CRC Project CM-136-09-1B

INTERMEDIATE-LEVEL ETHANOL BLENDS ENGINE DURABILITY STUDY

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COORDINATING RESEARCH COUNCIL, INC.

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Final Report

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Intermediate-Level Ethanol Blends

Engine Durability Study

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Acronyms and Abbreviations

ALDL	Assembly Line Diagnostic Link
ASTM	ASTM International Standards organization www.astm.org
CO	Carbon Monoxide
CRC	Coordinating Research Council
DOE	United States Department of Energy
DTC	Diagnostic Trouble Code
E0	Gasoline fuel with 0 volume percent ethanol
E10	Gasoline fuel with 10 volume percent ethanol
E15	Gasoline fuel with 15 volume percent ethanol
E20	Gasoline fuel with 20 volume percent ethanol
E85	Ethanol fuel blend with 51 to 83 volume percent ethanol designed for flexible-fuel vehicles
ECU	Engine Control Unit
EOT	End of Test
FEV	www.fev.com
FFV	Flexible-Fuel Vehicle
FTI	Fluid Technologies, Inc.
FTP75	Federal Test Procedure 75
HC	Hydrocarbon
Hz	Hertz, periodic interval of one second
LEV	Low Emission Vehicle
MAP	Manifold Air Pressure
NLEV	National Low Emissions Vehicle
NMOG	Non-Methane Organic Gases
Non-FFV	Non-Flexible-Fuel Vehicle
NO_x	Nitrogen Oxide
O_2	Oxygen
OBD	On-Board Diagnostics
OEM	Original Equipment Manufacturer
PBOB	Premium Blend for Oxygenate Blending
PCV	Positive Crankcase Ventilation
RON	Research Octane Number
RPM	Revolutions per Minute
SOT	Start of Test
THC	Total Hydrocarbon
U.S. EPA	United States Environmental Protection Agency
WOT	Wide Open Throttle

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EXECUTIVE SUMMARY

The goal of the Coordinating Research Council (CRC) Project CM-136-09-1B, "Intermediate-Level Ethanol Blends – Engine Durability Study," was to investigate the effects of two intermediate-level ethanol blends on several models of current, on-road, non-Flexible-Fuel Vehicles (non-FFVs).

The motivation to conduct the study originated in response to the 2007 Energy Independence and Security Act which mandates 36 billion gallons of renewable fuels be used by 2022. Since the passage of this Act, ethanol production has risen dramatically. This mandate, in addition to marginal implementation of E85, has produced interest in increasing the percentage of ethanol that can be used in motor gasoline for conventional-fuel vehicles beyond the current limit of 10 volume percent (E10). Decisions in 2010 and 2011 by the U.S. EPA to allow up to 15 volume percent ethanol in motor gasoline for 2001 and later model passenger car and light-duty trucks has increased the importance of this study.

The objective of this durability study was to identify possible engine component wear caused by additional ethanol content in the fuel using an engine test cycle employed by an original equipment manufacturer (OEM) member of CRC to test for engine durability. The engines were tested with E20, and then, as appropriate, E15 and E0, for 500 test cycles, corresponding to 500 hours, with monitoring at regular intervals. To test the effect of ethanol on in-use engine durability, vehicles with engines of various valvetrain types were chosen. FEV and the CRC project panel agreed to test eight vehicle types which represented a selection of various valvetrain type engines in popular light-duty automotive applications in non-FFVs from model year 2001 through 2009.

The different types of vehicles of various engine configurations, sizes, valvetrain types and mileage were tested with E20, then on E15 if they failed on E20, and then on E0 if they failed on E15. Vehicles which passed the test on E20 were not retested on lower ethanol blends. "Pass" and "Fail" criteria for five different categories were determined at the beginning of the program and were assessed on each engine after completion of the durability test. These five categories are: emissions during the FTP75 test, diagnostic trouble codes (DTCs), valve clearance, compression and leakage. An engine was deemed to have failed the test if it failed in at least one of these five categories. Details for the specifications of the pass/fail criteria can be found in Section D.3.8 of this report.

Each chosen engine was tested in duplicate on each fuel. Eight different vehicle types (two samples of each type) were tested with E20. Results of the E20 testing are as follows: three vehicle types (five vehicle samples) failed the durability testing on E20; three other vehicle types (four vehicle samples) did not pass all specified criteria after the 500 hour durability test, but were waived after a detailed review of the data with the respective OEM contact. These vehicles are shown as waived in the table in Figure 1. Further details as to why the waiver was received can be found in Section E of this report.

When an engine failed the durability test on E20, another set of duplicate vehicles with the same engine type was procured from the used car market and scheduled for durability testing with E15. When an engine failed on E15, then another set of duplicate vehicles with the same engine type was procured from the used car market and scheduled for durability testing with E0. In total, 28 engines from eight different vehicle types were tested during this study (16 on E20, 6 on E15 and 6 on E0).

The failed and waived engines in the overview table in Figure 1 have an associated letter or letters in parentheses. The key to explain the meaning of these letters are as follows:

- E = Emissions during EOT FTP75 testing
- D = Diagnostic Trouble Code (DTC) detected at EOT
- V = Valve clearance measurement on at least one valve out of OEM specification at EOT
- C = Compression measurement on at least one cylinder out of OEM specification at EOT
- L = Leakage measurement on at least one cylinder above 10% at EOT

Figure 1: Overall Results

Sample / Vehicle	E20		E15		E0	
	Sample A	Sample B	Sample C	Sample D	Sample E	Sample F
Vehicle 1	Pass	Pass				
Vehicle 2	Fail (L)	Fail (L)	Fail (E)	Fail (L)	Pass	Pass
Vehicle 3	Pass	Fail (V,L)	Fail (L)	Pass	Pass	Pass
Vehicle 4	Waived (L)	Pass				
Vehicle 5	Waived (E,D)	Pass				
Vehicle 6	Waived (L)	Waived (L)				
Vehicle 7	Pass	Pass				
Vehicle 8	Fail (E,C,L)	Fail (C,L)	Fail (E,L)	Fail (C,L)	Fail (E,C,L)	Fail (E,L)

Waived = Vehicle did not pass all specified criteria after the 500 hour durability test, but was not retested on E15 or E0 after a detailed review of the data with the respective OEM contact and concurrence by CRC.

The three vehicle types which failed on E20 were then tested with E15. All three vehicle types also failed this testing. The vehicles which failed the E15 durability test were then tested with E0 to ensure that these failures were not associated with any factors other than the concentration of ethanol in the fuel. In summary, 12 out of 28 tested engines were deemed to have failed the prescribed durability test.

Different types of failures were observed throughout the testing. The failed engines were sent to the respective OEM for a detailed teardown analysis. FEV was not involved in the teardown activities. Any statements with regard to the results of the engine teardown analyses were provided to FEV in writing by the respective OEM technical contact to be included in this report.

The test results and exhibited failures of the various vehicles can be summarized as follows:

<u>Vehicle 1:</u> (Both samples passed E20)

No issues were detected with either of the Vehicle 1 engines tested on E20. No further testing on E15 or E0 was conducted.

<u>Vehicle 2: (Both samples failed E20, E15)</u>

Both Vehicle 2 engines tested on E20 failed the leakage criterion. Both vehicle 2 engines tested also failed on E15, one of them because of increased emissions at EOT and the other one failed the leakage criterion. Both Vehicle 2 engines tested on E0 passed all criteria. The cylinder head teardown analysis conducted by the OEM on all failed engines of Vehicle 2 revealed uneven wear and pitting of the intake valve seats as the root cause for the increased leakage.

<u>Vehicle 3: (Samples showed mixed results on E20 and E15, both passed E0)</u>

Testing Vehicle 3 engines showed mixed results. One out of two engines tested on E20 failed the test and one out of two engines tested on E15 failed the test. Both Vehicle 3 engines tested on E0 passed all criteria. The teardown analysis conducted by the OEM on both failed Vehicle 3 engines revealed widened exhaust valve seats on all cylinders and wear on several intake valve seats. The engine which failed on E20 also showed valve lash degradation.

The OEM examined internal historical production records and these revealed that there had been changes in the intake valve seat material used for this engine following its initial production years. The failed engines were equipped with lower grade material valve seats which were not considered robust enough to ethanol blends higher than E10. The OEM technical contact commented that the test results of this study have validated this position. Further details about the OEM commentary can be found in Section E.4.7 of this report. It should also be noted that the OEM changed to the improved valve seat material in later model years of the investigated engine.

Vehicle 4: (One sample passed, the other was waived on E20)

Mechanically there were no issues detected with either of the Vehicle 4 engines tested on E20 with the exception of a leakage measurement slightly above 10% on only one cylinder of one engine (the second engine passed all criteria including leakage). An engine teardown analysis conducted by the OEM revealed no issues with the engine with the slightly increased leakage.

Both engines showed elevated emissions at EOT during the simulated engine dynamometer FTP75 test. The catalyst of Sample A engine was sent to the OEM who installed it on another vehicle and tested that vehicle on a vehicle chassis emission roll. A FTP75 test was conducted with the vehicle with the reinstalled catalyst, and it passed all emission constituents.

Sample B showed a similar elevated emission behavior. For Sample B the OEM reinstalled the engine and catalyst into the vehicle and conducted a vehicle chassis roll FTP75 test. The vehicle passed the emission test for all exhaust emission constituents.

Upon review of the results and recommendation by the OEM technical contact, the CRC group waived this engine from further testing.

Vehicle 5: (One sample passed, the other was waived on E20)

One Vehicle 5 engine passed the testing on E20 for all criteria. The other engine passed all criteria in the engine dynamometer test cell, but failed the EOT vehicle emission test. In addition, a diagnostic fault code, P0420, was set when the engine was reinstalled in the vehicle. The fault code was not present during engine dynamometer testing. The P0420 code indicates low catalyst efficiency; the service manual instructs replacement of the catalyst. The vehicle completed the EOT chassis roll FTP75 with this code active; the catalyst was not replaced and the vehicle failed the EOT FTP75 vehicle emission test.

The emission results were discussed with the OEM. The OEM indicated known issues with vehicle 5 catalysts; thus, they are offering extended warranty for catalyst replacement. It was decided not to retest this vehicle type on E15 and E0 because this failure was deemed not to be caused by the increased ethanol content. Another factor in this decision was that the second vehicle sample of this vehicle type passed all criteria. No teardown analysis was conducted by the OEM as the measured valve clearance, compression and leakage on both tested engines were all within specifications.

Vehicle 6: (Both samples waived on E20)

Both Vehicle 6 engines tested on E20 failed the leakage criterion by a small margin, but passed all other criteria including EOT vehicle emission tests. The OEM completed cylinder head teardowns on both engines. It was noted that the valves showed carbon impregnation, but overall the valve seats did not show abnormal deposits or wear and were acceptable to the OEM. Upon recommendation by the OEM both engines were waived from further testing.

Vehicle 7: (Both samples passed on E20)
No issues were detected with either Vehicle 7 engine tested on E20. No further testing on E15 or E0 was conducted.

Vehicle 8: (All engines failed on E20, E15 and E0)

All six Vehicle 8 engines tested on E20, E15 and E0 failed the test. All failed the leakage criterion. Both engines tested on E20, one engine tested on E15 and one engine tested on E0 failed the compression criterion. One engine tested on E20, one engine tested on E15 and both engines tested on E0 failed the emission criterion. The second E20 engine completed the 500 hour test with failed leakage and failed compression criteria, but was not reinstalled into the vehicle as it experienced a catastrophic failure during an EOT WOT test which was conducted in the engine dynamometer test cell upon request by the respective OEM technical contact.

Teardown analyses conducted by the OEM on the failed engines revealed heavier pitting on the exhaust valve seats of the engines run on E20 and E15. Moderate wear was noted on intake valve seats and normal wear was noted on intake and exhaust valves. No issues were noted on engine bearings, pistons and piston rings. The teardown analyses conducted by the OEM revealed that the engines which ran on E20 and E15 showed higher wear and heavier pitting of the exhaust valves compared to the engines which ran on E0. However, pitting on the E0 engines was still severe enough that they also failed the leakage criterion.

Upon examination of the test results and engine design, the OEM determined that the valvetrain design inhibited valve rotation at lower engine speeds and that the limited amount of time spent over 3500 rpm in the test combined with the valve spring design led to abnormally high valve seat wear for all of the fuel combinations due to inhibited valve rotation. Unlike other engines in the test, this particular engine's spring design is more sensitive to the rpm threshold and would be better suited for a test with intervals at higher speeds. In retrospect, it would be expected for the engine to experience abnormal valve seat wear during this test cycle, regardless of fuel composition. Due to this reason, Vehicle 8 is shown in a different color in the overview results (see Figure 1).

It should be noted that the engine which experienced the catastrophic failure had severe damage in one cylinder, but the teardown analysis results for that cylinder were not considered in the final analysis for this report as the EOT WOT test was not part of this CRC Intermediate-Level Ethanol Blend Engine Durability Study and was only conducted upon a special request by the respective OEM.

Conclusions

After completion of all testing and detailed review of the experienced failure modes, the following conclusions can be drawn:

- Out of eight different tested engine types, one had a design that was (in retrospect) inappropriate for the test cycle, two failed on E20 and E15, and five passed on E20 and by assumption E15 and E0 (see Figure 1).
- Out of the two failed tested engine types, both successfully completed the reference testing on E0.
- There is an 11% chance that all three E15 failures (two with one vehicle type and one with another) would have occurred if failure were independent of ethanol. The results for E20 are the same. Combining the E15 results with the E20 results, there is a 7% chance that all six failures (two E15 and two E20 with one vehicle type and one E15 and one E20 with another) would have occurred with ethanol containing fuels if failure were independent of ethanol.
- For the failed engine which also failed on E0 reference fuel, the failures can not be directly linked to the ethanol content. The design of the engine interacting with the test cycle is the primary reason cited by the OEM maker for the observed failures.
- The observed failures do not show that specific valvetrain types are more or less sensitive to ethanol content.
- The majority of the failures can be linked to issues with valve seats, either related to material or wear/deformation.

The study has shown that two popular gasoline engines used in light-duty automotive applications of vehicles from model years 2001 through 2009 failed with mechanical damage when operated on intermediate-level ethanol blends (E15 and E20).

A. Introduction

The primary goal of Coordinating Research Council (CRC) Project CM-136-09-1B was to evaluate engines from in-use vehicles which are potentially sensitive to gasoline fuels containing ethanol at concentrations greater than 10 volume percent. When this program began, 10 volume percent was the maximum limit allowed by the US Environmental Protection Agency (EPA) for ethanol blended in unrestricted use commercial motor gasoline and is the maximum amount typically listed as being recommended in the owner's manuals for conventional fuel vehicles (non-Flexible-Fuel Vehicles or non-FFVs). FEV was chosen to assist CRC in obtaining and testing diversified vehicle types to evaluate the maximum number of potential failure modes. The vehicles were chosen based on CRC guidelines and tested to evaluate their sensitivities to different ethanol blends; namely, E20 and E15, as compared to E0. This study investigates in detail the effects of two intermediate-level ethanol blends, E20 and E15 and gasoline without ethanol (E0), on current on-road, non-FFV engines.

B. Background

B.1 Origination of Durability Study on Intermediate-Level Ethanol Blends

The motivation to conduct the study originated in response to the US Energy Independence and Security Act, passed in December 2007, which mandates 36 billion gallons of renewable-fuels be used by 2022. As a result of the Act, the mandated volume usage of ethanol is in the near future likely to exceed the amount that can be utilized at ten percent blending with gasoline. Certain stakeholders have been looking for an outlet for these increasing ethanol volumes beyond E85 Flexible-Vehicle fuel. E20[1] and E15[2,3] have been proposed as alternative blends that would enable complying with the volumetric requirements of the Act. A 2011 decision by the US EPA to allow up to 15 volume percent ethanol in motor gasoline for 2001 and later model passenger cars and light-duty trucks has increased the importance of this study.

This study reviews the effects of E15 and E20 ethanol blends on light-duty automotive engines not designed for their use.

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1 Minnesota Statutes on oxygenated gasoline; 239.791. https://www.revisor.mn.gov/statutes/?id=239.791.

2 Application for a Waiver Pursuant to Section 211(f) of the Clean Air Act for E-15, http://www.growthenergy.org/images/reports/WaiverApplication09.pdf.

3 ENVIRONMENTAL PROTECTION AGENCY; 74 FR 18228-18230.

Analogous studies on the effects of E15 have been funded by the Department of Energy (DOE) on marine outboard engines[4] and on marine inboard/outboard engines[5] and whole vehicles undergoing catalyst testing.[6] DOE itself has conducted tests on ground supported and handheld outdoor power equipment[7].

B.2 Ethanol Fuel Effects on Engine Durability

Gasoline blended with ethanol at 10 volume percent or less has been widely used for a number of years. The reasons for blending ethanol into gasoline have varied over time. For example, the high octane number of ethanol has encouraged its use as an octane number booster. Another reason to use ethanol is the enleaning effect of the oxygen contained within the ethanol which results in a leaner air-fuel mixture. This enleanment can reduce vehicle carbon monoxide production under certain conditions. Ethanol can also be used as a gasoline extender. Although ethanol is known for its solvency and corrosive nature, material changes have made current engines and vehicles robust to ethanol concentrations in gasoline of up to 10 volume percent.

The engine durability testing in this CRC study addresses possible concerns due to the use of gasoline blends containing 15 or 20 volume percent ethanol.

B.2.1 Valve and Valve Seat Wear

Engine valve and valve seat wear were two main areas of concern which prompted initiation of the engine durability study. As a gasoline blend component, ethanol acts as a diluent that increases the solvency of the mixture for polar species. In addition, both ethanol and its partial combustion products can promote corrosion.

Three main engine wear mechanisms are impacted by ethanol fuels: abrasive wear, adhesive wear and corrosion. Figure B.2.1.1 below summarizes the paths by which the presence of ethanol in gasoline contributes to these three different mechanisms.

These wear mechanisms can lead to engine valve seat recession. Eventually, the valve will not completely seal and will produce a higher than acceptable leakage. Severe

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4 High Ethanol Fuel Endurance: A Study of the Effects of Running Gasoline with 15% Ethanol Concentration in Current Production Outboard Four-Stroke Engines and Conventional Two-Stroke Outboard Marine Engines; David Hilbert. http://www.nrel.gov/docs/fy12osti/52909.pdf.

5 Volvo Penta 4.3 GL E15 Emissions and Durability Test; George Zoubul, Mel Cahoon, and Richard Kolb. http://www.nrel.gov/docs/fy12osti/52577.pdf.

6 Powertrain Component Inspection from Mid-Level Blends Vehicle Aging Study, http://info.ornl.gov/sites/publications/files/Pub28733.pdf. EPA Docket #EPA–HQ–OAR–2009–0211-14016.

7 Effects of Intermediate Ethanol Blends on Legacy Vehicles and Small Non-Road Engines: Report 1-Updated, Knoll et al, 2009; http://www.nrel.gov/docs/fy09osti/43543.pdf.

recession will result in the valve lifter riding on the cam lobe base circle and preventing the valve from closing completely. Alternatively, uneven wear or corrosion around the valve or valve seat perimeter can also result in poor sealing and leakage. High leakage results in loss of compression, cylinder misfires, and even catalyst damage.

Figure B.2.1.1: Ethanol Fuel Wear Mechanisms

Abrasive Wear	Adhesive Wear	Corrosion
Valve Impact Load	Valve Impact Load	May contribute to wear on the intake side
Sliding/Rotational Motion	Micro welding due to lack of lubricity	Ethanol blends can absorb 50X as much H2O as gasoline alone
Valve Head Flex Motion	Ethanol has less lubricity than gasoline	Acetic acid formation during combustion
Valve Seat Film		

The valvetrain design has an impact on allowable system wear. Therefore, this study evaluated engines with a variety of valve designs:

- Mechanical valvetrains that do not use hydraulic lash adjusters
  - These designs have a minimal ability to accommodate valve and valve seat wear
  - In some cases they require regular maintenance of threaded adjusters or shim replacement to adjust the valve clearance
- Hydraulic lash adjusters with a small allowable travel
  - These designs have the second least ability to accommodate valve and valve seat wear and are typically found in overhead cam designs
- Hydraulic lash adjusters with a large allowable travel
  - These designs have the most ability to accommodate valve and valve seat wear and are typically found in cam-in-block or pushrod designs
- Non-premium valve seat materials that were not designed for ethanol fuels
  - These may show more sensitivity to fuel composition
- Engines with small valves leading to low seat loads
- Engines with large valves leading to high seat loads

Engines with these qualities were chosen to sample a variety of valvetrain designs.

B.2.2 Catalyst Durability

Catalyst durability is also affected with the use of intermediate-level ethanol blend fuels as the engine control unit (ECU) will adapt to the specific fuel being used through short-term and long-term fuel trims. The impact of the adaptation will depend on the OEM's specific closed loop fueling control algorithms and oxygen sensor sensitivity. This can lead to the engine running slightly leaner or richer compared to the original E0 calibration.

Modern closed-loop engine control systems change the fuel flow to match the oxygen flow into the cylinder, ensuring stoichiometric operation. However, most vehicles use switching type oxygen sensors and open loop control during periods of commanded enrichment such as heavy throttle operation. During heavy throttle operation, the oxygen sensor feedback is not used and the ECU will command a specified enrichment schedule. The enriched combustion helps to cool the exhaust gases and keeps the temperatures at acceptable levels for the catalyst, exhaust valves and oxygen sensor.

The amount of enrichment can be based on the learned fuel trims, which will vary depending on the fuel type. However, some vehicles do not use the learned fuel trims when calculating the amount of fuel required for operation during periods of commanded enrichment. When the fuel contains ethanol, the use of a baseline (unlearned) fuel trim results in open loop operation that is leaner than anticipated. The magnitude of this leaner operation is proportional to the amount of oxygen contributed by the ethanol in the gasoline, so fuels with increasing ethanol levels produce progressively leaner operation.

The lean combustion mixture causes elevated oxygen concentrations in the exhaust gas and can impact the oxygen sensor, and catalyst.[8,9] Lean combustion also results in elevated in-cylinder engine, oxygen sensor, and catalyst temperatures. A reduction in oxygen sensor or catalyst performance will impact emissions output and, as a result, air quality.

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8 Market Barriers to the Uptake of Biofuels Study: Testing Gasoline Containing 20% Ethanol (E20) Report to Environment Australia. http://www.environment.gov.au/atmosphere/fuelquality/publications/testing-passenger-fleet/pubs/gasoline.pdf.

9 Market Barriers to the Uptake of Biofuels Study: Testing Gasoline Containing 20% Ethanol (E20) Phase 2B Final Report to the Australian Department of the Environment and Heritage. http://www.environment.gov.au/atmosphere/fuelquality/publications/biofuels-2004/pubs/biofuels-2004.pdf.

C. Test Approach and Vehicle Acquisition

C.1 Test Approach

The testing procedure consisted of engine dynamometer testing for eight diversified vehicle/engine types. The engines were tested using an engine durability test cycle that is similar to OEM practice. The engines were removed from the vehicles and installed within engine dynamometer test cells. Measurements of the valvetrain clearances and valve stem locations were made prior to test. No disassembly beyond removal of the valve covers was done unless, after testing was complete, the engines experienced problems and further diagnosis was required.

The wiring harness between the ECU and the vehicle was extended to ensure that the ECU could still communicate with the various body controllers of the vehicle parked in front of the test cell. This so-called "umbilical cord" method has been developed by FEV during many years of benchmarking activities and ensures correct operation of the ECU within the engine dynamometer test cell.

Engines were tested in the test cells in "rounds" of four engines, initially meaning four different engines were tested in one group at the same time in two test cells, each test cell housing two engines. Later in the program, a round of engines consisted of only two engines as the testing progress did not require occupying two test cells simultaneously; testing continued with the parallel testing of two engines in one test cell. The test results overview in Section E of this report shows the results in chronological order of test rounds.

