2	13.3	1.0	1821.8	0.94	14.20	0.46		
5	1501.0	2.03	2.76	0.58	0.43	1.15	n/a	691.7	104.8	22.4	13.0	0.9	2505.5	1.47	13.05	1.51		

Engine #3, End of Life, E15, E15													DRY				Specific Emissions (g/kW-hr)	
Mode	Engine Speed	Observed Torque		Observed Power		Fuel Flow	BSFC	EGT	Muffler Exit	Intake Air	AFR	Lambda	HC	CO	CO2	O2		
(-)	(RPM)	(ft-lb)	(Nm)	(HP)	(kW)	(kg/hr)	(g/kW-hr)	(°C)	(°C)	(°C)	(-)	(-)	(ppmC1)	(%)	(%)	(%)	HC	5.45
1	8754.3	73.95	100.57	123.26	92.20	26.24	285.43	839.6	777.8	23.5	12.3	0.9	2972.2	3.43	12.42	0.45	CO	93.04
2	7438.5	36.80	50.05	52.12	38.98	11.83	304.38	804.1	614.6	24.4	12.6	0.9	3655.5	2.75	12.64	0.73	CO2	770.85
3	6562.0	23.59	32.08	29.47	22.05	7.24	329.55	822.3	543.1	24.2	13.0	0.9	1569.2	1.80	13.56	0.39		
4	5689.5	13.77	18.73	14.92	11.16	4.48	402.67	846.6	466.0	24.4	13.4	1.0	1657.9	0.67	14.39	0.46		
5	1506.8	0.84	1.14	0.24	0.18	1.12	n/a	685.6	101.3	23.7	13.0	0.9	2825.6	1.42	13.33	1.07		

Engine #4, E0 Engine, Indolene Fuel

Engine #4, Beginning of Life, E0, Indolene															DRY				Specific Emissions (g/kW-hr)	
Mode	Engine Speed	Observed Torque		Observed Power		Fuel Flow	BSFC	Spark Plug Seat	EGT	Mid-Pipe	Muffler Exit	Intake Air	AFR	Lambda	HC	CO	CO2	O2		
(-)	(RPM)	(ft-lb)	(Nm)	(HP)	(kW)	(kg/hr)	(g/kW-hr)	(°C)	(°C)	(°C)	(°C)	(°C)	(-)	(-)	(ppmC1)	(%)	(%)	(%)	HC	53.83
1	8150.9	72.76	98.65	112.92	84.20	36.15	429.37	72.6	598.6	679.3	624.9	-1.5	10.6	0.7	42935.0	7.04	6.22	5.32	CO	188.45
2	6931.1	37.70	51.11	49.75	37.10	11.75	316.86	65.0	729.1	665.5	522.7	-1.1	12.6	0.9	18232.9	3.42	9.49	3.86	CO2	633.27
3	6116.2	24.76	33.58	28.84	21.51	5.93	275.59	60.7	621.1	548.2	387.5	-1.4	13.4	0.9	4581.5	1.36	9.86	5.80		
4	5294.6	14.30	19.38	14.41	10.75	3.23	301.05	57.4	573.4	434.6	255.2	-2.5	13.8	0.9	4048.2	0.55	10.74	5.43		
5	1200.0	-0.08	-0.11	-0.02	-0.01	0.43	n/a	48.0	163.4	119.0	101.2	-2.2	12.9	0.9	11121.4	0.19	3.37	16.03		

Engine #4, Middle of Life, E0, Indolene															DRY				Specific Emissions (g/kW-hr)	
Mode	Engine Speed	Observed Torque		Observed Power		Fuel Flow	BSFC	Spark Plug Seat	EGT	Mid-Pipe	Muffler Exit	Intake Air	AFR	Lambda	HC	CO	CO2	O2		
(-)	(RPM)	(ft-lb)	(Nm)	(HP)	(kW)	(kg/hr)	(g/kW-hr)	(°C)	(°C)	(°C)	(°C)	(°C)	(-)	(-)	(ppmC1)	(%)	(%)	(%)	HC	52.42
1	8150.6	73.86	100.15	114.63	85.48	36.31	424.76	69.0	595.7	668.3	620.6	-2.3	10.5	0.7	43048.7	7.35	6.06	5.38	CO	196.60
2	6931.3	37.82	51.28	49.92	37.22	11.59	311.33	66.7	726.1	660.9	537.1	-2.7	12.4	0.8	18154.8	3.79	9.60	3.84	CO2	609.43
3	6120.6	24.31	32.95	28.33	21.12	5.67	268.32	63.9	642.4	547.0	397.1	-1.4	13.3	0.9	3666.5	1.51	9.98	5.61		
4	5301.2	13.99	18.97	14.12	10.53	3.10	294.70	58.9	583.8	425.4	266.2	-0.9	13.7	0.9	3897.1	0.59	10.82	5.57		
5	1200.1	0.91	1.23	0.21	0.15	0.47	n/a	49.3	175.9	136.3	101.5	-0.7	12.6	0.9	10362.0	0.23	3.70	15.73		