C.2 Fuel

The gasoline used for this ethanol blend durability study was obtained from the Detroit Marathon Petroleum terminal. The additive treat rate was specified at a level three times higher than legally required for deposit control to reduce the possibility of deposits affecting the test results and to compensate for the dilution effect of the ethanol. The ethanol content was specified to the fuel supplier to be within one percentage point of the target. The ethanol content for E20 was required to be 20 +/- 1 volume percent or between 19 volume percent and 21 volume percent. The fuel supplier contracted by FEV was required to provide a fuel analysis according to ASTM D5599 in order to ensure the appropriate ethanol content quality for every batch. INTERTEK laboratory was used to analyze the ethanol content. The fuel supplier used the splash blending method to create the appropriate ratio of gasoline to ethanol. Fuel was procured in bulk, and up to 20,000 gallons of the same batch was stored in an off-site holding tank. Fuel deliveries were made from this storage location to FEV. In addition, FEV used production automotive flexible-fuel vehicle sensors in their test cells to constantly monitor the ethanol content of the fuel being used for the durability study.

After completion of testing of all engines on E20, the same supplier's blending, storage and quality control methods were used to procure E15 fuel for the next round of testing. The ethanol content of E15 was required to be 15 +/-1 volume percent.

None of the engines tested on E20 or E15 showed evidence of knocking combustion during testing. Ethanol is known to reduce the knock tendency in engines and leads to an increased Research Octane Number (RON). In order to also maintain this condition for engine operation on E0, premium fuel was used for the E0 testing. The gasoline obtained from the Detroit Marathon terminal is called PBOB (Premium Blendstock for Oxygenate Blending). This fuel is designed to become premium after the addition of 10 volume percent ethanol. Without ethanol addition, the octane number of the E0, as measured by (R+M)/2, is between 90.2 and 91.2, slightly less than the 93-94 octane number of the E20 splash blends and the 92-93 octane number of the E15 splash blends. All tested engines are specified to be operated with regular fuel. The decision to operate the engines on E0 using premium fuel ensured that the non-knocking conditions were maintained for these engines.

Fuel samples were drawn upon delivery to FEV and analyzed by Paragon Labs. All fuel sample inspections as analyzed by Paragon Labs can be found in Appendix H.

C.2.1 The choice of the base fuel E0 vs. E10

This test program was designed to determine the effects of Intermediate-Level Ethanol Blends on current, on-road, non-Flexible-Fuel Vehicles (non-FFVs). As mentioned, analogous studies on the effects of E15 have been funded by the DOE on marine outboard engines[10] and on marine inboard/outboard engines[11] and whole vehicles undergoing catalyst testing.[12,13] These tests compared E0 with E15 and, in the case of the whole vehicles undergoing catalyst testing, E20. DOE also conducted evaporative emissions tests on the whole vehicles undergoing catalyst testing using E0 and E15.[14]

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10 High Ethanol Fuel Endurance: A Study of the Effects of Running Gasoline with 15% Ethanol Concentration in Current Production Outboard Four-Stroke Engines and Conventional Two-Stroke Outboard Marine Engines; David Hilbert. http://www.nrel.gov/docs/fy12osti/52909.pdf.

11 Volvo Penta 4.3 GL E15 Emissions and Durability Test; George Zoubul, Mel Cahoon, and Richard Kolb. http://www.nrel.gov/docs/fy12osti/52577.pdf.

12 Powertrain Component Inspection from Mid-Level Blends Vehicle Aging Study, http://info.ornl.gov/sites/publications/files/Pub28733.pdf, . EPA Docket #EPA–HQ–OAR–2009–0211-14016.

13 Oak Ridge National Laboratories, Final Report Catalyst Durability Study. http://www.osti.gov/bridge/servlets/purl/1035578/1035578.pdf.

14 Vehicle Aging and Comparative Emissions Testing Using E0 and E15 Fuels; Docket #EPA-HQ-OAR-2009-0211-14015.

These data were referenced by EPA[15] in its initial E15 waiver decision. As part of this decision, EPA, in its Technical Summary analyzing the results of the DOE testing,[16] stated: "The number of vehicles in a matched set varied during the test program according to the number of fuels being targeted for test. In some cases four ethanol blend levels were tested (E0, E10, E15, and E20), while in other cases a subset of these fuels were tested. Since the waiver request is for E15, this analysis focuses on those vehicles that were aged on E15 compared to those vehicles that were aged on E0." This EPA focus on E15 and E0 was supported by DOE, which performed catalyst durability testing of 19 vehicle types on E0 and E15, 15 vehicle types on E20 and only 5 vehicle types on E10.

In its follow-up decision,[17] EPA presents comparisons of E0 and E15 in eight vehicles designed to National Low Emissions Vehicle (NLEV) and Tier 1 emissions standards. DOE ran the program where these vehicles underwent catalyst durability tests on E0, E15 and E20 fuels.[18]

All these studies were similar in that E15, and, in many cases E20, was compared to gasoline containing no ethanol, the reference fuel. By reference testing with E0 rather than E10, any failures on the reference fuel, E0, cannot be linked to ethanol in the fuel. This reference testing on E0 was selected for this work, as it followed both EPA and DOE practice and, in the event of a failure on the reference fuel, would make it clear that ethanol was not a primary factor.

Further following DOE practice, durability testing was conducted on commercial E0 rather than certification fuel due to the substantial cost savings. All emission testing was conducted using Federal Certification fuel.

Two engines/vehicles of each type were initially tested on E20 fuel. If either was determined to have failed the durability test, then an additional two engines/vehicles of each type were tested on E15 fuel. In the event the engine/vehicle type was confirmed to have failed on E20 and E15, then two additional engines/vehicles were tested on E0 to determine if the durability issues faced in the previous failures were caused by the fuel or other factors not related to ethanol content.

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15 ENVIRONMENTAL PROTECTION AGENCY; 75 FR 68120.

16 Technical Summary of DOE Study on E15 Impacts on Tier 2 Vehicles and Southwest Research Institute Teardown Report. EPA Docket #EPA–HQ–OAR–2009–0211-14019.

17 ENVIRONMENTAL PROTECTION AGENCY; 76 FR 4670ff.

18 Data from Pre-Tier 2 DOE Catalyst Durability Program (V4/CRC E-87-2). EPA Docket #EPA-HQ-OAR-2009-0211-14052.

C.3 Vehicle Acquisition and Preparation

The vehicle models were selected by the CRC project panel based on engine valvetrain type varieties. The CRC Performance Committee Gasoline Engine Deposits Group and FEV worked together to choose the required vehicles. The vehicles chosen were non-FFVs. Once the model types were chosen, a search was conducted to find appropriate used vehicles matching the pre-requisites of the CRC project panel. Once several vehicles were found which fit the target mileage range (see below), the OEM technical contact was approached to check warranty data of the candidate vehicles. Only vehicles that had no issues identified within the OEM warranty system were selected for procurement. The test vehicles were purchased as used cars from dealerships. The following steps were taken to ensure each vehicle selected was appropriate for this program:

- Each of the vehicles was inspected prior to purchase for compression and leakage levels to verify that the engine was in sound mechanical condition. Any vehicles with pending or existing Diagnostic Trouble Codes (DTC) were repaired by the seller prior to purchase and delivery.
- All vehicles completed an emission test after purchase to verify all emission control components were in place, connected and functioning as designed and intended. Any vehicle that did not pass the standard for the Federal Test Procedure 75 (FTP75) emissions test was not used for the durability testing.
- A maximum odometer mileage guideline was established based on the model years selected by the project panel. Test vehicles were accepted into the program based in part on the criterion that the odometer did not indicate an average annual mileage accumulation in excess of 12,000 miles per year of age.

The vehicle models which were selected are shown below (along with the associated exhaust emissions certification standard and valvetrain type):

• 2001 Honda CR-V, 2.0L I4	Tier 1 NLEV	Rocker Arm, Threaded Adjuster
• 2002 VW Jetta, 2.0L I4	Tier 1 NLEV	Direct Acting, Hydraulic
• 2004 Scion xA, 1.5L I4	Tier 2 Bin 9	Direct Acting, Mechanical
• 2005 Chevrolet Colorado, 3.5L I5	Tier 2 Bin 9	Roller Finger Follower, Hydraulic
• 2007 Ford Edge, 3.5L V6	Tier 2 Bin 5	Direct Acting, Mechanical
• 2007 Dodge Ram, 5.7L V8	Tier 2 Bin 5	Pushrod, Hydraulic
• 2009 Dodge Caliber, 2.4L I4	Tier 2 Bin 4	Direct Acting, Mechanical
• 2009 Chevrolet Aveo, 1.6L I4	Tier 2 Bin 5/4	Direct Acting, Mechanical

Note: The 2009 Chevrolet Aveo is certified as Tier 2 Bin 4 in California and the Northeast states and as Tier 2 Bin 5 in other parts of the United States. One of the initially procured Chevrolet Aveo vehicles was originally sold in California, but was procured as a used car for this study from a Michigan dealership.

D. Test Procedure, Boundary Conditions and Test Equipment

D.1 Description of Test Method

D.1.1 General Overview

The following sequence was used to evaluate the engines:

- Procure in-use vehicle from used car dealer
- Complete compression and leakdown checks
- Perform vehicle FTP75 on chassis roll dynamometer
- Remove engine from vehicle
- Record engine valve measurements
- Install engine in engine dynamometer test cell
- Complete start-of-test FTP75 simulation (Rounds 1 and 2 only)
- Complete 500 cycle durability test schedule
    - Engine checks completed every 50 hours
        - Oil and filter replacement, oil sample
        - Cylinder compression and leakdown checks
        - Run seven standard test points (seven point FTP75 simulation for calculated fuel economy)
        - Inspect spark plugs and air filter
    - Engine checks completed every 100 hours
        - Replace spark plugs and air filter, in addition to 50 hour checks and tests
- Complete end-of-test FTP75 simulation (Rounds 1and 2 only)
- Record engine valve measurements
- Remove engine from engine dynamometer test cell
- Install engine back into vehicle (after Rounds 1and 2)
- Complete end-of-test vehicle FTP75 on chassis roll dynamometer (after rounds 1and 2)

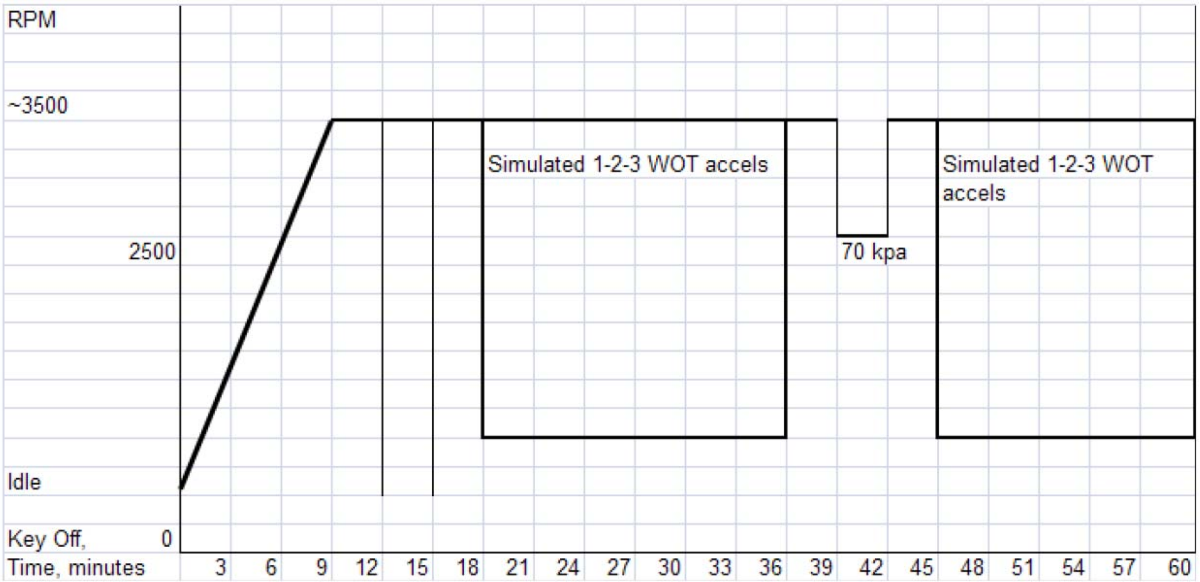
D.2 Durability Test Cycle

After the engine baseline evaluations were completed, the engine was installed in FEV's test cell along with the relevant vehicle exhaust system including catalyst(s) and oxygen sensor(s), base instrumentation for monitoring critical parameters to engine operating condition, and the emission measurement setup. Downstream of the last monitoring O_2 sensor the exhaust system was modified in order to adapt to the test cell exhaust system.

The test procedure consisted of accelerated testing to reduce test times and expose failures, if any. Accelerated testing is a standard practice in the automotive industry for producing faster results and higher expected performance from engines/vehicles. The severity helps reduce test time and compensate for the inherently small sample size associated with durability tests. Extended light-load operation is an option but greatly increases the duration, sample size, and cost of test programs. Given the lack of recent automotive experience with extended light-load operation and the industry emphasis on rapid implementation of intermediate-level ethanol blends, accelerated testing was determined to be the best approach for this program.

The engine durability protocol used for the evaluations consisted of 500 transient hours with each cycle 60 minutes in duration. The test cycle is a standard engine durability cycle from a local OEM except that the maximum engine speed was limited to 3500 rpm. The speed limitation was chosen for two reasons: first, the lower maximum speed significantly reduces the test severity making it more likely that the test engines will complete test without failures unrelated to the test objective; second, high speed testing can conceal valve seat wear issues by increasing oil pullover through the positive crankcase ventilation (PCV) and lubricating the valve seats. The entire 500 hours were run with the respective fuel (E20, E15, or E0). Relating test cycle duration to vehicle mileage involves vehicle weight and tow capacity, transmission and final drive gear ratios, and engine power and torque curves. Nonetheless, the test cycle used should correlate with ~100,000 miles of vehicle usage.

Figure D.2.1: Durability Cycle



D.3 Engine Data Measurements

D.3.1 Overview

During the durability testing, key measurement parameters were recorded continuously with a 1Hz refresh rate. These parameters included but were not limited to engine oil temperature, engine oil pressure, coolant temperature, exhaust gas temperature, torque, power, fuel flow, and exhaust air-fuel ratio. ECU data available through the OBD connector were monitored and saved together with the dynamometer data via the assembly line diagnostic link (ALDL). The measurements which FEV recorded from the ECU included:

- RPM – Engine Speed
- MAP – Intake Manifold Air Pressure
- Mass Air Flow
- Spark Advance
- Calculated Load Variable
- Coolant Temperature
- Vehicle Speed
- Fuel Control System Status
- Fuel Trim
- Intake Air Temperature
- Oxygen Sensor Output
- Air-Fuel Ratio Sensor Output
- Commanded Equivalence Ratio/Air Fuel Ratio
- Catalyst Temperature

Figure D.3.1.1: Data Measurement Overview

Measurement	Description	Measurement Frequency		
		SOT	Every 50 hours	EOT
Vehicle FTP75	A baseline emissions test was completed on the vehicle to determine that it meets the required specifications for emissions levels. Testing was completed with federal emissions certification fuel. *FTP75 done for vehicles after Rounds 1and 2	**X**		**X***
Valve Clearance Measurements	Valve clearance measurements were conducted per the OEM's service manual, unless otherwise instructed by the OEM.	**X**		**X**
Engine Dynamometer FTP75*	The same schedule that was completed on the vehicle level was replicated at the engine/dynamometer level to correlate the results from the vehicle to the engine dynamometer. Testing was completed with federal emissions certification fuel. *Dynamometer FTP75 conducted for vehicles in Rounds 1 and 2 only.	**X**		**X**
Cylinder Compression	Compression measurements on each cylinder were conducted per the OEM's service manual, unless otherwise instructed by the OEM.	**X**	**X**	**X**
Leakage	Leakage measurements on each cylinder were conducted per the OEM's service manual, unless otherwise instructed by the OEM.	**X**	**X**	**X**

Diagnostic tools were used to record all fault codes observed during each durability test.

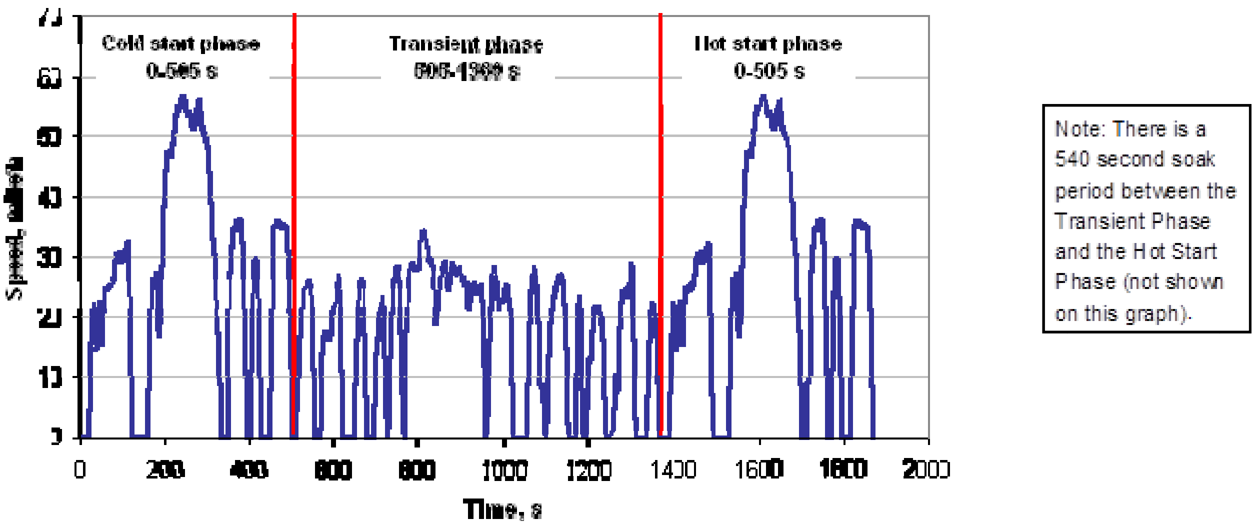
Figure D.3.1.1 provides a brief description of all data that were recorded. Each measurement is discussed in detail in the following sections.

D.3.2 Vehicle FTP75

The FTP75 was used as the basis to measure emissions and fuel economy at the start of test. A baseline emissions test was completed on a chassis dynamometer to determine that the test vehicle met its applicable exhaust certification standard. If the vehicle did not pass the baseline FTP75, another used vehicle was acquired for testing. The FTP75 test was run with Indolene (Federal Emission Certification fuel).

The schedule for the FTP75 emission test is shown below. A 540 second soak period between the transient phase and the hot start phase was also included for the testing, but is not shown in Figure D.3.2.1.

Figure D.3.2.1: FTP75 Schedule



An end-of-test (EOT) FTP75 emissions measurement was performed after the engine was reinstalled in the vehicle following the 500 hours of durability testing. This was done only after Rounds 1 and 2. In Rounds 1 and 2 the FTP75 tests were not done and only the engine dynamometer method (discussed in the following sections) was used to determine EOT emissions. After Rounds 1 and 2 (with the exception of Sample A of Vehicle 7 in Round 3), the program switched to an EOT vehicle FTP75 test to have a direct correlation to the one performed at SOT.

D.3.3 Engine Dynamometer FTP75

In the beginning of the program, a simulated FTP75 was conducted in the engine dynamometer test cell at SOT and EOT with the engines of Rounds 1 and 2. Based on data captured during the SOT vehicle emission chassis roll FTP75 test of each vehicle, a vehicle specific engine speed load trace was programmed into the engine dynamometer controller. The engine was then operated throughout this trace, and modal emissions were captured. All captured modal emissions data were used to calculate total emissions similar to bag results captured during a vehicle chassis roll FTP75 emission test. This method is termed the "FEV method for predicting vehicle emissions" as these data were not captured on a vehicle chassis emission roll, but calculated in a similar way using a prescribed engine speed load trace in the engine dynamometer test cell.

However, there were several differences between the vehicle FTP75 and the engine dynamometer simulated FTP75 that did not allow for a direct comparison:

- The engines were tested using an eddy-current dynamometer for quasi-transient testing. The FTP75 cycle could be replicated with the exception of the coast-down periods, which requires motoring capabilities (where the dynamometer drives the engine); an eddy-current dynamometer does not provide motoring capabilities.
- During coast-downs in a vehicle test, the fuel is usually cut-off and a spike in emissions readouts occurs as combustion is not occurring. The coast-down sections during the engine dynamometer testing were conducted with the engine fired on a low load in order to replicate the required engine speed trace. This was necessary as the transmission and vehicle driveline inertia is absent from the setup and the inertia effects cannot be replicated with an eddy-current dynamometer.

The differences described above yielded divergent emission and fuel economy results for the overall FTP75 schedule; the engine dynamometer testing did not provide an absolute number for emission correlation. However, since a direct correlation for start-of-test in the engine dynamometer test cell and end-of-test in the engine dynamometer test cell existed, it was possible to compare the relative increase over the durability test.

The dynamometer FTP75 method was discontinued after Rounds 1 and 2 due to repeatability concerns and also because it was possible to have a direct correlation to the SOT vehicle FTP75 emissions test with an EOT vehicle FTP75 emissions test.

D.3.4 Valve Clearance Measurements

To help gauge the effect of ethanol on valve and valve seat durability, valve clearance measurements were conducted at the start and end of each test. These measurements were used as an indicator of valve seat recession and were undertaken in the place of a full engine disassembly and inspection protocol which would have had the undesired effect of altering the “as received” condition of the test engine. All engine valve clearance measurements were taken according to specifications given by the respective vehicle OEM. For some applications, special fixtures were provided by the OEMs to measure valve clearance or tip position according to specific OEM measurement procedures.

Each OEM provided detailed pass/fail criteria for this category for their application at the beginning of the project. An engine was declared to have failed if its valve clearance measurements or valve tip measurements exceeded the OEM specifications after completion of the 500 hour durability test.

D.3.5 Cylinder Compression and Leakage

Cylinder compression and leakage were measured on every engine to evaluate its overall condition over the course of the durability test. Compression and leakdown measurements were considered directly proportional to the ability of the engine to seal the combustion chamber. The sealing elements are the valves, valve seats, and the piston ring pack.

Compression and leakdown were measured throughout the whole program with the same measurement equipment and methods on all investigated engines. In the beginning of the study, FEV investigated the repeatability of measurements with several leakdown gauges and with several technicians. As a result, it was determined to utilize the Snap-On® leakage tester model EEPV309A for all measurements within this program (see Figure D3.5.1). The tool was stored in a defined location at FEV and all technicians involved in this study were instructed to only use this Snap-On® tool for the leakdown measurements. Leakdown measurements were always conducted with a warm engine.

Figure D.3.5.1: Snap-On® EEPV309A Leakage Tester

Compression was measured on all cylinders at intervals of every 50 hours during the durability test cycle; if the measurement did not meet the criterion specified in the service manual, the OEM technical contact was immediately notified. Similarly, leakage was also measured on all cylinders every 50 hours of testing. If any of the leakdown values exceeded the ten percent threshold, the OEM technical representative was notified immediately.

If the measurement thresholds were surpassed, testing was only resumed after approval from the OEM technical representative.

Each OEM provided detailed pass/fail criteria for this category for their application at the beginning of the project. An engine required an OEM teardown if leakage measurements on at least one cylinder exceeded 10% after completion of the 500 hour durability test or compression measurements fell below OEM tolerance specifications. A persistent cylinder leakage of 10% or more on at least one cylinder from initial (non-leaking) compression pressure is commonly used and accepted by several involved OEMs as failure criterion.

In this program any leakdown beyond the 10% threshold at EOT was used as an indicator that engine inspection was required. Transient leakdown beyond 10% can occur due to transient carbon deposits on the valve seat or other reasons thus EOT OEM inspection was used as the final determinant of valve sealing integrity and the engines were returned to the OEMs for teardown and assessment.

Detailed leakdown data is presented in appendix H.2 as an average of all cylinders of a measured engine compared to the minimum and maximum values of the measured cylinders of that engine to show variation among the cylinders.

Detailed compression data is shown in the same manner in appendix H.3.

D.3.6 Service Intervals

Engine checks were performed every 50 hours for mandatory service. These mandatory service checks included compression and leakdown measurements on all cylinders, collecting an oil sample for analysis and changing the oil and air filter. All oil samples were sent to Fluid Technologies, Inc. (FTI) for analysis. Results of the detailed oil analyses have been included in appendix H.4 of this final report for reference. However, none of the observed failures were deemed to be oil related. Additionally, at every 100 hours the spark plugs and air filter were changed.

The chart in Figure D.3.6.1 below shows the frequency of each inspection and the parts which were replaced.

Figure D.3.6.1: Service Interval Chart

Engine Checks every 50 hours											
	0	50	100	150	200	250	300	350	400	450	500
Engine Fluid Levels	X	X	X	X	X	X	X	X	X	X	X
Oil and Filter Change	X	X	X	X	X	X	X	X	X	X	X
Oil Sample	X	X	X	X	X	X	X	X	X	X	X
Cylinder Compression	X	X	X	X	X	X	X	X	X	X	X
Cylinder Leak-Down	X	X	X	X	X	X	X	X	X	X	X
Spark Plug Inspection		X		X		X		X		X	
Spark Plug Change	X		X		X		X		X		X
Air Filter Replacement	X		X		X		X		X		X
Valve Clearance Measurement	X										X

The results were reviewed after every inspection, and reviewed with the respective OEM technical expert in the event of any issues or needed clarifications.

D.3.7 Pass/Fail Criteria Summary

The success of each test was based on the measurements being within the specification limits described within the vehicle manuals:

- Compression loss according to OEM specifications
- Leakdown loss of 10% or less
- Valve measurements within manufacturer's specifications
- The absence of fuel-related diagnostic trouble codes
- Measured vehicle emissions during FTP75 test remaining within certification tolerance limits compared to SOT data

D.4 Boundary Conditions

The engines were operated under the following specifications:

- Fuel was closely monitored in the test cell using a flexible-fuel vehicle sensor to ensure ethanol content was within ± 1 volume percent. The fuel analysis for ethanol content was completed through INTERTEK laboratories per ASTM standard D5599.
- Federal Emissions Certification fuel (Indolene) was used for all FTP75 testing at start and end of the durability testing for engine dynamometer and vehicle tests.
- The oil used was per the required manufacturer specification.

	Dodge Caliber	Scion xA	Ford Edge	Chevrolet Colorado	Dodge Ram	Chevrolet Aveo	Honda CR-V	VW Jetta
Engine Oil Type	5W-20 mineral	5W-30 mineral	5W-20 synthetic	5W-30 mineral	5W-20 synthetic	5W-30 mineral	5W-30 mineral	5W-30 mineral
Engine Oil Fill Amount (qts)	5	4	5.5	6	6.6	4.5	4	3.8

- Engine checks were completed every 50 hours. OEM service parts were used at all service intervals.
- The intake air was not conditioned.
- The engine was setup with a Super Flow® cooling tower to simulate the presence of a radiator.
- The vehicle exhaust setup was used through the second catalyst. No mufflers were used. This method ensured that the exhaust gas dynamics were maintained as the first catalyst is the main reflection point in the system for any exhaust gas dynamic pressure waves. The catalysts are also the main contributor for exhaust back pressure. The exhaust back pressure level can be considered equal to the vehicle as the muffler is not contributing substantially to the overall exhaust back pressure level.

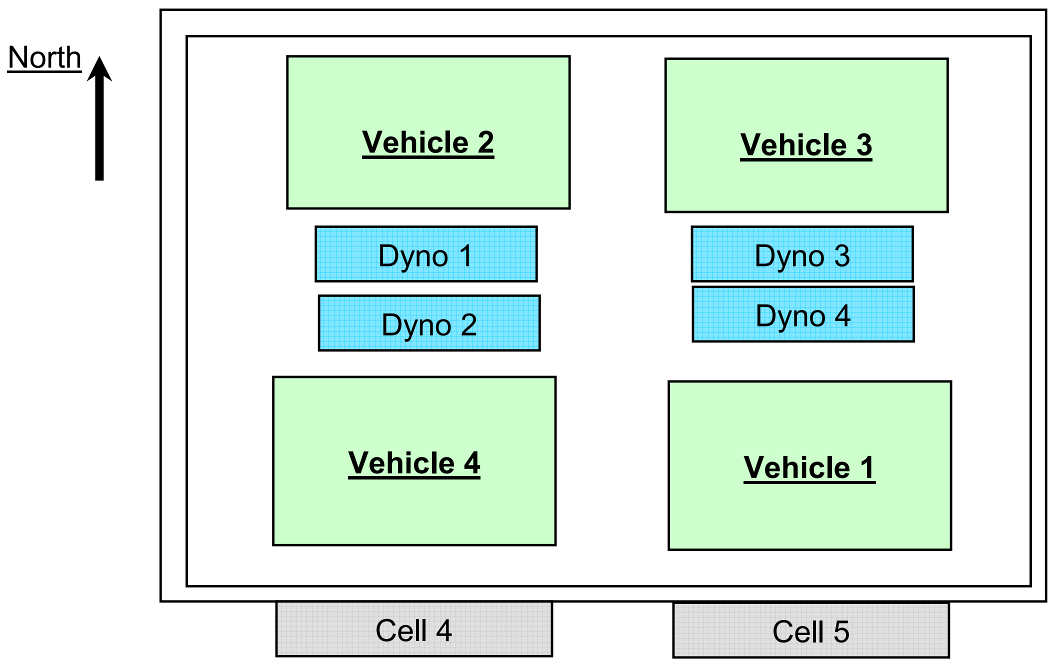
- An emissions probe was added to the exhaust manifold before the close-coupled catalyst for emissions sampling. A second emissions probe was installed in the tailpipe location.
- All OEM sensors were installed during test.

D.5 Test Bench and Test Equipment

D.5.1 Test Bench

The engines were removed from the vehicle after initial evaluations and checks and installed in the test cell. Due to the complexity of today's engines, engines have to communicate with the vehicle engine control unit (ECU) for engine and vehicle related control units; namely, traction control, automatic transmissions, fuel level sensor, and gear positions which would prevent limp-home modes. The test cells were setup to run two engines at the same time. The setup layout is shown in Figure D.5.1.1

Figure D.5.1.1: Engine Dynamometer Test Cell Setup

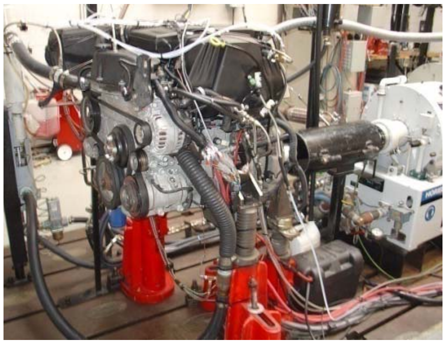


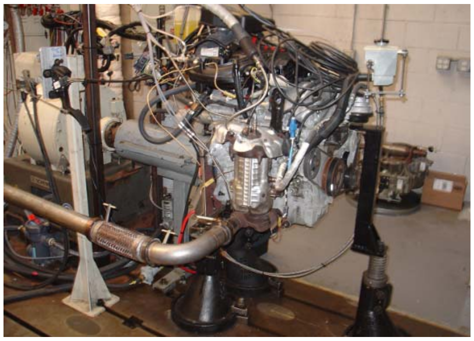
The vehicle was left intact with an "umbilical cord" used to connect the vehicle to the engine in the test cell. The vehicle was parked outside the test cell to allow communication with the engine ECU. This ensured the engine would function through its operation range without limiting power output due to DTCs.

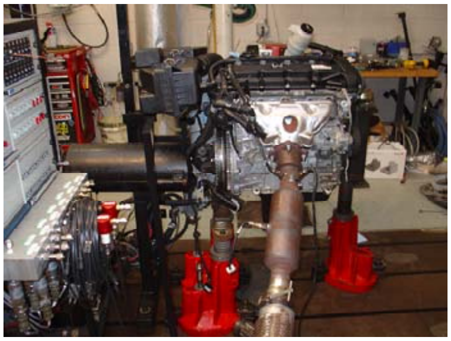
Figure D.5.1.2 shows example vehicle setups used during the project. The cables routed underneath the cars are the "umbilical cords" which relay ECU information and other vehicle information from the vehicle to the engine present inside the test cell.

Figure D.5.1.2: Umbilical Cord Vehicle to Engine Setup

Examples of the engine setup in the dynamometer test cells are shown in Figure D.5.1.3:







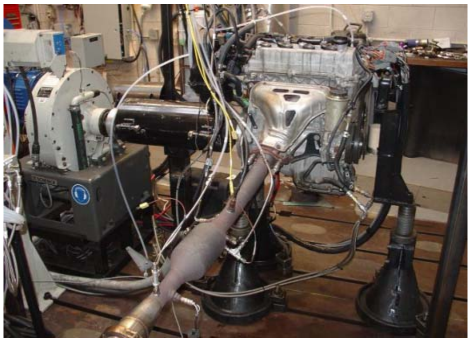


Figure D.5.1.3: Engine Setup in Test Cells

Figures D.5.1.4 and D.5.1.5 show the engine instrumentation which was applied and used to record measurements throughout the testing.

Figure D.5.1.4: Inline Engine Instrumentation Layout

Static Temperatures & Pressures

Location	Description
1	Ambient
2	Before airbox
3	Intake plenum
4	Fuel supply
5	Fuel meter
6	Coolant in
7	Coolant out
8	Oilpan temp
9	Oil gallery pressure, temp
10	Before catalyst
11	After catalyst
12	Catalyst Midbed
13	Dyno water
14	Crank case pressure

Location	Description
15	λ Probe
16	Emissions before catalyst
17	Emissions after catalyst

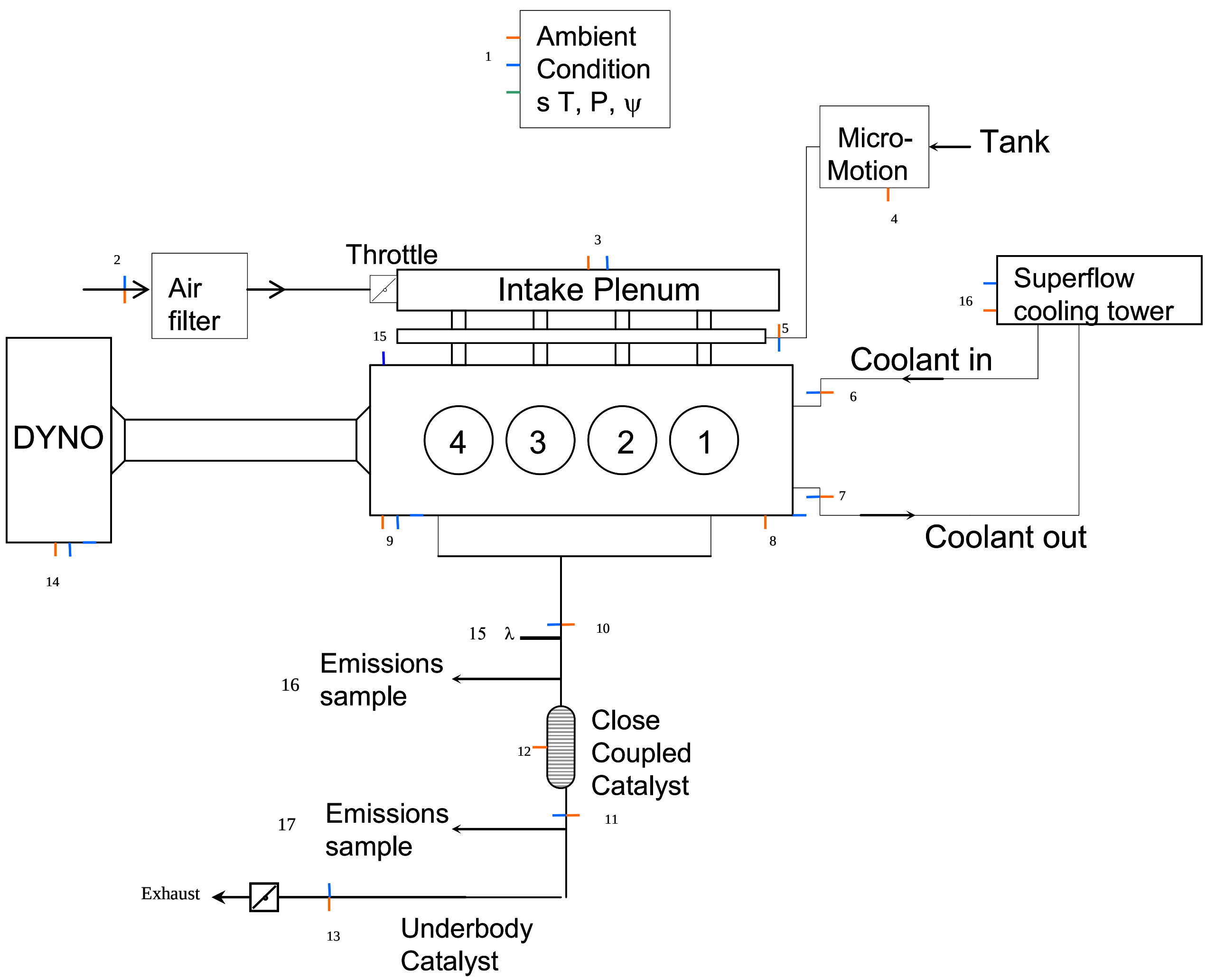


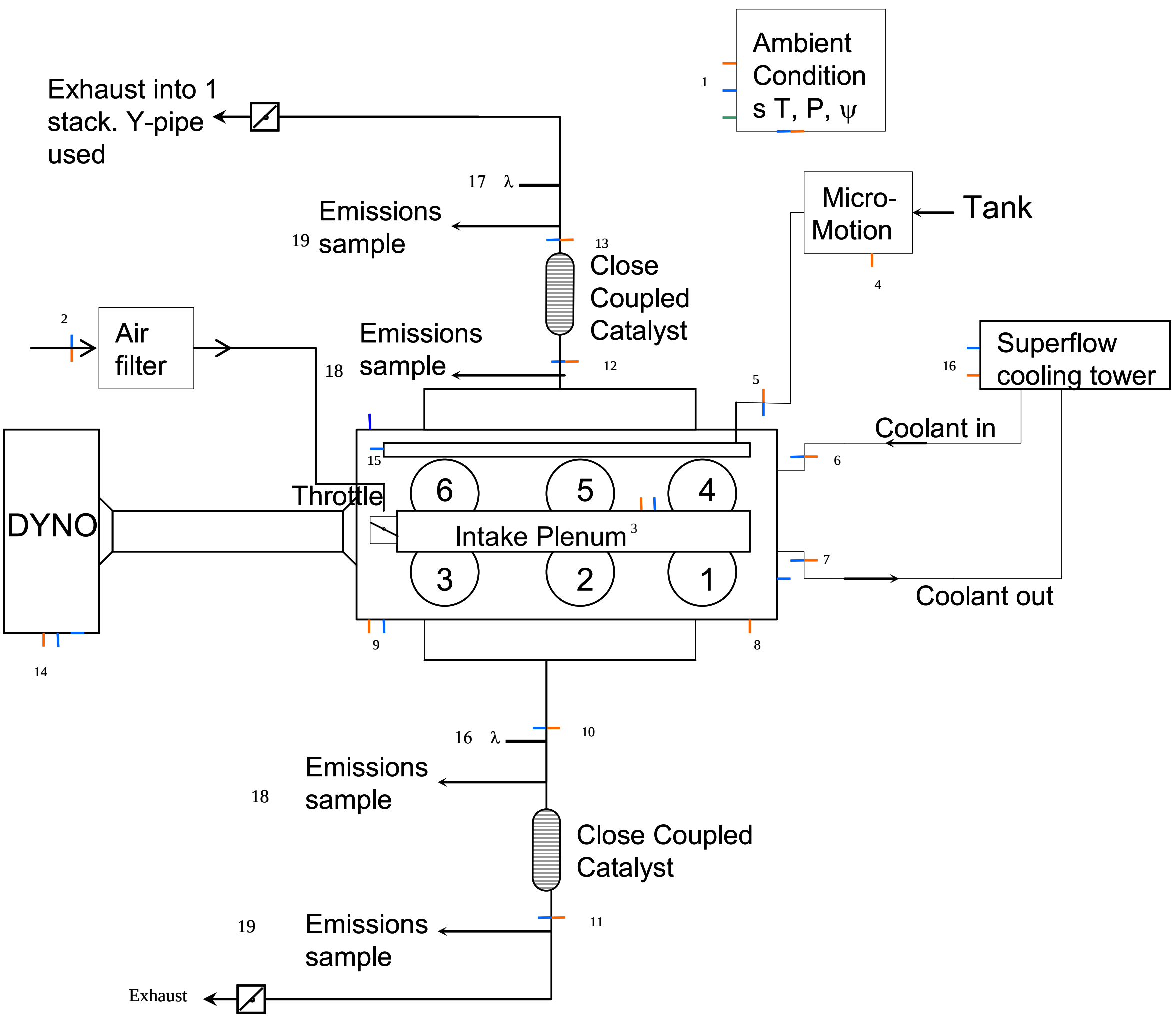
Figure D.5.1.5: V Engine Instrumentation Layout

Static Temperatures & Pressures

Location	Description
1	Ambient
2	Before airbox
3	Intake plenum
4	Fuel supply
5	Fuel meter
6	Coolant in
7	Coolant out
8	Oilpan temp
9	Oil gallery pressure, temp
10	Before catalyst B1
11	After catalyst B1
12	Before catalyst B2
13	After catalyst B2
14	Dyno water
15	Crank case pressure

Miscellaneous

Location	Description
16	λ Probe B1
17	λ Probe B2
18	Emissions before catalyst
19	Emissions after catalyst



FEV

E. Results

E.1 Summary

The following eight engines were evaluated on E20 as part of the durability testing:

- 2001 Honda CR-V, 2.0L I4 Tier 1 NLEV; (71,412 / 110,681Miles)
- 2002 VW Jetta, 2.0L I4 Tier 1 NLEV; (77,891 / 106,761 Miles)
- 2004 Scion xA, 1.5L I4 Tier 2 Bin 9; (61,351 / 56,671 Miles)
- 2005 Chevrolet Colorado, 3.5L I5 Tier 2 Bin 9; (48,109 / 33,972 Miles)
- 2007 Ford Edge, 3.5L V6 Tier 2 Bin 5; (17,906 / 14,450 Miles)
- 2007 Dodge Ram, 5.7L V8 Tier 2 Bin 5; (28,597 / 26,078 Miles)
- 2009 Dodge Caliber, 2.4L I4 Tier 2 Bin 4; (11,941 / 12,494 Miles)
- 2009 Chevrolet Aveo, 1.6L I4 Tier 2 Bin 5/4; (8,327 / 3,758 Miles)

Each of the vehicles was chosen as representative of the in-use vehicle population most likely to display durability issues due to use of higher ethanol level content in the fuel. Two samples from each vehicle were tested. The mileage of each vehicle for testing on E20 at time of procurement is indicated in brackets. For those vehicles tested on E15 and E0, comparable vehicles with similar mileage were procured.

The engines were judged for pass/fail on five criteria:

- Compression loss according to OEM specifications
- Leakdown loss of ten percent or less
- Valve measurements within manufacturer’s specifications
- The absence of fuel-related diagnostic trouble codes
- Measured vehicle emissions during FTP75 test remaining within certification tolerance limits compared to start-of-test data

The following Figure E.1.1 summarizes the durability test results and shows an overview of the detailed results for all pass/fail criteria for all 28 tested engines. The individual engines description column is color coded the same way as in the overall overview in Figure 1 (green = passed, red = failed, yellow = waived, purple = excluded from final assessment).

Detailed results for leakage and compression measurements plus oil analyses data for all tested engines can be found in summarized form in the appendix.

The detailed results are masked in order to ensure OEM confidentiality, including their technical data. The provided vehicle list is not in order within the table below to maintain this confidentiality.

Figure E.1.1: Summary of Durability Testing Results

Rounds 1 and 2

Round	Description	Emissions	DTC	Valve Clearance	Compression	Leakage
1	Vehicle 1 – Sample A – E20	Waived	Pass	Pass	Pass	Pass
1	Vehicle 2 – Sample A – E20	Pass	Pass	Pass	Pass	Fail
1	Vehicle 3 – Sample A – E20	Pass	Pass	Pass	Pass	Pass
1	Vehicle 4 – Sample A – E20	Pass	Pass	Pass	Pass	Fail
2	Vehicle 1 – Sample B – E20	Pass	Pass	Pass	Pass	Pass
2	Vehicle 2 – Sample B – E20	Pass	Pass	Pass	Pass	Fail
2	Vehicle 3 – Sample B – E20	Pass	Pass	Fail	Pass	Fail
2	Vehicle 4 – Sample B – E20	Pass	Pass	Pass	Pass	Pass

Note: Vehicle 1 in Round 1 was marked waived for emissions as a dynamometer exchange in the middle of the 500 hour durability test prevented correlation to the measured SOT emissions. Further details are described in section E.2.1.

Rounds 3 and 4

Round	Description	Emissions	DTC	Valve Clearance	Compression	Leakage
3	Vehicle 5 – Sample A – E20	Fail	Fail	Pass	Pass	Pass
3	Vehicle 6 – Sample A – E20	Pass	Pass	Pass	Pass	Fail
3	Vehicle 7 – Sample A – E20	Pass	Pass	Pass	Pass	Pass
3	Vehicle 8 – Sample A – E20	Fail	Pass	Pass	Fail	Fail
4	Vehicle 5 – Sample B – E20	Pass	Pass	Pass	Pass	Pass
4	Vehicle 6 – Sample B – E20	Pass	Pass	Pass	Pass	Fail
4	Vehicle 7 – Sample B – E20	Pass	Pass	Pass	Pass	Pass
4	Vehicle 8 – Sample B – E20	N/A	N/A	N/A	Fail	Fail

Round	Description	Emissions	DTC	Valve Clearance	Compression	Leakage
Rounds 5 and 6						
Round	**Description**	**Emissions**	**DTC**	**Valve Clearance**	**Compression**	**Leakage**
5	Vehicle 2 – Sample C – E15	Fail	Pass	Pass	Pass	Pass
5	Vehicle 3 – Sample C – E15	Pass	Pass	Pass	Pass	Fail
6	Vehicle 2 – Sample D – E15	Pass	Pass	Pass	Pass	Fail
6	Vehicle 3 – Sample D – E15	Pass	Pass	Pass	Pass	Pass
Rounds 7 and 8						
Round	**Description**	**Emissions**	**DTC**	**Valve Clearance**	**Compression**	**Leakage**
7	Vehicle 8 – Sample C – E15	Fail	N/A	N/A	N/A	Fail
7	Vehicle 3 – Sample E – E0	Pass	Pass	Pass	Pass	Pass
8	Vehicle 8 – Sample D – E15	N/A	N/A	N/A	Fail	Fail
8	Vehicle 3 – Sample F – E0	Pass	Pass	Pass	Pass	Pass
Note: Vehicle 8 in Rounds 7 and 8 did not complete the 500 hour durability test and therefore several criteria were not assessed and marked N/A. Details are described in Sections E.9.3 and E.9.4.						
Rounds 9 and 10						
Round	**Description**	**Emissions**	**DTC**	**Valve Clearance**	**Compression**	**Leakage**
9	Vehicle 8 – Sample E – E0	Fail	Pass	Pass	Fail	Fail
9	Vehicle 2 – Sample E – E0	Pass	Pass	Pass	Pass	Pass
10	Vehicle 8 – Sample F – E0	Fail	Pass	Pass	Pass	Fail
10	Vehicle 2 – Sample F – E0	Pass	Pass	Pass	Pass	Pass

The data indicate that some of the engine samples showed issues with higher ethanol content fuel. Specifically, the main issues included excessive valve leakage and elevated emission levels.

E.2 Durability Testing: Vehicle 1

E.2.1 Vehicle 1 – Sample A – E20

E.2.1.1 Summary – Vehicle 1 – Sample A – E20

Sample A completed 500 hours of durability testing. The engine passed the criteria for leakage, compression, diagnostic trouble codes, as well as valve clearance measurements. The engine dynamometer based EOT emission test was waived after technical challenges prevented comparison of the SOT and EOT emission data. After detailed review with the OEM technical contact and discussion with the CRC panel it was determined that no additional testing with E15 or E0 was required for this vehicle.