Engine #4, E15 Engine, E15 Fuel

Engine #4, Beginning of Life, E15, E15															DRY				Specific Emissions (g/kW-hr)	
Mode	Engine Speed	Observed Torque		Observed Power		Fuel Flow	BSFC	Spark Plug Seat	EGT	Mid-Pipe	Muffler Exit	Intake Air	AFR	Lambda	HC	CO	CO2	O2		
(-)	(RPM)	(ft-lb)	(Nm)	(HP)	(kW)	(kg/hr)	(g/kW-hr)	(°C)	(°C)	(°C)	(°C)	(°C)	(-)	(-)	(ppmC1)	(%)	(%)	(%)	HC	53.82
1	8151.0	75.04	101.74	116.46	86.84	35.98	414.32	80.4	628.6	704.5	668.9	0.9	10.8	0.8	38552.7	5.19	7.42	5.01	CO	123.62
2	6931.3	37.66	51.06	49.70	37.06	12.02	324.43	71.1	735.0	659.7	536.1	-2.4	12.6	0.9	17816.4	1.82	10.45	4.04	CO2	689.95
3	6115.9	24.43	33.13	28.45	21.22	6.15	289.85	66.4	602.3	520.2	380.8	0.1	12.9	0.9	6464.8	0.52	9.99	6.51		
4	5300.6	14.21	19.27	14.35	10.70	3.49	326.19	61.7	536.2	406.0	258.4	-0.6	12.9	0.9	4696.4	0.44	9.91	6.87		
5	1200.0	0.22	0.30	0.05	0.04	0.45	n/a	52.1	146.5	92.9	59.0	-0.9	12.0	0.9	10536.7	0.16	3.09	16.48		

Engine #4, Middle of Life, E15, E15															DRY					
Mode	Engine Speed	Observed Torque		Observed Power		Fuel Flow	BSFC	Spark Plug Seat	EGT	Mid-Pipe	Muffler Exit	Intake Air	AFR	Lambda	HC	CO	CO2	O2	Specific Emissions (g/kW-hr)	
(-)	(RPM)	(ft-lb)	(Nm)	(HP)	(kW)	(kg/hr)	(g/kW-hr)	(°C)	(°C)	(°C)	(°C)	(°C)	(-)	(-)	(ppmC1)	(%)	(%)	(%)	HC	52.02
1	8150.8	74.63	101.19	115.82	86.37	35.50	411.02	80.8	618.4	715.5	672.8	0.0	10.9	0.8	38625.3	4.98	7.57	4.94	CO	118.70
2	6930.7	38.42	52.09	50.70	37.81	11.96	316.32	73.0	721.6	662.0	546.9	-3.1	12.5	0.9	17089.8	1.91	10.51	3.97	CO2	681.65
3	6116.2	24.32	32.98	28.32	21.12	5.94	281.41	66.1	605.0	518.4	383.2	-0.5	12.9	0.9	5948.8	0.44	9.88	6.85		
4	5300.9	14.35	19.45	14.48	10.80	3.40	315.04	61.8	544.5	402.5	251.4	-0.9	13.0	0.9	4317.8	0.45	10.24	6.33		
5	1159.3	0.46	0.63	0.10	0.08	0.40	n/a	51.5	131.1	88.3	48.5	0.3	12.0	0.9	8672.7	0.20	3.08	16.48		

Engine #4, End of Life, E15, E15															DRY					
Mode	Engine Speed	Observed Torque		Observed Power		Fuel Flow	BSFC	Spark Plug Seat	EGT	Mid-Pipe	Muffler Exit	Intake Air	AFR	Lambda	HC	CO	CO2	O2	Specific Emissions (g/kW-hr)	
(-)	(RPM)	(ft-lb)	(Nm)	(HP)	(kW)	(kg/hr)	(g/kW-hr)	(°C)	(°C)	(°C)	(°C)	(°C)	(-)	(-)	(ppmC1)	(%)	(%)	(%)	HC	42.37
1	8149.9	74.47	100.96	115.55	86.17	37.47	434.90	83.1	620.8	732.5	729.2	3.2	10.9	0.8	28901.7	5.31	7.72	4.35	CO	133.37
2	6931.1	37.80	51.26	49.89	37.20	12.46	335.03	76.7	721.7	693.8	598.6	-2.8	12.7	0.9	7313.7	1.81	10.95	3.41	CO2	771.92
3	6116.3	24.04	32.59	27.99	20.87	6.76	323.95	68.1	580.8	511.1	385.6	1.5	12.9	0.9	8154.2	0.30	8.90	8.27		
4	5300.5	14.09	19.10	14.22	10.60	3.83	361.24	63.1	519.4	402.9	265.0	2.4	12.8	0.9	6631.7	0.27	8.63	8.78		
5	1199.9	0.12	0.17	0.03	0.02	0.49	n/a	52.6	134.5	99.6	78.2	2.0	11.8	0.9	10790.3	0.17	3.19	16.43		