Figure E.2.1.1: Vehicle 1 – Sample A – E20 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 1 – Sample A – E20	Waived	Pass	Pass	Pass	Pass

E.2.1.2 FTP75 – Vehicle 1 – Sample A – E20

The vehicle completed testing using the FEV engine dynamometer method for predicted vehicle emissions. However, the results from the EOT emission test could not be correlated to the SOT emission results due to an unplanned exchange of the dynamometer during the 500 hour durability test, leading to an inertia difference which impacted the EOT emission test. Detailed steady-state emission data captured throughout the durability test cycle was analyzed and was shared with the OEM technical specialist which showed no degradation of the catalyst throughout the durability test. It was decided by the OEM technical contact and the CRC panel that no further emission test related activity was necessary.

E.2.1.3 Valve Clearance – Vehicle 1 – Sample A – E20

The engine was checked for valve clearances pre- and post-durability test. The engine showed no valve clearance degradation over the durability testing. All values were within the required OEM specification.

E.2.1.4 Compression, Leakage – Vehicle 1 – Sample A – E20

The cylinder compression values remained within ten percent throughout the 500 hours of testing; no issues were noted.

The leakage numbers were below ten percent on all cylinders for all checkpoints during testing.

E.2.1.5 Engine Teardown – Vehicle 1 – Sample A – E20

An engine teardown was not conducted as the engine passed all mechanical pass/fail criteria.

E.2.2 Vehicle 1 – Sample B – E20

E.2.2.1 Summary – Vehicle 1 – Sample B – E20

Vehicle 1 – Sample B – E20 completed 500 hours of durability testing. The engine passed the criteria for leakage, compression, emissions, diagnostic trouble codes and valve clearance measurements.

Figure E.2.2.1: Vehicle 1 – Sample B – E20 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 1 – Sample B – E20	Pass	Pass	Pass	Pass	Pass

E.2.2.2 FTP75 – Vehicle 1 – Sample B – E20

The FTP75 emissions were measured using the FEV engine dynamometer method for predicted vehicle emissions. The results showed that the EOT values were slightly elevated, but within acceptable limits and therefore passed the emission criteria.

E.2.2.3 Valve Clearance – Vehicle 1 – Sample B – E20

The engine was checked for valve clearances pre- and post-durability test. The engine showed no valve clearance degradation over the durability testing. All values were within the required OEM specification.

E.2.2.4 Compression, Leakage – Vehicle 1 – Sample B – E20

The cylinder compression values remained within ten percent throughout the 500 hours of testing; no issues were noted.

The leakage numbers were below ten percent on all cylinders for all checkpoints during testing.

E.2.2.5 Engine Teardown – Vehicle 1 – Sample B – E20

An engine teardown was not conducted as the engine passed all pass/fail criteria.

E.3 Durability Testing: Vehicle 2

E.3.1 Vehicle 2 – Sample A – E20

E.3.1.1 Summary – Vehicle 2 – Sample A – E20

Vehicle 2 – Sample A – E20 completed 500 hours of durability testing. The engine passed the criteria for compression, emissions, diagnostic trouble codes and valve clearance measurements. However, the engine failed the leakage requirement and failed the subsequent teardown inspection due to uneven wear and pitting on the valve seat.

Figure E.3.1.1: Vehicle 2 – Sample A – E20 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 2 – Sample A – E20	Pass	Pass	Pass	Pass	Fail

An additional 50 hours of testing was completed after all EOT checks. This testing was performed to understand if the leakage would increase further or decrease. Following the additional testing, compression and leakage measurements were retaken. The compression numbers remained consistent, while the leakage numbers decreased on two cylinders but remained above ten percent. All other cylinders were below the ten percent pass/fail criteria.

E.3.1.2 FTP75 - Vehicle 2 – Sample A – E20

Emissions were measured on a chassis roll dynamometer and per the FEV engine dynamometer method for predicted vehicle emissions. Although emissions degradation was observed over time from the start to end of the engine dynamometer testing, the estimated final vehicle results were within the required emissions standard.

E.3.1.3 Valve Clearance – Vehicle 2 – Sample A – E20

The engine was checked for valve clearances pre- and post- durability test. The engine showed no valve clearance degradation over the durability testing. All values were within the required OEM specification.

E.3.1.4 Compression, Leakage – Vehicle 2 – Sample A – E20

The compression numbers remained within ten percent of the SOT values throughout the 500 test hours. The leakdown measurements all remained below ten percent up through 450 hours. At 500 hours, the leakdown measurements on two cylinders were above the ten percent limit.

An additional 50 hours of testing was completed after all EOT checks. Following the additional testing, compression and leakage measurements were retaken. The compression numbers remained consistent and within pass/fail criteria, while the leakage numbers decreased on two cylinders but remained above ten percent. All other cylinders were below the ten percent pass/fail criteria. Therefore, the engine was determined to require teardown inspection due to leakage.

E.3.1.5 Engine Teardown – Vehicle 2 – Sample A – E20

The OEM completed a partial teardown of this engine. It was noted that the valves in Cylinder #3 showed uneven wear and pitting on the valve seat and that the cylinder leakdown found by FEV was a result of a leaking intake valve. This is an observation also made on other durability engines tested with ethanol blends during the development of flexible-fuel engines. As a result of this wear, the test was deemed a failure.

E.3.2 Vehicle 2 – Sample B – E20

E.3.2.1 Summary – Vehicle 2 – Sample B – E20

Vehicle 2 – Sample B – E20 completed 500 hours of durability testing. The engine passed the criteria for compression, emissions, diagnostic trouble codes and valve clearance measurements. However, the engine failed the leakage requirement.

Figure E.3.2.1: Vehicle 2 – Sample B – E20 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 2 – Sample B – E20	Pass	Pass	Pass	Pass	Fail

E.3.2.2 FTP75 - Vehicle 2 – Sample B – E20

Emissions were measured on a chassis roll dynamometer and per the FEV engine dynamometer method for predicted vehicle emissions. The vehicle passed the EOT emission test per the FEV engine dynamometer method.

E.3.2.3 Valve Clearance – Vehicle 2 – Sample B – E20

The engine was checked for valve clearances pre- and post-durability test. The engine showed no valve clearance degradation over the durability testing. All values were within the required OEM specification.

E.3.2.4 Compression, Leakage – Vehicle 2 – Sample B – E20

The compression numbers remained within ten percent of the SOT values throughout the 500 test hours. The leakdown measurements all remained below ten percent up through 450 hours; one cylinder had leakdown above ten percent at this time. At 500 hours, the leakdown measurements on two cylinders were above the ten percent limit. Therefore, the engine was determined to require teardown inspection due to leakage.

E.3.2.5 Engine Teardown – Vehicle 2 – Sample B – E20

The OEM completed a partial teardown on this engine. It was noted that the valves in Cylinders #1 and #3 showed uneven wear and pitting on the valve seat and that the cylinder leakdown found by FEV was a result of intake valve leakage. As a result of this wear, the test was deemed a failure.

E.3.3 Vehicle 2 – Sample C – E15

E.3.3.1 Summary – Vehicle 2 – Sample C – E15

Vehicle 2 – Sample C – E15 completed 500 hours of durability testing. The engine passed the criteria for compression, leakage, diagnostic trouble codes and valve clearance measurements. However, the engine failed the emissions requirement.

Figure E.3.3.1: Vehicle 2 – Sample C – E15 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 2 – Sample C – E15	Fail	Pass	Pass	Pass	Pass

E.3.3.2 FTP75 - Vehicle 2 – Sample C – E15

Emission measurements were recorded by comparing initial and EOT emissions on a chassis dynamometer. The vehicle failed the EOT emissions showing an increase in NMOG (11% above emission standard) and NO_x (63% above emission standard).

E.3.3.3 Valve Clearance – Vehicle 2 – Sample C – E15

The engine was checked for valve clearances pre- and post-durability test. The engine showed no valve clearance degradation over the durability testing. All values were within the required OEM specification.

E.3.3.4 Compression, Leakage – Vehicle 2 – Sample C – E15

The cylinder compression values remained within ten percent throughout the 500 hours of testing; no issues were noted.

The leakage numbers were below ten percent on all cylinders for all checkpoints during testing.

E.3.3.5 Engine Teardown – Vehicle 2 – Sample C – E15

The cylinder head had minor uneven wear on intakes towards the spark plug. This wear is unlikely to cause a sealing issue. No measurable exhaust seat wear was observed.

E.3.4 Vehicle 2 – Sample D – E15

E.3.4.1 Summary – Vehicle 2 – Sample D – E15

Vehicle 2 – Sample D – E15 completed 500 hours of durability testing. The engine passed the criteria for compression, emissions, diagnostic trouble codes and valve clearance measurements. However, the engine failed the leakage requirement

Figure E.3.4.1: Vehicle 2 – Sample D – E15 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 2 – Sample D – E15	Pass	Pass	Pass	Pass	Fail

E.3.4.2 FTP75 - Vehicle 2 – Sample D – E15

Emission measurements were recorded comparing initial and end of test emissions on a chassis dynamometer. All emissions (CO, NMOG and NO_x) were within the certification limits and the vehicle passed the EOT vehicle emission test.

E.3.4.3 Valve Clearance – Vehicle 2 – Sample D – E15

The engine was checked for valve clearances pre- and post-durability test. The engine showed no valve clearance degradation over the durability testing. All values were within the required OEM specification.

E.3.4.4 Compression, Leakage – Vehicle 2 – Sample D – E15

The compression numbers remained within ten percent of the SOT values throughout the 500 hour durability test. The leakdown measurement for one cylinder was higher than ten percent at the 300 and 400 hour test points. At the 500 hour EOT, the leakdown measurements for several cylinders were above ten percent.

Compression and leakage were measured at the end of the wide open throttle (WOT) run to assess if the results would improve. The compression and leakdown numbers did improve and only one cylinder was higher than ten percent leakdown. However, the results did not meet the 10% criteria and the engine was returned to the OEM for examination.

E.3.4.5 Engine Teardown – Vehicle 2 – Sample D – E15

Several chambers in the cylinder head had uneven wear on intakes, particularly towards the spark plug. Intake roundness and runout were beyond specification. No measurable exhaust seat wear was observed.

E.3.5 Vehicle 2 – Sample E – E0

E.3.5.1 Summary – Vehicle 2 – Sample E – E0

Vehicle 2 – Sample E – E0 completed 500 hours of durability testing. The engine passed all test criteria.

Figure E.3.5.1: Vehicle 2 – Sample E – E0 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 2 – Sample E – E0	Pass	Pass	Pass	Pass	Pass

E.3.5.2 FTP75 – Vehicle 2 – Sample E – E0

Emission measurements were recorded comparing initial and EOT emissions on a chassis dynamometer. All emissions (CO, NMOG and NO_x) were within the certification limits and the vehicle passed the EOT vehicle emission test.

E.3.5.3 Valve Clearance – Vehicle 2 – Sample E – E0

The engine was checked for valve clearances pre- and post-durability test. The engine showed no valve clearance degradation over the durability testing. All values were within the required OEM specification.

E.3.5.4 Compression, Leakage – Vehicle 2 – Sample E – E0

The cylinder compression values were within specifications throughout the test.

The leakage number on one cylinder increased above 10% at 450 hours, but decreased again below 10% at EOT. All cylinders were below 10% at EOT. The excursion beyond the 10% threshold resulted in OEM inspection of the cylinder head.

E.3.5.5 Engine Teardown – Vehicle 2 – Sample E – E0

The valve seats showed acceptable wear without any pitting.

E.3.6 Vehicle 2 – Sample F – E0

E.3.6.1 Summary – Vehicle 2 – Sample F – E0

Vehicle 2 – Sample F – E0 completed 500 hours of durability testing. The engine passed the criteria for compression, leakage, diagnostic trouble codes, valve clearance and emissions.

Figure E.3.6.1: Vehicle 2 – Sample F – E0 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 2 – Sample F – E0	Pass	Pass	Pass	Pass	Pass

E.3.6.2 FTP75 – Vehicle 2 – Sample F – E0

Initial and end of test emissions measurements were performed on a chassis dynamometer. All emissions (CO, NMOG and NO_x) were within the certification limits and the vehicle passed the EOT vehicle emission test.

E.3.6.3 Valve Clearance – Vehicle 2 – Sample F – E0

The engine was checked for valve clearances pre- and post-durability test. The engine showed no valve clearance degradation over the durability testing. All values were within the required OEM specification.

E.3.6.4 Compression, Leakage – Vehicle 2 – Sample F – E0

The cylinder compression values remained within specifications throughout the 500 hours of testing; no issues were noted.

The leakage numbers were above 10% on one cylinder at 250 hours and 450 hours, but were measured below 10% on all cylinders at EOT. The excursion beyond the 10% threshold resulted in OEM inspection of the cylinder head.

E.3.6.5 Engine Teardown – Vehicle 2 – Sample F – E0

The valve seats showed acceptable wear without any pitting.

E.4 Durability Testing: Vehicle 3

E.4.1 Vehicle 3 – Sample A – E20

E.4.1.1 Summary – Vehicle 3 – Sample A – E20

Vehicle 3 – Sample A – E20 completed 500 hours of durability testing. The engine passed the criteria for leakage, compression, emissions, diagnostic trouble codes and valve clearance measurements.

Figure E.4.1.1: Vehicle 3 – Sample A – E20 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 3 – Sample A – E20	Pass	Pass	Pass	Pass	Pass

E.4.1.2 FTP75 – Vehicle 3 – Sample A – E20

SOT emissions were measured on a chassis roll dynamometer and per the FEV engine dynamometer method for predicted vehicle emissions. EOT emissions were also measured per the FEV engine dynamometer method to estimate a correlation with initial vehicle emissions. The emissions degraded over the test for HC and CO. However, using the FEV predicted emissions method, the emissions passed the required standard.

E.4.1.3 Valve Clearance – Vehicle 3 – Sample A – E20

The engine was checked for valve clearances pre- and post-durability test. The engine showed no valve clearance degradation over the durability testing. All values were within the required OEM specification.

E.4.1.4 Compression, Leakage – Vehicle 3 – Sample A – E20

The cylinder compression values remained within ten percent throughout the 500 hours of testing; no issues were noted.

The leakage numbers were below ten percent on all cylinders for all checkpoints during testing.

E.4.1.5 Engine Teardown – Vehicle 3 – Sample A – E20

Although this engine did not fail the 500 hour test, it was torn down and inspected by the OEM in order to compare it to the duplicate engine of the same kind (Sample B) which failed the test on E20. No issues were found upon inspection of the cylinder head.

E.4.2 Vehicle 3 – Sample B – E20

E.4.2.1 Summary – Vehicle 3 – Sample B – E20

Vehicle 3 – Sample B – E20 completed 500 hours of durability testing. The engine passed the criteria for compression, diagnostic trouble codes and emissions, but failed valve clearance and leakage requirements.

Figure E.4.2.1: Vehicle 3 – Sample B – E20 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 3 – Sample A – E20	Pass	Pass	Fail	Pass	Fail

E.4.2.2 FTP75 – Vehicle 3 – Sample B – E20

SOT emissions were measured on a chassis roll dynamometer and per the FEV engine dynamometer method for predicted vehicle emissions. EOT emissions were also measured per the FEV engine dynamometer method to estimate a correlation with initial vehicle emissions. The SOT to EOT emissions delta in the engine dynamometer test was added to the initial vehicle FTP75 emissions. The estimated final vehicle emission results show that NO_x and CO were within the standards and, therefore, passed the test.

E.4.2.3 Valve Clearance – Vehicle 3 – Sample B – E20

The valve clearance measurements revealed degradation in one cylinder. All other valve measurement values remained within the required OEM specification.

E.4.2.4 Compression, Leakage – Vehicle 3 – Sample B – E20

Leakdown on one cylinder increased beyond ten percent at 100 hours and remained high throughout testing. Other cylinders remained below ten percent leakage until 325 hours.

At this point the leakage in one cylinder was measured at twelve percent, while another cylinder was much higher than ten percent. This correlated with the cylinder that exhibited an intake valve clearance out of tolerance. These two cylinders remained high for remainder of the testing.

Compression in one cylinder was low at 100 hours; two cylinders were low by the end of the test. However, they were still within the 25% range of maximum compression.

Engine power and torque decreased seven to nine percent across the test.

The engine failed the test for leakage in multiple cylinders and the engine was returned to the OEM for examination.

E.4.2.5 Engine Teardown – Vehicle 3 – Sample B – E20

Exhaust seats were widened in all cylinders. Intake valve seat wear on several intake valves was noted. One intake seat exhibited more than normal wear. The valve which was matched to the worst intake seat wear appeared also to be in worse shape than the other intake valves and had degraded clearance.

E.4.3 Vehicle 3 – Sample C – E15

E.4.3.1 Summary – Vehicle 3 – Sample C – E15

Vehicle 3 – Sample C – E15 completed 500 hours of durability testing. The engine passed the criteria for compression, diagnostic trouble codes, valve clearance and emissions, but failed leakage requirements.

Figure E.4.3.1: Vehicle 3 – Sample C – E15 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 3 – Sample C – E15	Pass	Pass	Pass	Pass	Fail

E.4.3.2 FTP75 – Vehicle 3 – Sample C – E15

Emission measurements were recorded comparing initial and EOT emissions on a chassis dynamometer. All emissions (CO, NMOG and NO_x) were within the certification limits and the vehicle passed the EOT vehicle emission test.

E.4.3.3 Valve Clearance – Vehicle 3 – Sample C – E15

The engine was checked for valve clearances pre- and post-durability test. The engine showed no valve clearance degradation over the durability testing. All values were within the required OEM specification.

E.4.3.4 Compression, Leakage – Vehicle 3 – Sample C – E15

Cylinder compression values remained within ten percent throughout the 500 hours of testing; no issues were noted.

Leakdown measurements were below ten percent for the first 250 hours. At 300 hours the leakage on two cylinders increased above ten percent. Leakage on three cylinders was above the threshold at the end of testing and the engine was returned to the OEM for examination.

E.4.3.5 Engine Teardown – Vehicle 3 – Sample C – E15

Exhaust seats were widened in all cylinders. Several guides exhibited slightly more than normal wear. A majority of leakage appeared to come through the exhaust. Carbon deposits were noted on all seats. No issues were noted with any of the valves.

E.4.4 Vehicle 3 – Sample D – E15

E.4.4.1 Summary – Vehicle 3 – Sample D – E15

Vehicle 3 – Sample D – E15 completed 500 hours of durability testing. The engine passed the criteria for compression, leakage, diagnostic trouble codes, valve clearance and emissions.

Figure E.4.4.1: Vehicle 3 – Sample D – E15 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 3 – Sample D – E15	Pass	Pass	Pass	Pass	Pass

E.4.4.2 FTP75 – Vehicle 3 – Sample D – E15

Emission measurements were recorded comparing initial and EOT emissions on a chassis dynamometer. All emissions (CO, NMOG and NO_x) were within the certification limits and the vehicle passed the EOT vehicle emission test.

E.4.4.3 Valve Clearance – Vehicle 3 – Sample D – E15

The engine was checked for valve clearances pre- and post-durability test. The engine showed no valve clearance degradation over the durability testing. All values were within the required OEM specification.

E.4.4.4 Compression, Leakage – Vehicle 3 – Sample D – E15

The cylinder compression values remained within ten percent throughout the 500 hours of testing; no issues were noted.

The leakage numbers were below ten percent on all cylinders for all checkpoints during testing.

E.4.4.5 Engine Teardown – Vehicle 3 – Sample D – E15

An engine teardown was not conducted as the engine passed all pass/fail criteria.

E.4.5 Vehicle 3 – Sample E – E0

E.4.5.1 Summary – Vehicle 3 – Sample E – E0

Vehicle 3 – Sample E – E0 completed 500 hours of durability testing. The engine passed the criteria for compression, leakage, diagnostic trouble codes, valve clearance measurements and emissions.

Figure E.4.5.1: Vehicle 3 – Sample E – E0 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 3 – Sample E – E0	Pass	Pass	Pass	Pass	Pass

E.4.5.2 FTP75 – Vehicle 3 – Sample E – E0

Emission measurements were recorded comparing initial and EOT emissions on a chassis dynamometer. All emissions (CO, NMOG and NO_x) were within the certification limits and the vehicle passed the EOT vehicle emission test.

E.4.5.3 Valve Clearance – Vehicle 3 – Sample E – E0

The engine was checked for valve clearances pre- and post-durability test. The engine showed no valve clearance degradation over the durability testing. All values were within the required OEM specification.

E.4.5.4 Compression, Leakage – Vehicle 3 – Sample E – E0

The cylinder compression values remained within ten percent throughout the 500 hours of testing; no issues were noted.

The leakage numbers were below ten percent on all cylinders for all checkpoints during testing.

E.4.5.5 Engine Teardown – Vehicle 3 – Sample E – E0

An engine teardown was not conducted as the engine passed all pass/fail criteria.

E.4.6 Vehicle 3 – Sample F – E0

E.4.6.1 Summary – Vehicle 3 – Sample F – E0

Vehicle 3 – Sample F – E0 completed 500 hours of durability testing. The engine passed the criteria for compression, leakage, diagnostic trouble codes, valve clearance and emissions.

Figure E.4.6.1: Vehicle 3 – Sample F – E0 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 3 – Sample F – E0	Pass	Pass	Pass	Pass	Pass

E.4.6.2 FTP75 – Vehicle 3 – Sample F – E0

Emission measurements were recorded comparing initial and EOT emissions on a chassis dynamometer. All emissions (CO, NMOG and NO_x) were within the certification limits and the vehicle passed the EOT vehicle emission test.

E.4.6.3 Valve Clearance – Vehicle 3 – Sample F – E0

The engine was checked for valve clearances pre- and post-durability test. The engine showed no valve clearance degradation over the durability testing. All values were within the required OEM specification.

E.4.6.4 Compression, Leakage – Vehicle 3 – Sample F – E0

The cylinder compression values remained within ten percent throughout the 500 hours of testing; no issues were noted.

The leakage numbers were below ten percent on all cylinders for all checkpoints during testing.

E.4.6.5 Engine Teardown – Vehicle 3 – Sample F – E0

An engine teardown was not conducted as the engine passed all pass/fail criteria.

E.4.7 Vehicle 3 – Additional OEM Comments on Failures

Vehicle 3 was chosen by the OEM to be part of this study as a test engine because it is a high production volume engine not specifically designed for E20 fuel. Internal testing conducted by the OEM had validated this engine design to operate on Brazilian E22 fuel, and therefore, it was expected that both engines would pass the E20 testing without incident. After the unexpected failure of the engine to meet the leakdown and compression criteria, investigation of production records revealed that intake seat materials had been changed after the first year of production.

The new seat materials were the ones used on the engine design that the OEM had validated on Brazilian E22. The original production seats used a material that was not considered robust to ethanol blends higher than E10. All Vehicle 3 engines used for this testing were produced before the intake valve seat upgrade was implemented and had the inferior intake seat materials.

-2 engines run on E0 passed because the engine was validated on E0

-1 engine run on E20 failed because the intake seat materials were not robust to blends higher than E10

-1 engine run on E15 failed but it appears the leakdown/compression loss was a result of exhaust seat wear

The 500-hour test plan devised for this CRC study exposed a known weakness with greater than E10 fuels without over-stressing those same components when running E0 fuel.

E.5 Durability Testing: Vehicle 4

E.5.1 Vehicle 4 – Sample A – E20

E.5.1.1 Summary – Vehicle 4 – Sample A – E20

Vehicle 4 – Sample A – E20 completed 500 hours of durability testing. The engine passed the criteria for emissions, diagnostic trouble codes, compression and valve clearance. However, the engine failed the leakage requirement.

Figure E.5.1.1: Vehicle 4 – Sample A – E20 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 4 – Sample A – E20	Pass	Pass	Pass	Pass	Fail

E.5.1.2 FTP75 – Vehicle 4 – Sample A – E20

SOT emissions were measured on a chassis roll dynamometer and per the FEV engine dynamometer method for predicted vehicle emissions. EOT emissions were also measured per the FEV engine dynamometer method to estimate a correlation with initial vehicle emissions.

The estimated final vehicle emissions were above the required standard for NO_x and CO. However, the actual catalyst was provided back to the OEM and was installed in a vehicle for chassis roll emission testing. The OEM indicated that the catalyst was still performing within specification, and therefore, was deemed a “pass”.

E.5.1.3 Valve Clearance – Vehicle 4 – Sample A – E20

The engine was checked for valve clearances pre- and post-durability test. The engine showed no valve clearance degradation over the durability testing. All values were within the required OEM specification.

E.5.1.4 Compression, Leakage – Vehicle 4 – Sample A – E20

The engine passed the compression criterion.

The leakage numbers were below ten percent on all cylinders for the majority of the testing. However, at 100 hours the leakage increased above ten percent on two cylinders. At the next check interval of 150 hours, one cylinder was above the ten percent limit. The 250 hour check also showed leakage higher than ten percent for one cylinder. After 250 hours, leakage on the same cylinder remained below ten percent until EOT.

At EOT, however, the cylinder with high leakdown surpassed the ten percent leakage threshold (measured leakage was eleven percent). The engine though was considered to have passed the leakage test per recommendation from the project panel members after engine teardown by the OEM and is therefore shown as waived in the overview table.

E.5.1.5 Engine Teardown – Vehicle 4 – Sample A – E20

At EOT, the engine was sent to the OEM for further analysis. The OEM reported no unusual wear on the valves or valve seats. Valve lash was also measured and was found to be within tolerance.

E.5.2 Vehicle 4 – Sample B – E20

E.5.2.1 Summary – Vehicle 4 – Sample B – E20

Vehicle 4 – Sample B – E20 completed 500 hours of durability testing. The engine passed the criteria for leakage, compression, emissions, diagnostic trouble codes and valve clearance.

Figure E.5.2.1: Vehicle 4 – Sample B – E20 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 4 – Sample B – E20	Pass	Pass	Pass	Pass	Pass

E.5.2.2 FTP75 – Vehicle 4 – Sample B – E20

SOT emissions were measured on a chassis roll dynamometer and per the FEV engine dynamometer method for predicted vehicle emissions. EOT emissions were also measured per the FEV engine dynamometer method to estimate a correlation with initial vehicle emissions.

The emission results degraded over time using the FEV predicted emissions method and the engine did not pass the required emissions criterion. However, the engine and exhaust system were sent to the OEM, reinstalled in the production vehicle, and subjected to additional vehicle chassis roll emission testing. According to the OEM technical contact, the vehicle then successfully passed the chassis roll FTP75 emissions test. Thus, the engine was determined to have passed the emissions criterion.

E.5.2.3 Valve Clearance – Vehicle 4 – Sample B – E20

The engine was checked for valve clearances pre- and post-durability test. The engine showed no valve clearance degradation over the durability testing. All values were within the required OEM specification.

E.5.2.4 Compression, Leakage – Vehicle 4 – Sample B – E20

The cylinder compression values remained within ten percent throughout the 500 hours of testing; no issues were noted.

The leakage numbers were below ten percent on all cylinders for the majority of testing. However, at 150 hours the leakage increased above ten percent on two cylinders. After 150 hours, leakage on all cylinders remained below ten percent through EOT. Thus, the engine was determined to have passed the leakdown and compression test.

E.6 Durability Testing: Vehicle 5

E.6.1 Vehicle 5 – Sample A – E20

E.6.1.1 Summary – Vehicle 5 – Sample A – E20

Vehicle 5 – Sample A – E20 completed 500 hours of durability testing. The engine passed the criteria for leakage, compression and valve clearance. The engine failed the requirements for emissions and DTCs.

Figure E.6.1.1: Vehicle 5 – Sample A – E20 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 5 – Sample A – E20	Fail	Fail	Pass	Pass	Pass

E.6.1.2 FTP75 – Vehicle 5 – Sample A – E20

Emission measurements were recorded comparing initial and EOT emissions on a chassis dynamometer. The EOT vehicle emissions showed an increased level of CO (33% above emission standard) and NO_x (50% above emission standard) and did not meet the certification limits based on vehicle mileage.

In addition, DTC P0420 was set when the engine was reinstalled in the vehicle. The fault code was not present during engine dynamometer testing. The P0420 code indicates low catalyst efficiency; the service manual instructs replacement of the catalyst. The vehicle completed the EOT chassis roll FTP75 with this code active; the catalyst was not replaced, and the vehicle failed the EOT FTP75 vehicle emission test.

The emission results were discussed with the OEM. The OEM indicated known issues with vehicle 5 catalysts, and as such, they are offering extended warranty for catalyst replacement. It was decided not to retest this vehicle type on E15 because this failure was deemed not to be caused by the increased ethanol content. Another factor in this decision was that the second vehicle sample of this vehicle type passed all criteria.

E.6.1.3 Valve Clearance – Vehicle 5 – Sample A – E20

The engine was checked for valve clearances pre- and post-durability test. The engine showed no valve clearance degradation over the durability testing. All values were within the required OEM specification.

E.6.1.4 Compression, Leakage – Vehicle 5 – Sample A – E20

The cylinder compression values remained within ten percent throughout the 500 hours of testing; no issues were noted.

The leakage numbers were below ten percent on all cylinders for all checkpoints during testing.

E.6.1.5 Engine Teardown – Vehicle 5 – Sample A – E20

The cylinder heads from the engine were sent to the OEM for analysis. It was reported that the valves and valve seats did not show evidence of wear or unusual patterns and were pronounced normal.

E.6.2 Vehicle 5 – Sample B – E20

E.6.2.1 Summary – Vehicle 5 – Sample B – E20

Vehicle 5 – Sample B – E20 completed 500 hours of durability testing. The engine passed the criteria for leakage, compression, emissions, DTCs, and valve clearance.

Figure E.6.2.1: Vehicle 5 – Sample B – E20 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 5 – Sample B – E20	Pass	Pass	Pass	Pass	Pass

E.6.2.2 FTP75 – Vehicle 5 – Sample B – E20

Emission measurements were recorded comparing initial and end of test emissions on a chassis dynamometer. All emissions (CO, NMOG and NO_x) were within the certification limits and the vehicle passed the EOT vehicle emission test.

E.6.2.3 Valve Clearance – Vehicle 5 – Sample B – E20

The engine was checked for valve clearances pre- and post- durability test. The engine showed no valve clearance degradation over the durability testing. All values were within the required OEM specification.

E.6.2.4 Compression, Leakage – Vehicle 5 – Sample B – E20

The cylinder compression values remained within ten percent throughout the 500 hours of testing; no issues were noted.

The leakage numbers were below ten percent on all cylinders for all checkpoints during testing.

E.6.2.5 Engine Teardown – Vehicle 5 – Sample B – E20

An engine teardown was not conducted as the engine passed all pass/fail criteria.

E.7 Durability Testing: Vehicle 6

E.7.1 Vehicle 6 – Sample A – E20

E.7.1.1 Summary – Vehicle 6 – Sample A – E20

Vehicle 6 – Sample A – E20 completed 500 hours of durability testing. The engine passed the criteria for compression, valve clearance, emissions and DTCs, but failed the leakage requirements.

Based on a detailed analysis by the OEM, the engine was determined to have no issues relating to valve or valve seat wear.

Figure E.7.1.1: Vehicle 6 – Sample A – E20 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 6 – Sample A – E20	Pass	Pass	Pass	Pass	Fail

E.7.1.2 FTP75 – Vehicle 6 – Sample A – E20

Emission measurements were recorded comparing initial and end of test emissions on a chassis dynamometer. All emissions (CO, NMOG and NO_x) were within the certification limits, and the vehicle passed the EOT vehicle emission test.

E.7.1.3 Valve Clearance – Vehicle 6 – Sample A – E20

The engine was checked for valve clearances pre- and post-durability test. The engine showed no valve clearance degradation over the durability testing. All values were within the required OEM specification.

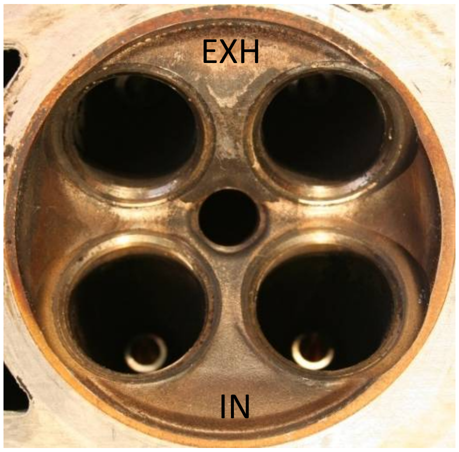
E.7.1.4 Compression, Leakage – Vehicle 6 – Sample A – E20

The cylinder compression values remained within ten percent throughout the 500 hours of testing; no issues were noted.

The leakdown measurements all remained below ten percent through 400 hours. At 450 hours, the leakage increased above the ten percent threshold on one cylinder. At the 500 cycle check, the cylinder was below ten percent. The engine was sent to the OEM for analysis.

E.7.1.5 Engine Teardown – Vehicle 6 – Sample A – E20

The OEM completed a cylinder head teardown on this engine. It was noted that the valves showed carbon impregnation as shown in figure E.7.1.2. The valve seat showed some valve seat material transfer but it was not possible to determine a cause because the initial state of these seats was not known. Overall, the valve seat did not show any abnormal deposits or wear and was acceptable to the OEM.



CYL 1

(a)

(b)

Figure E.7.1.2: Valve Seat Pictures (a) and (b) after Test

E.7.2 Vehicle 6 – Sample B – E20

E.7.2.1 Summary – Vehicle 6 – Sample B – E20

Vehicle 6 – Sample B – E20 completed 500 hours of durability testing. The engine passed the criteria for compression, valve clearance, emissions and DTCs, but failed the leakage requirements.

Based on a detailed analysis by the OEM, the engine was determined to have no issues relating to valve or valve seat wear.

Figure E.7.2.1: Vehicle 6 – Sample B – E20 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 6 – Sample B – E20	Pass	Pass	Pass	Pass	Fail

E.7.2.2 FTP75 – Vehicle 6 – Sample B – E20

Emission measurements were recorded comparing initial and EOT emissions on a chassis dynamometer. All emissions (CO, NMOG and NO_x) were within the certification limits and the vehicle passed the EOT vehicle emission test.

E.7.2.3 Valve Clearance – Vehicle 6 – Sample B – E20

The engine was checked for valve clearances pre- and post-durability test. The engine showed no valve clearance degradation over the durability testing. All values were within the required OEM specification.

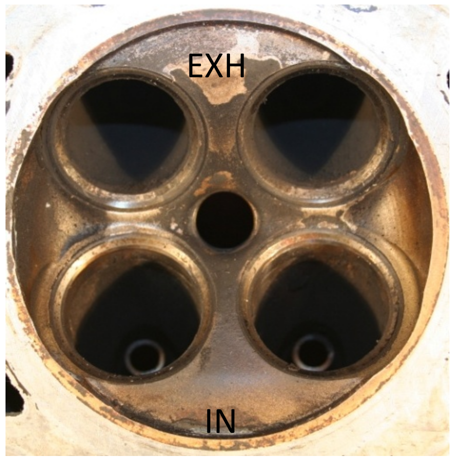
E.7.2.4 Compression, Leakage – Vehicle 6 – Sample B – E20

The cylinder compression values remained within ten percent throughout the 500 hours of testing; no issues were noted.

The leakdown measurements all remained below ten percent for 50 hours. At 50 hours, the leakage increased above the threshold to 11% on one cylinder. The same cylinder recorded leakage between eleven to fifteen percent throughout the remaining testing. The leakage on another cylinder measured eleven percent at 150 and 400 hours, respectively. The engine was sent to the OEM for analysis.

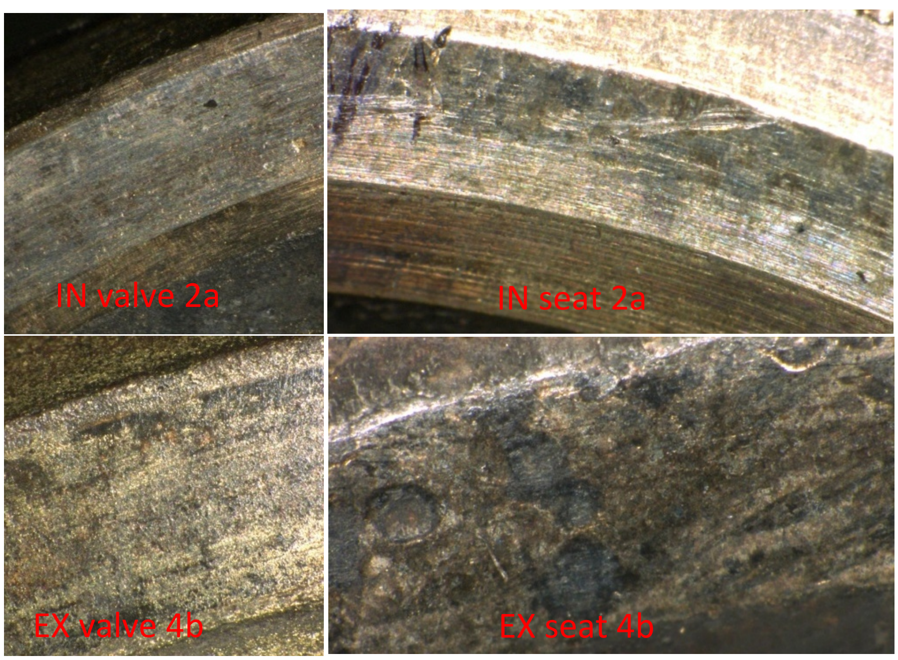
E.7.2.5 Engine Teardown – Vehicle 6 – Sample B – E20

The OEM completed a cylinder head teardown on this engine. It was noted that the valves showed carbon impregnation as shown in Figure E.7.2.2. The valve seat showed some valve seat material transfer but was not able to be assessed to accurate measurements as the initial state of these seats was not known. Overall, the valve seat did not show any abnormal deposits or wear and was acceptable to the OEM.



CYL 1

(a)



(b)

Figure E.7.2.2: Valve Seat Pictures (a) and (b) after Test

E.8 Durability Testing: Vehicle 7

E.8.1 Vehicle 7 – Sample A – E20

E.8.1.1 Summary – Vehicle 7 – Sample A – E20

Vehicle 7 – Sample A – E20 completed 500 hours of durability testing. The engine passed the criteria for compression, valve clearance, emissions, DTCs and leakage.

Figure E.8.1.1: Vehicle 7 – Sample A – E20 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 7 – Sample A – E20	Pass	Pass	Pass	Pass	Pass

E.8.1.2 FTP75 – Vehicle 7 – Sample A – E20

SOT emissions were measured on a chassis roll dynamometer and per the FEV engine dynamometer method for predicted vehicle emissions. EOT emissions were also measured per the FEV engine dynamometer method to estimate a correlation with initial vehicle emissions. EOT emissions met the required standard per the FEV predicted emissions method.

E.8.1.3 Valve Clearance – Vehicle 7 – Sample A – E20

The engine was checked for valve clearances pre- and post-durability test. The engine showed no valve clearance degradation over the durability testing. All values were within the required OEM specification.

E.8.1.4 Compression, Leakage – Vehicle 7 – Sample A – E20

The cylinder compression values remained within ten percent throughout the 500 hours of testing; no issues were noted.

The leakage numbers were below ten percent on all cylinders for all checkpoints during testing.

E.8.1.5 Engine Teardown – Vehicle 7 – Sample A – E20

An engine teardown was not conducted as the engine passed all pass/fail criteria.

E.8.2 Vehicle 7 – Sample B – E20

E.8.2.1 Summary – Vehicle 7 – Sample B – E20

Vehicle 7 – Sample B – E20 completed 500 hours of durability testing. The engine passed the criteria for compression, valve clearance, emissions, DTCs and leakage.

Figure E.8.2.1: Vehicle 7 – Sample B – E20 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 7 – Sample B – E20	Pass	Pass	Pass	Pass	Pass

E.8.2.2 FTP75 – Vehicle 7 – Sample B – E20

Emission measurements were recorded comparing initial and end of test emissions on a chassis dynamometer. All emissions (CO, NMOG and NO_x) were within the certification limits and the vehicle passed the EOT vehicle emission test.

E.8.2.3 Valve Clearance – Vehicle 7 – Sample B – E20

The engine was checked for valve clearances pre- and post-durability test. The engine showed no valve clearance degradation over the durability testing. All values were within the required OEM specification.

E.8.2.4 Compression, Leakage – Vehicle 7 – Sample B – E20

The cylinder compression values remained within ten percent throughout the 500 hours of testing; no issues were noted.

The leakage numbers were below ten percent on all cylinders for all checkpoints during testing.

E.8.2.5 Engine Teardown – Vehicle 7 – Sample B – E20

An engine teardown was not conducted as the engine passed all pass/fail criteria.

E.9 Durability Testing: Vehicle 8

E.9.1 Vehicle 8 – Sample A – E20

E.9.1.1 Summary – Vehicle 8 – Sample A – E20

Vehicle 8 – Sample A – E20 completed 500 hours of durability testing. The engine passed the criteria for DTCs and valve clearance. However, the engine failed leakage, compression and emission requirements.

Figure E.9.1.1: Vehicle 8 – Sample A – E20 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 8 – Sample A – E20	Fail	Pass	Pass	Fail	Fail

E.9.1.2 FTP75 – Vehicle 8 – Sample A – E20

SOT and EOT emissions were measured on a chassis roll dynamometer. At EOT, NO_x emissions did not pass the required standard (14% above emission standard) and the vehicle failed the EOT emission test.

E.9.1.3 Valve Clearance – Vehicle 8 – Sample A – E20

The engine was checked for valve clearances pre- and post- durability test. The engine showed no valve clearance degradation over the durability testing. All values were within the required OEM specification.

E.9.1.4 Compression, Leakage – Vehicle 8 – Sample A – E20

The compression on one cylinder was low. It failed the compression specification at 450 and 500 hours (specification = lowest compression cylinder is within 25% of highest compression cylinder). All other cylinders maintained good compression across the testing duration.

The leakdown measurements all remained below ten percent until the engine reached 300 hours. At that time, one cylinder increased beyond the ten percent threshold; the leakage on this cylinder increased throughout the remainder of the testing. The leakage was monitored every 25 hours following the 300 cycle check. A second cylinder increased beyond ten percent leakage at 375 hours and continued to increase for the remainder of the testing. All other cylinders remained below the ten percent specification.

E.9.1.5 Engine Teardown – Vehicle 8 – Sample A – E20

Heavy pitting was observed on exhaust valve seats. Moderate wear was noted on intake valve seats and normal wear was noted on intake and exhaust valves. No issues were noted on engine bearings, pistons and piston rings.

E.9.2 Vehicle 8 – Sample B – E20

E.9.2.1 Summary – Vehicle 8 – Sample B – E20

Vehicle 8 – Sample B – E20 completed 500 hours of durability testing, but failed the compression and leakage criteria.

The engine had higher leakdown on one cylinder at EOT. At EOT the OEM technical contact requested that a WOT test be performed. During the WOT test the engine experienced a catastrophic failure and engine testing was stopped. Leakage in one cylinder was measured to be 100% indicating no compression. The results were shared with OEM and a decision was made to send the engine to the OEM for further analysis. EOT valve measurements and emission testing were not completed at FEV.

Figure E.9.2.1: Vehicle 8 – Sample B – E20 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 8 – Sample B – E20	N/A	N/A	N/A	Fail	Fail

E.9.2.2 FTP75 – Vehicle 8 – Sample B – E20

SOT emissions were recorded but EOT emission testing was not performed as there was no compression in one cylinder and the engine was sent to the OEM for further analysis prior to completion of the durability test.

E.9.2.3 Valve Clearance – Vehicle 8 – Sample B – E20

Valve clearance measurements were measured at SOT but were not completed due to the above-mentioned engine failure.

E.9.2.4 Compression, Leakage – Vehicle 8 – Sample B – E20

Leakdown measurements all remained below ten percent until the engine reached 250 hours. At that time, one cylinder increased beyond the ten percent threshold and increased throughout the remainder of the testing. The compression on the same cylinder was low, but still within specification (specification = lowest compression cylinder is within 25% of the highest compression cylinder).

The rest of the cylinders maintained leakage and compression with specification for the duration of the 500 hours.

At the EOT WOT checks, the engine showed a drop in power. The leakage in one cylinder was 100% and compression was zero.

E.9.2.5 Engine Teardown – Vehicle 8 – Sample B – E20

Heavy pitting was observed on exhaust valve seats. Moderate wear was noted on intake valve seats and normal wear was noted on intake and exhaust valves. No issues were noted with respect to engine bearings, pistons and piston rings.

E.9.3 Vehicle 8 – Sample C – E15

E.9.3.1 Summary – Vehicle 8 – Sample C – E15

Vehicle 8 – Sample C – E15 completed 350 hours of durability testing after which the engine failed due to leakage above ten percent in multiple cylinders. Compression also dropped on several cylinders.

The engine was removed from the test cell with approval from the OEM technical specialist. The engine was sent for emission testing and the vehicle failed an FTP75 emission test. The valve measurements at SOT and at 350 hours showed no valve clearance degradation.

Figure E.9.3.1: Vehicle 8 – Sample C – E15 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 8 – Sample C – E15	Fail	N/A	N/A	N/A	Fail

E.9.3.2 FTP75 – Vehicle 8 – Sample C – E15

Emission measurements were recorded comparing initial and EOT emissions on a chassis dynamometer. The vehicle failed the FTP75 emission test, both NMOG (27% above emission standard) and NO_x (22% above emission standard) were high correlating to the high leakdown measurements.

E.9.3.3 Valve Clearance – Vehicle 8 – Sample C – E15

The engine was checked for valve clearances pre- and post- durability test. The engine showed no valve clearance degradation over the durability testing. All values were within the required OEM specification. However, the EOT measurements were conducted at only 350 hours. The valve clearance measurements were waived as the engine did not complete 500 hours of durability testing.

E.9.3.4 Compression, Leakage – Vehicle 8 – Sample C – E15

Cylinder compression values dropped during the test, but remained within OEM specifications. The compression measurements were waived as the engine did not complete 500 hours of durability testing.

One cylinder measured leakage above ten percent at 100 and 150 hours. Additional cylinders had leakage above ten percent at the 200 hour, 250 hour and 300 hour inspections. Leakdown measurements exceeded ten percent in multiple cylinders at the 350 hour inspection.

E.9.3.5 Engine Teardown – Vehicle 8 – Sample C – E15

Heavy pitting was observed on exhaust valve seats. Moderate wear was noted on intake valve seats and normal wear was noted on intake and exhaust valves.

E.9.4 Vehicle 8 – Sample D – E15

E.9.4.1 Summary – Vehicle 8 – Sample D – E15

Vehicle 8 – Sample D – E15 completed 250 hours of durability testing after which the engine failed leakage and compression requirements. One cylinder was above the ten percent limit and compression also dropped more than the OEM specification.

After the 250 hour check, the engine was removed from test with the consent of the OEM technical specialist. The engine was sent for emission testing and the vehicle passed the FTP75 emission test. Valve measurements at SOT and 250 hours showed no valve wear degradation.

Figure E.9.4.1: Vehicle 8 – Sample D – E15 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 8 – Sample D – E15	N/A	N/A	N/A	Fail	Fail

E.9.4.2 FTP75 – Vehicle 8 – Sample D – E15

Emission measurements were recorded comparing initial and EOT emissions on a chassis dynamometer. The vehicle passed the FTP75 emission test but was considered waived as the engine did not complete 500 hours of durability testing.

E.9.4.3 Valve Clearance – Vehicle 8 – Sample D – E15

The engine was checked for valve clearances pre- and post-durability test. The engine showed no valve clearance degradation over the durability testing. All values were within the required OEM specification. However, the EOT measurements were conducted at only 250 hours. The valve clearance measurements were waived as the engine did not complete 500 hours of durability testing.

E.9.4.4 Compression, Leakage – Vehicle 8 – Sample D – E15

At 250 hours cylinder compression on one cylinder dropped below the OEM specified tolerance.

Leakage was higher than ten percent in the same cylinder at 200 and 250 hours. Leakage at 250 hours was considerably higher in this cylinder and the engine was removed from test. All other cylinders remained within leakage and compression limits.

E.9.4.5 Engine Teardown – Vehicle 8 – Sample D – E15

Heavy pitting was observed on exhaust valve seats. Moderate wear was noted on intake valve seats and normal wear was noted on intake and exhaust valves.

E.9.5 Vehicle 8 – Sample E – E0

E.9.5.1 Summary – Vehicle 8 – Sample E – E0

Vehicle 8 – Sample E – E0 completed 500 hours of durability testing. The engine passed the criteria for diagnostic trouble codes and valve clearance. However, the engine failed leakage, compression and emission requirements.

Figure E.9.5.1: Vehicle 8 – Sample E – E0 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 8 – Sample E – E0	Fail	Pass	Pass	Fail	Fail

E.9.5.2 FTP75 – Vehicle 8 – Sample E – E0

Emission measurements were recorded comparing initial and end of test emissions on a chassis dynamometer. The vehicle failed the FTP75 emission test, and both NMOG (39% above emission standard) and NO_x (56% above emission standard) were high correlating to the high leakdown measurements.

E.9.5.3 Valve Clearance – Vehicle 8 – Sample E – E0

The engine was checked for valve clearances pre- and post-durability test. The engine showed no valve clearance degradation over the durability testing. All values were within the required OEM specification.

E.9.5.4 Compression, Leakage – Vehicle 8 – Sample E – E0

The compression was low in multiple cylinders.

The leakdown measurements all remained below ten percent until the engine reached 150 hours. At that time, two cylinders increased beyond the ten percent threshold; the leakage on these cylinders increased throughout the remainder of the testing. At EOT multiple cylinders exceeded the 10% leakage threshold.

E.9.5.5 Engine Teardown – Vehicle 8 – Sample E – E0

Some pitting was observed on exhaust valve seats. Moderate wear was noted on intake valve seats and normal wear was noted on intake and exhaust valves.

E.9.6 Vehicle 8 – Sample F – E0

E.9.6.1 Summary – Vehicle 8 – Sample F – E0

Vehicle 8 – Sample F – E0 completed 500 hours of durability testing. The engine passed the criteria for diagnostic trouble codes, valve clearance and compression. However, the engine failed leakage and emission requirements.

Figure E.9.6.1: Vehicle 8 – Sample F – E0 Results Summary

	Emissions	DTC	Valve Clearance	Compression	Leakage
Vehicle 8 – Sample F – E0	Fail	Pass	Pass	Pass	Fail

E.9.6.2 FTP75 – Vehicle 8 – Sample F – E0

Emission measurements were recorded comparing initial and EOT emissions on a chassis dynamometer. The vehicle failed the FTP75 emission test, both NMOG (>100% above emission standard) and NO_x (>100% above emission standard) were high correlating to the high leakdown measurements.

E.9.6.3 Valve Clearance – Vehicle 8 – Sample F – E0

The engine was checked for valve clearances pre- and post-durability test. The engine showed no valve clearance degradation over the durability testing. All values were within the required OEM specification.

E.9.6.4 Compression, Leakage – Vehicle 8 – Sample F – E0

The compression was within specifications on all cylinders.

The leakdown measurements exceeded the 10% threshold on all cylinders at EOT.

E.9.6.5 Engine Teardown – Vehicle 8 – Sample F – E0

Some pitting was observed on exhaust valve seats. Moderate wear was noted on intake valve seats and normal wear was noted on intake and exhaust valves. No issues were noted on engine bearings, pistons and piston rings.

E.9.7 Vehicle 8 – Additional OEM Provided Comments on Failures

The teardown analyses conducted by the OEM revealed that the engines which ran on E20 and E15 showed higher wear and heavier pitting of the exhaust valve seats compared to the engines which ran on E0. However, pitting on the E0 engines was still severe enough that they also failed the leakage criteria. No issues were noted on engine bearings, pistons and piston rings.

Upon examination of the test results and engine design the OEM determined that the valvetrain design inhibited valve rotation at lower engine speeds and that the limited amount of time spent over 3500 rpm in the test combined with the valve spring design led to abnormally high valve seat wear for all of the fuel combinations due to inhibited valve rotation. Unlike other engines in the test, this particular engine's spring design is more sensitive to the rpm threshold and would be better suited for a test with intervals at higher speeds. In retrospect, it would be expected for the engine to experience abnormal valve seat wear during this test cycle, regardless of fuel composition.

F. Statistical Analysis of Test Results

The test cycle employed in this test program is usually run in triplicate. If all three tests pass, then there is less than 50% likelihood that the proportion of engines in the population that would fail the test cycle is greater than 20% assuming a Binomial probability rule. While this might not seem very robust, the increased stress of the test cycle relative to normal use has helped ensure good field reliability for engines that have passed this test.

Due to limited funding in this test program duplicate rather than triplicate samples were used. If both tests pass, then there is less than 50% likelihood that the proportion of engines in the population that would fail the test cycle is greater than 30%. For the engine where one of two samples failed, the population failure rate would exceed 70% with less than 50% likelihood although testing four additional engines successfully would return the failure rate limit below 30%. For the engine where two samples failed, the failure rate limit cannot be calculated using this Binomial technique. However, testing an additional seven engines successfully would return the failure rate limit below 30%.

With 14 passes and zero failures on E0, the population failure rate would exceed 5% with less than 50% likelihood. For E15 and E20, each with 11 passes and 3 failures the population failure rate would exceed 26% with less than 50% likelihood. To illustrate the difference between 5% and 26% failure rate limits, in the latter case, a sample of 62 additional engines would need to be run without failure to ensure the failure rate would not exceed 5% with less than 50% likelihood.

Another approach for comparing failure rates is Fisher's Exact Test.[19] We might compare E0 with E15 and E20 separately.

19 Technical Summary of DOE Study on E15 Impacts On Tier 2 Vehicles and Southwest Research Teardown Report. EPA Docket #EPA–HQ–OAR–2009–0211-14019.

Figure F.1: Fisher's Exact Probability Test for Ethanol (E15 only)

	Pass	Fail	Total
E0	14	0	14
E15	11	3	14
Total	25	3	28

There is an 11% chance that all three failures would have occurred with E15 if failure were independent of ethanol (Figure F1).

The results for E20 are the same. If we combine E15 and E20, to compare E0 with both ethanol containing fuels, there is a 7% chance that all six failures would have occurred with ethanol containing fuels if failure were independent of ethanol (Figure F2).

Figure F.2: Fisher's Exact Probability Test for Ethanol (E15 and E20 combined)

	Pass	Fail	Total
E0	14	0	14
E15 and E20	22	6	28
Total	36	6	42

G. Conclusions

After completion of all testing and detailed review of the experienced failure modes, the following conclusions can be drawn:

- Out of eight different tested engine types, one had a design that was (in retrospect) inappropriate for the test cycle, two failed on E20 and E15, and five passed on E20 and by assumption E15 and E0 (see Figure 1).

- Out of the two failed tested engine types, both successfully completed the reference testing on E0.

- There is an 11% chance that all three E15 failures (two with one vehicle type and one with another) would have occurred if failure were independent of ethanol. The results for E20 are the same. Combining the E15 results with the E20 results, there is a 7% chance that all six failures (two E15 and two E20 with one vehicle type and one E15 and one E20 with another) would have occurred with ethanol containing fuels if failure were independent of ethanol.

- For the failed engine which also failed on E0 reference fuel, the failures can not be directly linked to the ethanol content. The design of the engine interacting with the test cycle is the reason cited by the OEM maker to be the responsible cause for the occurred failures.

- The occurred failures do not show that specific valvetrain types are more or less sensitive to ethanol content.

- The majority of the failures can be linked to issues with valve seats, either related to material or wear/deformation.

The study has shown that two popular gasoline engines used in light-duty automotive applications of vehicles from model years 2001 through 2009 failed with mechanical damage when operated on intermediate-level ethanol blends (E15 and E20).

H. Appendix

H.1 Fuel Analyses

The following tables summarize the fuel analysis results of all E20, E15 and E0 fuel utilized during this study. The results are sorted by fuel type and tank number at FEV. Tank 10 and 11 were dedicated to this program throughout this study.

Fuel analysis overview – Tank 10 – E20

Tank 10											
Fuel Type	E20										
Delivery Date		10/13/2010	9/23/2010	9/16/2010	8/19/2010	8/10/2010	8/5/2010	7/28/2010	5/10/2010	4/26/2010	3/29/2010
Sample Date		10/13/2010	9/23/2010	9/16/2010	8/20/2010	8/10/2010	8/5/2010	7/28/2010	5/11/2010	4/27/2010	3/30/2010
Results Date		10/19/2010	9/29/2010	9/23/2010	8/27/2010	8/16/2010	8/11/2010	8/10/110	5/17/2010	5/4/2010	4/5/2010
Density @ 15C	g/ml	0.7487	0.7647	0.7652	0.7705	0.7635	0.7598	0.7541	0.7378	0.7378	0.7378
Density @ 20C	g/ml	0.7439	0.7603	0.7608	0.7661	0.7591	0.7553	0.7497	0.7332	0.7336	0.7332
Density @ 25C	g/ml	0.739	0.7558	0.7563	0.7616	0.7547	0.7509	0.7453	0.7284	0.7291	0.7287
Distillation											
Initial Boiling Point	Deg. F	89.4	106.4	105.8	118.3	110.6	110.9	105.5	88.8	89.6	86
5% Evaporated Temperature	Deg. F	110.7	135.8	136.6	144.4	140.4	141	133.8	109.2	109.2	107.8
10% Evaporated Temperature	Deg. F	123.4	143.2	143.8	149.8	147	147.2	141.5	121.3	121.5	120.9
20% Evaporated Temperature	Deg. F	141.1	152	152	155.8	154.2	153.9	150.7	138.7	138.9	139
30% Evaporated Temperature	Deg. F	153.3	158.6	158.7	161	159.5	159	157.3	150.8	151.1	151.2
40% Evaporated Temperature	Deg. F	160.4	162.9	162.9	164.1	162	162.6	161.8	157.3	158.6	158.7
50% Evaporated Temperature	Deg. F	164.6	166	165.6	167.6	166.3	164.9	165.4	162.4	163	163.2
60% Evaporated Temperature	Deg. F	168.6	213.5	218.3	230	225.2	226.5	212.5	165.7	166.3	166.3
70% Evaporated Temperature	Deg. F	242.7	249.2	249.3	252.6	251.5	248.7	248.8	229.9	231.3	229.9
80% Evaporated Temperature	Deg. F	274.1	278.5	279.4	282	277.2	276.7	269.5	261.3	259	260.7
90% Evaporated Temperature	Deg. F	322.2	325.3	328	331.5	329.5	326.8	327.6	314.9	315.3	315.4
95% Evaporated Temperature	Deg. F	357.9	360.6	361	363.6	361.5	358.7	362.7	355.3	355.2	355.1
End Point	Deg. F	405.4	406.8	408.4	412.6	414.5	411.9	411.7	413	410	410.9
% Overhead Recovery	%	96.8	97.7	98.1	98.1	97.7	97.8	97.5	96.6	96.4	96.5
% Residue	%	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
% Loss	%	2.1	1.2	0.8	0.8	1.2	1.1	1.4	2.3	2.5	2.4
Oxygenates											
Methanol	L.V. %	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
Ethanol	L.V. %	20.9	20.9	20.63	20.9	20.7	20.47	20.24	20.17	20.52	20.99
Tert-Butanol	L.V. %	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
MTBE	L.V. %	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
t-Amyl Methyl Ether	L.V. %	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
Octane Numbers											
Research	Octane	100.1	99.7	100	100.4	100	100	99.5	99.6	99.8	100
Motor	Octane	88.2	87.3	87.5	88	87.7	88	87.5	88.2	88.2	88.2
(R+M)/2	Octane	94.2	93.5	93.8	94.2	93.8	94	93.5	93.9	94	94.1
Heating Value NET	Btu/lb.	17108	16983	16903	16879	16984	17145	16716	17122	16980	17041
Heating Value NET	MJ/kg	39.792	39.502	39.316	39.259	39.504	39.878	38.881	39.827	39.496	39.638
Heating Value GROSS	Btu/lb.	18351	18194	18112	18085	18209	18380	17977	18398	18263	18322
Heating Value GROSS	MJ/kg	42.684	42.32	42.128	42.065	42.354	42.751	41.814	42.793	42.479	42.617
Total Sulfur	ppm wt.	10	9	8	11	13	16	15	17	16	16
Water	ppm wt.	2732	2872	2905	3784	4592	3805	3287	2955	2801	2708
Carbon	wt. %	78.95	79.72	79.47	79.71	79.3	78.85	79.43	78.27	78.06	77.8
Hydrogen	wt. %	13.63	13.28	13.25	13.22	13.43	13.54	13.82	13.98	14.06	14.4
Oxygen	wt. %	7.42	7	7.28	7.07	7.27	7.61	6.75	7.75	7.88	8.16

Fuel analysis overview – Tank 11 – E20

Tank 11															
Fuel Type	E20														
Delivery Date		10/15/2010	10/8/2010	10/5/2010	9/28/2010	9/20/2010	9/14/2010	8/17/2010	8/9/2010	8/2/2010	7/16/2010	5/10/2010	4/1/2010	3/24/2010	10/28/2009
Sample Date		10/15/2010	10/8/2010	10/5/2010	9/28/2010	9/20/2010	9/14/2010	8/18/2010	8/9/2010	8/2/2010	7/19/2010	5/11/2010	4/5/2010	3/25/2010	11/19/2009
Results Date		10/21/2010	10/15/2010	10/12/2010	10/6/2010	9/27/2010	9/20/2010	8/25/2010	8/13/2010	8/9/2010	7/27/2010	5/17/2010	4/9/2010	3/31/2010	11/25/2009
Density @ 15C	g/ml	0.7476	0.748	0.7516	0.7643	0.7678	0.7632	0.7629	0.7581	0.7532	0.752	0.7378	0.7331	0.7335	0.7416
Density @ 20C	g/ml	0.7432	0.7437	0.7474	0.7602	0.7635	0.7589	0.7585	0.7535	0.7488	0.7476	0.7332	0.7285	0.7288	0.747
Density @ 25C	g/ml	0.7387	0.7393	0.7422	0.7557	0.7589	0.7545	0.7541	0.7491	0.7444	0.743	0.7284	0.7236	0.7241	0.7424
Distillation															
Initial Boiling Point	Deg. F	86.2	89.4	94.6	106.9	109.4	104.7	104.5	106.8	103.3	101.9	88.8	81.5	82.4	84.6
5% Evaporated Temperature	Deg. F	107.1	108.9	117.2	137.3	140.3	133.3	134.5	133	134	131.1	109.2	98	98.7	103.4
10% Evaporated Temperature	Deg. F	120.3	121.3	128	144.2	146.5	141.7	142.1	141.1	141.4	139.9	121.3	112.1	112.1	116.3
20% Evaporated Temperature	Deg. F	138.7	139.2	143.2	152.4	154.1	151.2	150.9	150.4	150.4	150	138.7	132.6	132.1	134.3
30% Evaporated Temperature	Deg. F	151.8	152.1	153.8	157.8	159.6	157.7	157.3	157.2	156.9	156.4	150.8	148.3	148.3	148.5
40% Evaporated Temperature	Deg. F	159.6	159.4	160.2	161.6	163.7	162.5	161.3	161.7	161.8	161.2	157.3	157.6	157.1	157.7
50% Evaporated Temperature	Deg. F	164.1	164.3	164.7	166.2	166.9	166.4	165.5	164.7	165.4	165.3	162.4	161.5	162.3	163.3
60% Evaporated Temperature	Deg. F	167.9	167	170.3	200	225.3	206.7	204	203.8	207.4	183.5	165.7	165.8	165.7	167.5
70% Evaporated Temperature	Deg. F	240.4	236.7	243.9	245.2	253.7	250.5	246.8	246.4	248.3	242.6	229.9	222.8	220.9	247
80% Evaporated Temperature	Deg. F	272.6	268.6	273.4	274.8	276	276.6	275.7	275.4	272	269	261.3	257.8	255.5	284.9
90% Evaporated Temperature	Deg. F	321.2	322.2	323.8	325	327.8	322.5	326.2	323.5	324.2	325.6	314.9	310.2	312.4	330.2
95% Evaporated Temperature	Deg. F	355.2	352	356.3	354.6	360.2	359.6	359.9	358.1	361.5	361.5	355.3	354.3	354.6	363.2
End Point	Deg. F	406.4	406.5	408.6	401.5	410.1	407.9	409.3	412.8	412.3	413.1	413	407.6	408.9	417.7
% Overhead Recovery	%	96.3	96.5	97	97.5	98.1	97.6	97.9	97.6	97.9	97.4	96.6	95.7	95.9	96.2
% Residue	%	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
% Loss	%	2.6	2.4	1.9	1.4	0.8	1.3	1	1.3	1	1.5	2.3	3.2	3	2.7
Oxygenates															
Methanol	L.V. %	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
Ethanol	L.V. %	20.58	20.49	20.53	20.68	20.91	20.62	20.26	19.79	20.15	20.43	20.17	20.8	20.56	20.88
Tert-Butanol	L.V. %	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
MTBE	L.V. %	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
t-Amyl Methyl Ether	L.V. %	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
Octane Numbers															
Research	Octane	99.8	100	99.7	99.7	100	99.7	99.8	99.5	99.6	99.5	99.6	100	100	97.4
Motor	Octane	87.9	88	87.6	87.2	88	87.5	87.3	87.6	87.6	88.2	88.2	88.7	88.2	85.3
(R+M)/2	Octane	93.8	94	93.6	93.4	94	93.6	93.6	93.6	93.6	93.8	93.9	94.4	94.1	91.4
Heating Value NET	Btu/lb.	17011	17057	16937	17000	16952	17004	16657	17167	17212	16691	17122	17033	16844	16960
Heating Value NET	MJ/kg	39.568	39.675	39.396	39.542	39.431	39.55	38.745	39.93	40.034	38.824	39.827	36.619	39.18	39.45
Heating Value GROSS	Btu/lb.	18263	18301	18196	18220	18160	18214	17867	18409	18473	17955	18398	18319	18130	18176
Heating Value GROSS	MJ/kg	42.479	42.567	42.324	42.379	42.241	42.366	41.559	42.818	42.969	41.763	42.793	42.609	42.169	42.278
Total Sulfur	ppm wt.	11	10	11	9	11	9	9	16	15		17	14	13.9	23
Water	ppm wt.	2566	2464	2619	2859	3207	2734	2624	3001	2984	3175	2955	2715	2687	2402
Carbon	wt. %	78.86	78.95	79.39	79.65	79.78	79.66	79.65	79.19	79.09	78.85	78.27	78.02	77.85	78.97
Hydrogen	wt. %	13.72	13.63	13.8	13.37	13.24	13.27	13.26	13.61	13.83	13.85	13.98	14.09	14.09	13.33
Oxygen	wt. %	7.42	7.42	6.81	6.98	6.98	7.07	7.05	7.2	7.08	7.3	7.75	7.89	8.06	7.7

Fuel analysis overview – Tank 10 – E15

Tank 10									
Fuel Type	E15								
Delivery Date		2/28/2011	2/21/2011	2/4/2011	12/16/2010	12/7/2010	12/3/2010	11/30/2010	11/23/2010
Sample Date		2/28/2011	2/21/2011	2/4/2011	12/17/2010	12/7/2010	12/3/2010	11/30/2010	11/24/2010
Results Date		3/4/2011	2/25/2011	2/9/2011	12/22/2010	12/14/2010	12/10/2010	12/6/2010	12/2/2010
Density @ 15C	g/ml	0.741	0.7401	0.7477	0.7458	0.7461	0.7507	0.7482	0.7499
Density @ 20C	g/ml	0.7362	0.7354	0.7429	0.7412	0.7419	0.7459	0.7436	0.7458
Density @ 25C	g/ml	0.7315	0.7308	0.738	0.7364	0.7372	0.7415	0.7387	0.7411
Distillation									
Initial Boiling Point	Deg. F	83.4	82.5	85.6	85.3	84.3	88	89.5	91.6
5% Evaporated Temperature	Deg. F	100.3	100.8	105.4	102	103.2	111.2	108.5	112.3
10% Evaporated Temperature	Deg. F	114.5	113.5	119.6	115.1	116.2	123.4	120.9	124.2
20% Evaporated Temperature	Deg. F	132.7	132.7	138.8	133.2	134.8	139.5	136.3	139
30% Evaporated Temperature	Deg. F	148.7	148.6	153	147.7	148.6	151.1	148.7	150.2
40% Evaporated Temperature	Deg. F	158.1	158.4	160.9	156.9	157.3	158.8	156.9	158
50% Evaporated Temperature	Deg. F	164.4	163.8	164.4	163	163.3	164	162.2	163
60% Evaporated Temperature	Deg. F	174.3	180.4	220.7	199.8	207.3	219.6	201.2	205.2
70% Evaporated Temperature	Deg. F	248.3	247.4	252.9	249.2	246.5	253.3	247.6	247.6
80% Evaporated Temperature	Deg. F	264.6	277.3	279.7	276.3	277.1	280.9	277.9	279.5
90% Evaporated Temperature	Deg. F	324.1	325.3	326.9	319	321	321.5	320.1	323
95% Evaporated Temperature	Deg. F	358.7	359.2	358.6	347.7	347.8	352.9	348.7	353.9
End Point	Deg. F	412.1	408.1	408	402.7	401.7	402.3	405.4	412.6
% Overhead Recovery	%	95.4	96	95.7	95.8	96.1	96.8	96.1	96.6
% Residue	%	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
% Loss	%	3.5	2.9	3.2	3.1	2.8	2.1	2.8	2.3
Oxygenates									
Methanol	L.V. %	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
Ethanol	L.V. %	15.79	15.01	15.91	15.16	15.58	15.58	15.6	14.92
Tert-Butanol	L.V. %	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
MTBE	L.V. %	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
t-Amyl Methyl Ether	L.V. %	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
Octane Numbers									
Research	Octane	98.4	98.5	98.4	97.7	97.8	97.5	97.4	97.3
Motor	Octane	87.6	87.4	87.2	87	87.1	86.8	87.5	86.5
(R+M)/2	Octane	93	93	92.8	92.4	92.4	92.2	92.4	91.9
Heating Value NET	Btu/lb.	17564	17183	17501	17544	17407	17300	17376	17312
Heating Value NET	MJ/kg	40.853	39.968	40.707	40.808	40.488	40.241	40.416	40.268
Heating Value GROSS	Btu/lb.	18808	18414	18733	18781	18632	18520	18605	18545
Heating Value GROSS	MJ/kg	43.748	42.831	43.572	43.685	43.338	43.078	43.275	43.137
Total Sulfur	ppm wt.	15.4	13.8	17.6	23.3	25.3	25.8	25	25.2
Water	ppm wt.	2393	2019	2287	2383	1927	2153	2196	2160
Carbon	wt. %	80.12	80.19	80.36	80.62	80.74	80.73	80.84	80.76
Hydrogen	wt. %	13.64	13.49	13.5	13.56	13.43	13.37	13.47	13.52
Oxygen	wt. %	6.24	6.32	6.14	5.82	5.83	5.9	5.69	5.72

FEV

Fuel analysis overview – Tank 11 – E15

Tank 11									
Fuel Type	E15								
Delivery Date		4/28/2011	3/7/2011	3/2/2011	2/22/2011	2/14/2011	12/27/2010	12/10/2010	12/3/2010
Sample Date		4/28/2011	3/7/2011	3/2/2011	2/22/2011	2/14/2011	12/27/2010	12/10/2010	12/3/2010
Results Date		5/6/2011	3/11/2011	3/8/2011	3/1/2011	2/18/2011	1/3/2011	12/16/2010	12/10/2010
Density @ 15C	g/ml	0.7344	0.7307	0.7389	0.7379	0.7374	0.7465	0.7441	0.7436
Density @ 20C	g/ml	0.7303	0.7358	0.7343	0.7333	0.7326	0.7421	0.7396	0.739
Density @ 25C	g/ml	0.7251	0.731	0.7294	0.7288	0.7278	0.7375	0.7348	0.7341
Distillation									
Initial Boiling Point	Deg. F	81.1	90.2	81.8	83.3	81.6	86.6	83.7	82.7
5% Evaporated Temperature	Deg. F	98.3	113.8	100.7	100.2	96.9	104.1	100.9	99.2
10% Evaporated Temperature	Deg. F	110.4	125.7	112.5	112.3	110.1	116.3	113.4	113.1
20% Evaporated Temperature	Deg. F	129	137.8	131.6	131.3	129.7	133.4	132.2	131.8
30% Evaporated Temperature	Deg. F	145.5	149.6	147.5	147.4	146.1	147.5	146.8	146.9
40% Evaporated Temperature	Deg. F	155.7	158.1	157.5	157.3	157	156.8	156.3	156.5
50% Evaporated Temperature	Deg. F	162	162.8	162.8	163.1	162.4	163.1	162.8	162.1
60% Evaporated Temperature	Deg. F	174.5	196.5	173.3	175.9	174.3	201.6	192.2	192
70% Evaporated Temperature	Deg. F	240.5	244	245.1	245.6	242.7	249.3	244.4	245.8
80% Evaporated Temperature	Deg. F	271.1	272.6	271.9	273.9	274.5	276.4	277	269.4
90% Evaporated Temperature	Deg. F	321.3	315.7	317.7	323.9	323.3	317	318.8	318.7
95% Evaporated Temperature	Deg. F	358	334.8	359	358.5	357.1	348.1	348.5	348
End Point	Deg. F	412	395.8	407.5	411.4	408.4	404.4	402	401.9
% Overhead Recovery	%	96.2	96.2	96	95.8	95.3	96	96	95.7
% Residue	%	0.9	1.4	1	1.1	1.1	1.1	1.1	1.1
% Loss	%	2.9	2.4	3	3.1	3.6	2.9	2.9	3.2
Oxygenates									
Methanol	L.V. %	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
Ethanol	L.V. %	14.78	15.38	15.26	15.12	15.22	15.05	15.05	15.19
Tert-Butanol	L.V. %	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
MTBE	L.V. %	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
t-Amyl Methyl Ether	L.V. %	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
Octane Numbers									
Research	Octane	97.8	98.4	98.5	98.5	98.3	97.6	97.8	97.6
Motor	Octane	87.7	87.4	87.5	87.6	87.2	86.6	86.4	87.1
(R+M)/2	Octane	92.8	92.9	93	93	92.8	92.1	92.1	92.4
Heating Value NET	Btu/lb.	17581	17258	17520	17584	17395	17433	17494	17536
Heating Value NET	MJ/kg	40.895	40.141	40.751	40.901	40.46	40.548	40.69	40.789
Heating Value GROSS	Btu/lb.	18851	18515	18770	18846	18644	18661	18734	18769
Heating Value GROSS	MJ/kg	43.848	43.065	43.66	43.836	43.367	43.405	43.576	43.656
Total Sulfur	ppm wt.	14.4	13.8	12.4	13.3	14.5	23	23.9	23.9
Water	ppm wt.	2397	2028	2006	1969	2054	2190	1939	2119
Carbon	wt. %	80.22	80.52	80.47	80.23	80.46	80.82	80.91	80.86
Hydrogen	wt. %	13.92	13.78	13.71	13.83	13.7	13.46	13.6	13.51
Oxygen	wt. %	5.86	5.7	5.82	5.94	5.84	5.72	5.49	5.63

Fuel analysis overview – Tank 10 – E0

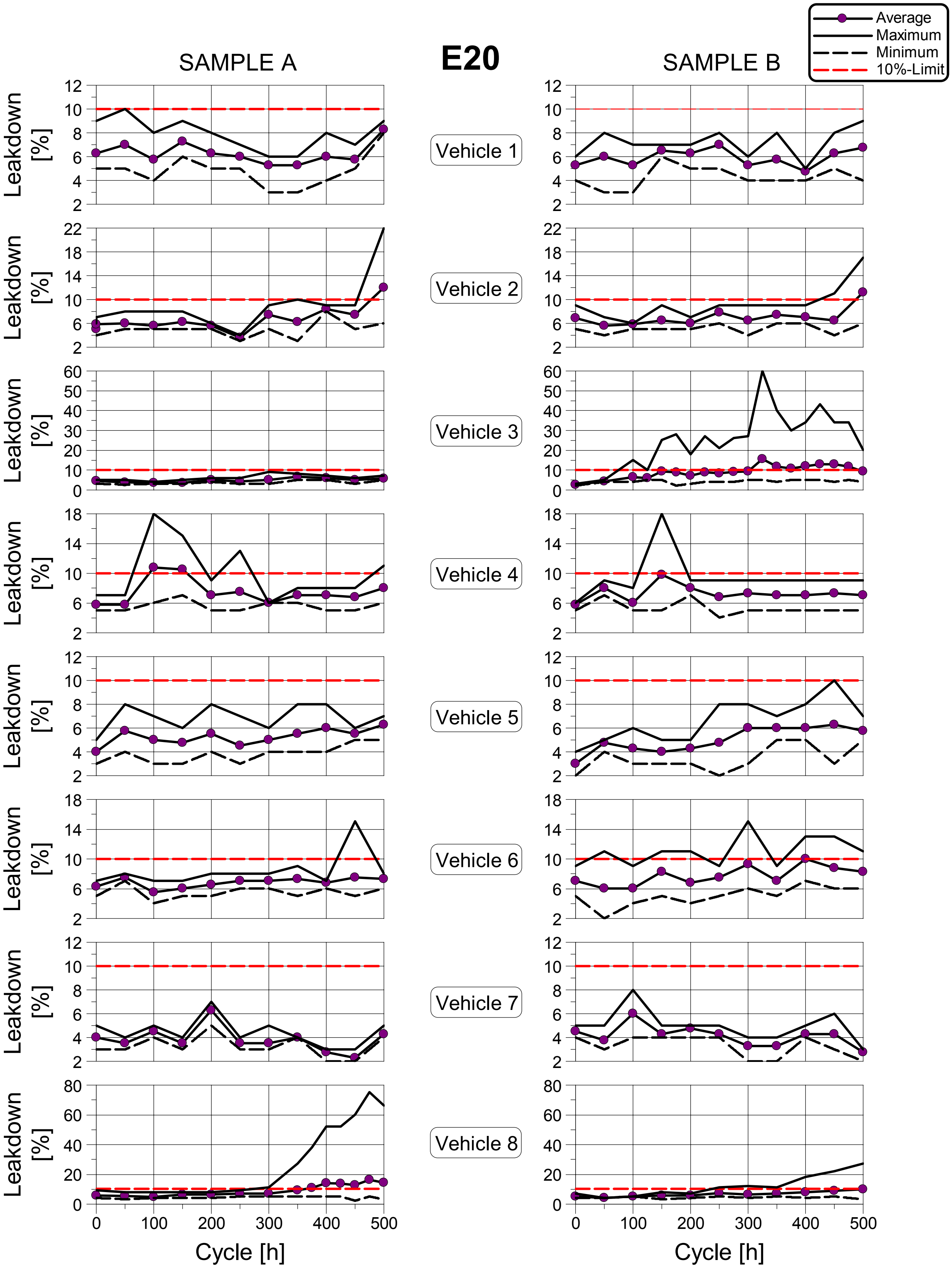
Tank 10								
Fuel Type	E0							
Delivery Date		12/20/2011	11/14/2011	11/4/2011	10/17/2011	6/20/2011	4/26/2011	4/13/2011
Sample Date		12/21/2011	11/14/2011	11/7/2011	10/17/2011	6/20/2011	4/26/2011	4/14/2011
Results Date		12/28/2011	11/21/2011	11/11/2011	10/21/2011	6/24/2011	5/2/2011	4/21/2011
Density @ 15C	g/ml	0.7268	0.7109	0.7302	0.7308	0.7381	0.7314	0.7283
Density @ 20C	g/ml	0.7222	0.7063	0.7256	0.7262	0.7339	0.727	0.7242
Density @ 25C	g/ml	0.7182	0.7023	0.7216	0.722	0.7296	0.7228	0.7199
Distillation								
Initial Boiling Point	Deg. F	81.9	82.7	89.6	84	97.6	91.2	88.2
5% Evaporated Temperature	Deg. F	110.9	96.5	121.6	108.9	142.6	134.3	115
10% Evaporated Temperature	Deg. F	132.2	112.6	141.9	128.6	163.6	154.1	136.1
20% Evaporated Temperature	Deg. F	171.1	144.1	175.5	161.8	190.7	186.9	171.2
30% Evaporated Temperature	Deg. F	203.8	183.2	203.6	195.4	209.8	209.7	201.6
40% Evaporated Temperature	Deg. F	222.1	212.1	221.5	218.1	222.4	223.6	220.1
50% Evaporated Temperature	Deg. F	233	226.5	232.4	230.7	231.6	233.1	231
60% Evaporated Temperature	Deg. F	243	236	242.4	241.1	241.2	242.5	240.7
70% Evaporated Temperature	Deg. F	255.4	247.1	255.5	254.4	253.4	254.8	252.7
80% Evaporated Temperature	Deg. F	279	266	278.5	277.1	275.3	281.7	274.7
90% Evaporated Temperature	Deg. F	329.1	316.3	329.1	325.5	325	338.3	326.1
95% Evaporated Temperature	Deg. F	359.8	356.7	362.2	361.9	362.8	378.6	358.6
End Point	Deg. F	423.1	415.7	417.2	416.7	421.1	417.1	422.1
% Overhead Recovery	%	96.2	95.5	97.4	96.8	97.9	97.5	96.8
% Residue	%	1.3	1	1	1.1	1	1	1
% Loss	%	2.5	3.5	1.6	2.1	1.1	1.5	2.2
Oxygenates								
Methanol	L.V. %	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
Ethanol	L.V. %	<0.20	0.24	<0.20	<0.20	<0.20	<0.20	0.32
Tert-Butanol	L.V. %	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
MTBE	L.V. %	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
t-Amyl Methyl Ether	L.V. %	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
Octane Numbers								
Research	Octane	93.4	93.8	93.4	93.6	93	93.1	93.3
Motor	Octane	88.1	88.6	87.9	87.5	87.3	87.5	87.4
(R+M)/2	Octane	90.8	91.2	90.6	90.6	90.2	90.3	90.4
Heating Value NET	Btu/lb.	18907	18956	18832	18946	18756	18863	18866
Heating Value NET	MJ/kg	43.977	44.092	43.803	44.068	43.627	43.876	43.882
Heating Value GROSS	Btu/lb.	20207	20326	20146	20232	20070	20178	20183
Heating Value GROSS	MJ/kg	47.001	47.277	46859	47.06	46.683	46.934	46.947
Total Sulfur	ppm wt.	12.1	13.4	15.5	22.7	11.9	13.1	13.3
Water	ppm wt.	63	75	52	68	76	140	77
Carbon	wt. %	85.75	84.99	85.6	85.9	85.6	85.59	85.56
Hydrogen	wt. %	14.25	15.01	14.4	14.1	14.4	14.41	14.44
Oxygen	wt. %	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

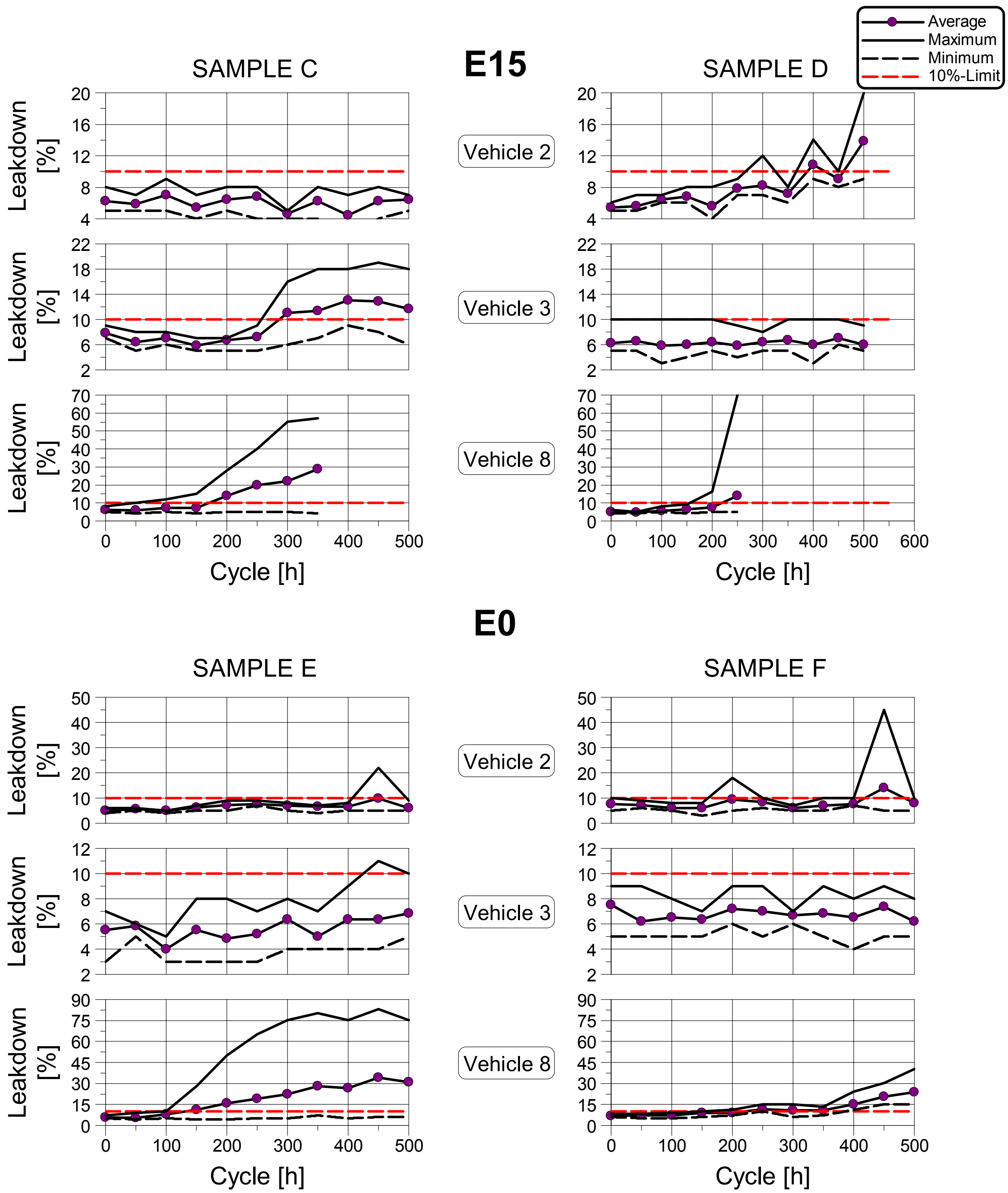
Fuel analysis overview – Tank 11 – E0

Tank 11				
Fuel Type	E0			
Delivery Date		10/17/2011	8/30/2011	8/12/2011
Sample Date		10/17/2011	8/30/2011	8/12/2011
Results Date		10/21/2011	9/6/2011	8/18/2011
Density @ 15C	g/ml	0.7308	0.7383	0.7371
Density @ 20C	g/ml	0.7262	0.7338	0.7326
Density @ 25C	g/ml	0.722	0.7299	0.7286
Distillation				
Initial Boiling Point	Deg. F	84	95.8	95.9
5% Evaporated Temperature	Deg. F	108.9	142.6	132
10% Evaporated Temperature	Deg. F	128.6	160.9	151.9
20% Evaporated Temperature	Deg. F	161.8	187.1	181.7
30% Evaporated Temperature	Deg. F	195.4	206.8	204
40% Evaporated Temperature	Deg. F	218.1	221.1	219.2
50% Evaporated Temperature	Deg. F	230.7	231	229.8
60% Evaporated Temperature	Deg. F	241.1	239.8	239.4
70% Evaporated Temperature	Deg. F	254.4	251.7	251.2
80% Evaporated Temperature	Deg. F	277.1	272.4	272.9
90% Evaporated Temperature	Deg. F	325.5	326.5	324.3
95% Evaporated Temperature	Deg. F	361.9	362.8	361.6
End Point	Deg. F	416.7	421.1	417.3
% Overhead Recovery	%	96.8	98.8	98
% Residue	%	1.1	1	0.9
% Loss	%	2.1	0.2	1.1
Oxygenates				
Methanol	L.V. %	<0.20	<0.20	<0.20
Ethanol	L.V. %	<0.20	<0.20	0.47
Tert-Butanol	L.V. %	<0.20	<0.20	<0.20
MTBE	L.V. %	<0.20	<0.20	<0.20
t-Amyl Methyl Ether	L.V. %	<0.20	<0.20	<0.20
Octane Numbers				
Research	Octane	93.6	93.2	93.4
Motor	Octane	87.5	86.9	87.1
(R+M)/2	Octane	90.6	90	90.2
Heating Value NET	Btu/lb.	18946	18628	18701
Heating Value NET	MJ/kg	44.068	43.328	43.498
Heating Value GROSS	Btu/lb.	20232	19931	19994
Heating Value GROSS	MJ/kg	47.06	46.36	46.507
Total Sulfur	ppm wt.	22.7	11.6	11.4
Water	ppm wt.	68	188	252
Carbon	wt. %	85.9	85.71	85.67
Hydrogen	wt. %	14.1	14.29	14.18
Oxygen	wt. %	<0.05	<0.05	0.15

H.2 Detailed Leakage Measurement Results

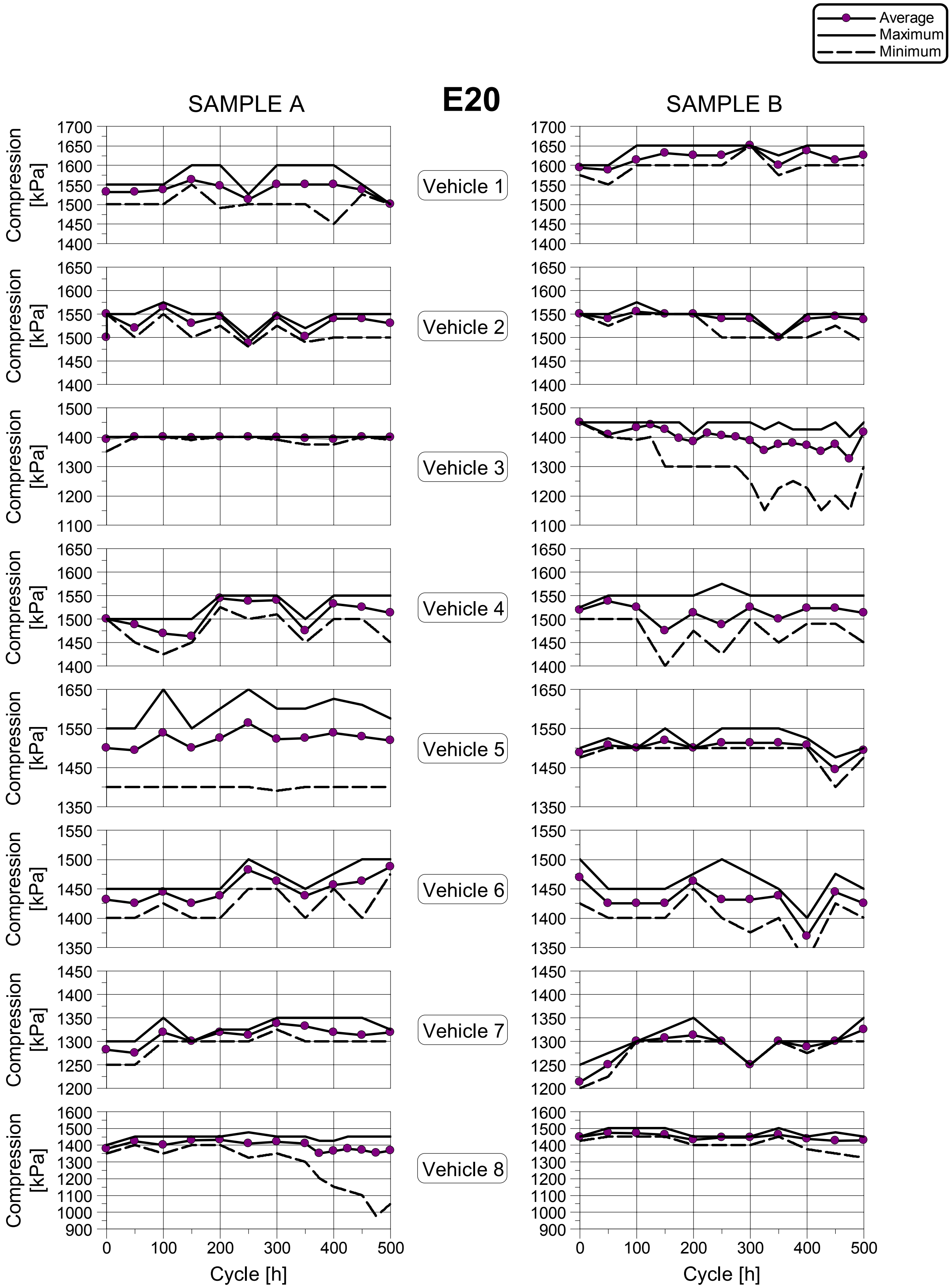
The following graphs summarize the leakage measurement results for all 28 tested engines.

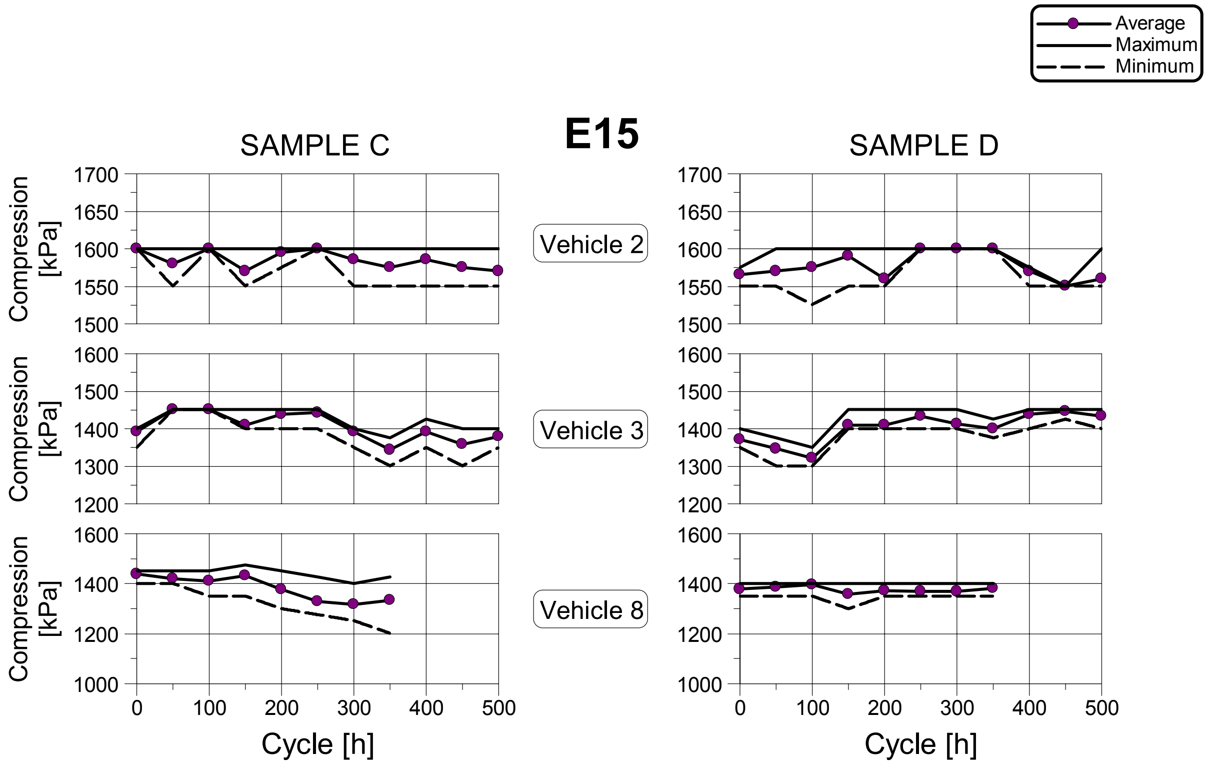

E20
SAMPLE A
SAMPLE B
Average
Maximum
Minimum
10%-Limit
Leakdown [%]
Vehicle 1
Vehicle 2
Vehicle 3
Vehicle 4
Vehicle 5
Vehicle 6
Vehicle 7
Vehicle 8
Cycle [h]
0
100
200
300
400
500

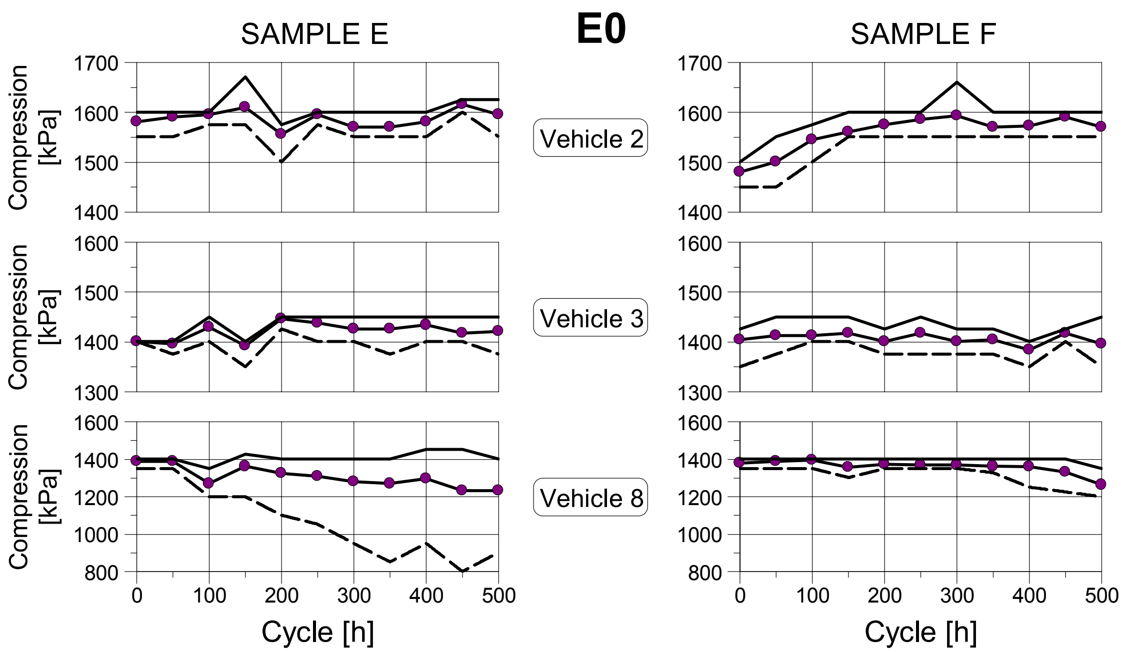

Average
Maximum
Minimum
10%-Limit
E15
SAMPLE C
SAMPLE D
Vehicle 2
Vehicle 3
Vehicle 8
Leakdown [%]
Cycle [h]
E0
SAMPLE E
SAMPLE F
Vehicle 2
Vehicle 3
Vehicle 8
Leakdown [%]
Cycle [h]

H.3 Detailed Compression Measurement Results

The following graphs summarize the compression measurement results for all 28 tested engines.


Average
Maximum
Minimum
SAMPLE A
E20
SAMPLE B
Vehicle 1
Vehicle 2
Vehicle 3
Vehicle 4
Vehicle 5
Vehicle 6
Vehicle 7
Vehicle 8
Compression [kPa]
Cycle [h]


Average
Maximum
Minimum
E15
SAMPLE C
SAMPLE D
Vehicle 2
Vehicle 3
Vehicle 8
Compression [kPa]
Cycle [h]


E0
SAMPLE E
SAMPLE F
Vehicle 2
Vehicle 3
Vehicle 8
Compression [kPa]
Cycle [h]

H.4 Oil Analyses

The following tables summarize the oil analysis results captured during the testing of the engines, sorted by vehicle and fuel type.

Oil Analysis Results of Engines tested with E20

Vehicle 1

Sample A

WEAR METALS AND ADDITIVES [ppm by weight]	CYCLE [h] 0	50	100	150	200	250	300	350	400	450	500
IRON	4	15	6	8	6	5	7	9	5	8	7
COPPER	<1	<1	<1	<1	<1	2	<1	<1	<1	5	143
CHROMIUM	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
LEAD	1	4	<1	<1	<1	<1	<1	3	1	<1	2
ALUMINUM	1	2	<1	1	2	1	<1	2	1	2	2
TIN	12	15	12	13	15	13	11	10	9	11	11
SILICON	9	10	8	7	8	8	12	15	12	16	16
ZINC	814	826	746	768	838	755	757	790	803	837	874
MAGNESIUM	10	11	10	9	10	9	10	12	11	11	12
CALCIUM	2165	2086	1901	1907	2103	1990	2007	1937	1915	1962	2171
PHOSPHORUS	1348	1229	1100	1126	1252	1128	1103	1321	1293	1361	1511
BARIUM	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
BORON	42	1	<1	<1	<1	<1	3	3	3	3	2
SODIUM	63	75	73	72	77	76	60	70	70	77	78
MOLYBDENUM	106	121	115	111	121	119	109	121	118	119	129
SILVER	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
NICKEL	2	1	2	1	<1	2	<1	5	3	2	4
TITANIUM	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
MANGANESE	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
ANTIMONY	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
CST @ 100C	8.7	8	7.7	7.9	8.1	7.9	7.4	8	7.8	7.8	8.4
TAN	1.24	1.64	1.82	1.82	1.81	1.75	1.72	1.74	1.74	1.86	2.05

Sample B

WEAR METALS AND ADDITIVES [ppm by weight]	CYCLE [h] 0	50	100	150	200	250	300	350	400	450	500
IRON	-	5	5	4	3	4	9	5	4	5	4
COPPER	-	<1	<1	1	1	6	<1	<1	13	7	50
CHROMIUM	-	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
LEAD	-	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
ALUMINUM	-	1	<1	<1	<1	<1	<1	1	<1	<1	<1
TIN	-	12	13	13	12	12	13	11	12	11	12
SILICON	-	6	5	7	5	7	9	7	8	7	6
ZINC	-	811	740	812	795	806	731	742	750	796	755
MAGNESIUM	-	15	13	14	15	14	11	14	14	14	14
CALCIUM	-	1609	1437	1570	1547	1530	2108	1552	1482	1528	1475
PHOSPHORUS	-	838	669	779	748	803	707	757	717	770	714
BARIUM	-	<1	<1	<1	<1	1	<1	<1	1	<1	<1
BORON	-	16	8	7	8	7	41	13	9	7	6
SODIUM	-	119	106	118	115	112	50	112	114	114	111
MOLYBDENUM	-	97	82	97	100	92	86	100	95	96	93
SILVER	-	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
NICKEL	-	<1	<1	<1	<1	<1	<1	1	<1	<1	<1
TITANIUM	-	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
MANGANESE	-	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
ANTIMONY	-	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
CST @ 100C	-	7.6	7.9	8.1	8.3	8.1	7.3	7.2	7.4	8.3	7.9
TAN	-	1.94	1.94	1.86	1.95	1.95	2.03	1.88	1.94	1.9	1.95

Vehicle 2

Sample A

WEAR METALS AND ADDITIVES [ppm by weight]

	CYCLE [h]										
	0	50	100	150	200	250	300	350	400	450	500
IRON	5.0	38.0	21.0	10.0	11.0	12.0	9.0	13.0	12.0	16.0	16.0
COPPER	14.0	7.0	54	178	167.0	98	37	9.0	<1	<1	<1
CHROMIUM	<1.0	<1.0	<1.0	<1.0	<1	<1	<1	<1	<1	<1	<1
LEAD	<1.0	<1.0	1	<1	<1	5.0	<1	<1	<1	<1	1.0
ALUMINUM	<1.0	3.0	3.0	2.0	2.0	4.0	2.0	4.0	2.0	4.0	6.0
TIN	12.0	13.0	15.0	13.0	16.0	19.0	12.0	14.0	10.0	13.0	16.0
SILICON	10.0	6.0	5.0	4.0	5.0	4.0	3.0	3.0	2.0	4.0	3.0
ZINC	836.0	856.0	816.0	807.0	859.0	833.0	788.0	809.0	698.0	827.0	845.0
MAGNESIUM	11.0	12.0	11.0	10.0	12.0	12.0	10.0	11.0	7.0	11.0	13.0
CALCIUM	2184.0	2142.0	2103.0	2029.0	2254.0	2357.0	1985.0	2189.0	1566.0	2127.0	2196.0
PHOSPHORUS	1449.0	1327.0	1212.0	1150.0	1211.0	1213.0	1080.0	1227.0	861.0	1253.0	1291.0
BARIUM	<1.0	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
BORON	11.0	<1.0	<1	<1	<1	<1	<1	<1	<1	<1	<1
SODIUM	68.0	81.0	79.0	78.0	81.0	87.0	73.0	81.0	58.0	76.0	71.0
MOLYBDENUM	126.0	120.0	127.0	120.0	133.0	145.0	115.0	131.0	78.0	126.0	129.0
SILVER	<1.0	<1.0	<1	<1	<1	<1	<1	<1	<1	<1	<1
NICKEL	<1.0	1.0	2.0	2.0	2.0	3.0	2.0	2.0	<1	1	3
TITANIUM	<1.0	1.0	<1	<1	<1	<1	<1	<1	<1	<1	<1
MANGANESE	<1.0	<1.0	<1	<1	<1	<1	<1	<1	<1	<1	<1
ANTIMONY	<1.0	<1.0	<1	<1	<1	<1	<1	<1	<1	<1	<1
CST @ 100C	8.6	8.1	8.6	8.5	8.5	8.5	8.2	8.5	8.3	8.8	8.5
TAN	1.78	1.78	1.65	1.72	1.63	1.80	1.68	1.80	1.79	1.79	1.81

Sample B

WEAR METALS AND ADDITIVES [ppm by weight]

	CYCLE [h]										
	0	50	100	150	200	250	300	350	400	450	500
IRON	2.0	14.0	12.0	123.0	9.0	8.0	9.0	10.0	13.0	9.0	8.0
COPPER	<1	2.0	<1	<1	<1	<1	<1	<1	<1	<1	<1
CHROMIUM	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
LEAD	<1	<1	<1	2	1.0	<1	<1	3.0	1.0	<1	1.0
ALUMINUM	1.0	4.0	4.0	5.0	<1	<1	<1	2.0	3.0	<1	<1
TIN	<1	11.0	10.0	11.0	13.0	14.0	8.0	8.0	8.0	7.0	8.0
SILICON	4.0	12.0	9.0	10.0	5.0	4.0	6.0	6.0	3.0	3.0	3.0
ZINC	811.0	853.0	884.0	913.0	775.0	800.0	905.0	918.0	939.0	950.0	929.0
MAGNESIUM	5.0	13.0	12.0	13.0	11.0	11.0	12.0	16.0	17.0	17.0	17.0
CALCIUM	1958.0	2075.0	2138.0	2250.0	18913.0	1903.0	1609.0	1556.0	1501.0	1575.0	1537.0
PHOSPHORUS	1336.0	1514.0	1486.0	1674.0	1110.0	1123.0	1014.0	1046.0	1082.0	1079.0	1060.0
BARIUM	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
BORON	37.0	3.0	3.0	2.0	<1	<1	<1	<1	<1	<1	<1
SODIUM	225.0	116.0	84.0	80.0	83.0	81.0	66.0	115.0	122.0	116.0	114.0
MOLYBDENUM	6.0	119.0	131.0	136.0	121.0	127.0	117.0	119.0	120.0	117.0	117.0
SILVER	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
NICKEL	3	3.0	3.0	3.0	3.0	1.0	1.0	1.0	4.0	<1	1
TITANIUM	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
MANGANESE	<1	1.0	<1	<1	<1	<1	<1	<1	<1	<1	<1
ANTIMONY	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
CST @ 100C	9.4	8.5	8.7	8.6	8.7	8.8	8.7	8.8	8.8	8.8	8.9
TAN	1.11	1.98	2.31	2.17	2.30	2.28	2.20	2.31	2.31	2.16	2.30

Vehicle 3

Sample A

WEAR METALS AND ADDITIVES [ppm by weight]

	CYCLE [h]										
	0	50	100	150	200	250	300	350	400	450	500
IRON	-	27.0	29.0	23.0	14.0	14.0	19.0	15.0	12.0	14.0	9.0
COPPER	-	16.0	2.0	<1.0	<1.0	9.0	<1.0	<1.0	2.0	<1.0	<1.0
CHROMIUM	-	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
LEAD	-	1.0	4.0	<1.0	<1.0	1.0	2.0	3.0	3.0	1.0	1.0
ALUMINUM	-	3.0	3.0	1.0	2.0	3.0	2.0	3.0	2.0	2.0	1.0
TIN	-	9.0	10.0	11.0	13.0	11.0	12.0	13.0	13.0	10.0	10.0
SILICON	-	13.0	13.0	10.0	11.0	11.0	11.0	11.0	11.0	10.0	10.0
ZINC	-	710.0	730.0	729.0	785.0	721.0	747.0	772.0	794.0	726.0	716.0
MAGNESIUM	-	11.0	11.0	11.0	23.0	13.0	12.0	11.0	24.0	12.0	10.0
CALCIUM	-	2386.0	2627.0	2432.0	2175.0	2558.0	2735.0	2789.0	2217.0	2591.0	2500.0
PHOSPHORUS	-	946.0	1025.0	1015.0	1138.0	1086.0	1105.0	1194.0	1197.0	1029.0	1051.0
BARIUM	-	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
BORON	-	47.0	49.0	45.0	1.0	42.0	49.0	53.0	2.0	45.0	46.0
SODIUM	-	26.0	27.0	26.0	48.0	20.0	15.0	10.0	40.0	15.0	8.0
MOLYBDENUM	-	88.0	98.0	89.0	120.0	105.0	105.0	105.0	123.0	106.0	97.0
SILVER	-	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
NICKEL	-	<1.0	2.0	2.0	2.0	1.0	2.0	2.0	1.0	1.0	<1.0
TITANIUM	-	<1.0	1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
MANGANESE	-	2.0	1.0	1.0	<1.0	<1.0	1.0	<1.0	<1.0	1.0	<1.0
ANTIMONY	-	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
CST @ 100C	-	7.2	7.6	7.8	7.3	7.7	7.7	7.5	7.0	7.7	7.3
TAN	-	1.12	1.19	1.22	1.70	1.53	1.52	1.80	1.77	1.21	1.24

Sample B

WEAR METALS AND ADDITIVES [ppm by weight]

	CYCLE [h]										
	0	50	100	150	200	250	300	350	400	450	500
IRON	-	27.0	17.0	10.0	15.0	15.0	16.0	15.0	17.0	13.0	10.0
COPPER	-	<1.0	18.0	16	<1.0	<1.0	8	<1.0	<1.0	3	<1.0
CHROMIUM	-	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
LEAD	-	4.0	<1.0	5	<1.0	1.0	3.0	<1.0	3.0	3.0	<1.0
ALUMINUM	-	4.0	3.0	3.0	1.0	<1.0	<1.0	1.0	1.0	2.0	1.0
TIN	-	9.0	9.0	10.0	9.0	<1.0	7.0	12.0	10.0	12.0	12.0
SILICON	-	27.0	24.0	26.0	20.0	17.0	15.0	11.0	12.0	9.0	11.0
ZINC	-	751.0	727.0	807.0	646.0	771.0	861.0	785.0	869.0	819.0	827.0
MAGNESIUM	-	12.0	12.0	12.0	11.0	12.0	13.0	11.0	13.0	12.0	18.0
CALCIUM	-	2373.0	2377.0	2606.0	2150.0	1977.0	2257.0	2298.0	2596.0	2406.0	2167.0
PHOSPHORUS	-	1235.0	1153.0	1314.0	896.0	840.0	973.0	785.0	934.0	839.0	819.0
BARIUM	-	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
BORON	-	53.0	46.0	49.0	48.0	22.0	32.0	52.0	57.0	55.0	28.0
SODIUM	-	9.0	11.0	11.0	12.0	9.0	10.0	14.0	16.0	14.0	26.0
MOLYBDENUM	-	90.0	97.0	102.0	98.0	96.0	103.0	91.0	102.0	95.0	101.0
SILVER	-	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
NICKEL	-	2	3.0	2.0	4.0	1.0	1.0	2.0	1.0	<1.0	<1.0
TITANIUM	-	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
MANGANESE	-	4.0	2.0	1.0	1	1	1.0	1	1	1.0	1
ANTIMONY	-	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
CST @ 100C	-	7.9	7.9	8.1	8.2	7.9	8.1	8.1	8.1	8.2	7.8
TAN	-	1.36	1.46	1.58	1.67	1.96	2.23	2.06	2.08	2.19	2.23

FEV

Vehicle 4

Sample A

WEAR METALS AND ADDITIVES [ppm by weight]

	CYCLE [h]										
	0	50	100	150	200	250	300	350	400	450	500
IRON	2	6	10	10	25	31	18	15	13	8	8
COPPER	<1	27	169	41	<1	1	<1	<1	<1	<1	<1
CHROMIUM	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
LEAD	<1	2	2	<1	<1	<1	<1	<1	<1	1	2
ALUMINUM	2	1	4	2	2	3	3	2	1	2	1
TIN	12	12	16	14	10	15	14	15	12	13	15
SILICON	6	7	8	5	5	5	6	4	5	4	5
ZINC	934	794	875	873	956	880	839	879	896	873	860
MAGNESIUM	24	25	28	26	22	26	27	27	27	26	26
CALCIUM	2319	2094	2399	2165	2546	2339	2312	2320	2209	2177	2190
PHOSPHORUS	1621	1213	1253	1178	1477	1307	1190	1266	1321	1217	1258
BARIUM	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
BORON	26	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
SODIUM	42	48	58	51	42	56	54	52	51	47	48
MOLYBDENUM	119	124	134	118	96	120	135	132	129	121	123
SILVER	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
NICKEL	1	<1	2	3	2	<1	3	2	1	1	1
TITANIUM	<1	<1	<1	<1	1	1	1	<1	<1	<1	<1
MANGANESE	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
ANTIMONY	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
CST @ 100C	8	7.4	7.6	7.8	8.8	8.1	8.2	8	8.1	8	7.9
TAN	1.46	1.49	1.78	1.89	1.71	1.93	2	1.87	1.95	1.99	1.82

Sample B

WEAR METALS AND ADDITIVES [ppm by weight]

	CYCLE [h]										
	0	50	100	150	200	250	300	350	400	450	500
IRON	2	8	10	10	8	-	8	7	7	5	5
COPPER	<1	<1	<1	<1	<1	-	9	<1	<1	<1	<1
CHROMIUM	<1	<1	<1	<1	<1	-	<1	<1	<1	<1	<1
LEAD	1	<1	<1	<1	2	-	1	1	2	<1	1
ALUMINUM	1	4	4	3	2	-	2	1	2	<1	<1
TIN	13	12	16	13	11	-	11	12	12	12	12
SILICON	4	10	7	7	8	-	7	9	9	4	3
ZINC	905	912	915	944	927	-	929	926	923	764	809
MAGNESIUM	23	26	27	27	28	-	28	29	28	24	25
CALCIUM	2221	2336	2351	2394	2213	-	2274	2298	2271	1838	1872
PHOSPHORUS	1564	1352	1314	1468	1566	-	1527	1576	1573	1020	1082
BARIUM	<1	<1	<1	<1	<1	-	<1	<1	<1	<1	<1
BORON	21	1	<1	<1	2		1	2	3	<1	<1
SODIUM	40	49	49	50	45	-	46	47	47	51	50
MOLYBDENUM	114	127	129	134	130	-	136	136	135	121	125
SILVER	<1	<1	<1	<1	<1	-	<1	<1	<1	<1	<1
NICKEL	2	1	1	1	2	-	4	1	3	3	2
TITANIUM	<1	<1	<1	<1	<1		<1	<1	<1	<1	<1
MANGANESE	<1	<1	<1	<1	<1	-	<1	<1	<1	<1	<1
ANTIMONY	<1	<1	<1	<1	<1	-	<1	<1	<1	<1	<1
CST @ 100C	8.3	7.9	8	7.9	8	-	8.1	8.1	8.1	8.1	8.1
TAN	1.64	1.61	1.65	1.73	2.3	-	2.21	2.08	2.27	2.3	2.09

Vehicle 7

Sample B

WEAR METALS AND ADDITIVES [ppm by weight]

	CYCLE [h]										
	0	50	100	150	200	250	300	350	400	450	500
IRON	-	-	-	-	-	-	5	8	6	6	5
COPPER	-	-	-	-	-	-	<1	<1	<1	<1	<1
CHROMIUM	-	-	-	-	-	-	<1	<1	<1	<1	<1
LEAD	-	-	-	-	-	-	2	<1	<1	<1	<1
ALUMINIUM	-	-	-	-	-	-	<1	1	<1	<1	<1
TIN	-	-	-	-	-	-	16	17	17	15	16
SILICON	-	-	-	-	-	-	1	1	<1	<1	<1
ZINC	-	-	-	-	-	-	893	959	871	844	912
MAGNESIUM	-	-	-	-	-	-	16	18	17	16	17
CALCIUM	-	-	-	-	-	-	1438	1615	1568	1512	1611
PHOSPHORUS	-	-	-	-	-	-	953	1040	1043	1002	1093
BARIUM	-	-	-	-	-	-	<1	<1	<1	<1	<1
BORON	-	-	-	-	-	-	13	12	13	11	14
SODIUM							134	139	133	121	133
MOLYBDENUM	-	-	-	-	-	-	113	117	114	109	111
SILVER	-	-	-	-	-	-	<1	<1	<1	<1	<1
NICKEL	-	-	-	-	-	-	3	1	<1	<1	<1
TITANIUM	-	-	-	-	-	-	<1	<1	<1	<1	<1
MANGANESE	-	-	-	-	-	-	<1	<1	<1	<1	<1
ANTIMONY	-	-	-	-	-	-	<1	<1	<1	<1	<1
CST @ 100C	-	-	-	-	-	-	9.1	9.1	9.1	9.2	9.2
TAN	-	-	-	-	-	-	1.8	1.8	1.68	1.77	1.75

Vehicle 8

Sample B

WEAR METALS AND ADDITIVES [ppm by weight]

	CYCLE [h]										
	0	50	100	150	200	250	300	350	400	450	500
IRON	-	-	-	-	-	-	27	23	23	23	29
COPPER	-	-	-	-	-	-	<1	<1	<1	<1	<1
CHROMIUM	-	-	-	-	-	-	<1	<1	<1	<1	<1
LEAD	-	-	-	-	-	-	<1	<1	<1	<1	<1
ALUMINUM	-	-	-	-	-	-	3	3	4	5	7
TIN	-	-	-	-	-	-	14	14	12	13	15
SILICON	-	-	-	-	-	-	1	<1	1	<1	<1
ZINC	-	-	-	-	-	-	954	891	828	947	956
MAGNESIUM	-	-	-	-	-	-	23	22	22	25	26
CALCIUM	-	-	-	-	-	-	1775	1695	1556	1788	1857
PHOSPHORUS	-	-	-	-	-	-	1109	1032	937	1105	1105
BARIUM	-	-	-	-	-	-	<1	<1	<1	<1	<1
BORON	-	-	-	-	-	-	7	8	6	6	7
SODIUM	-	-	-	-	-	-	121	125	110	124	123
MOLYBDENUM	-	-	-	-	-	-	131	124	120	129	133
SILVER	-	-	-	-	-	-	<1	<1	<1	<1	<1
NICKEL	-	-	-	-	-	-	2	1	5	1	3
TITANIUM	-	-	-	-	-	-	<1	<1	<1	<1	<1
MANGANESE	-	-	-	-	-	-	<1	<1	<1	<1	<1
ANTIMONY	-	-	-	-	-	-	<1	<1	<1	<1	<1
CST @ 100C	-	-	-	-	-	-	7.8	7.9	7.8	8	8.1
TAN	-	-	-	-	-	-	2.1	2	2.16	2.02	2.22

Oil Analysis Results of Engines tested with E15

Vehicle 2

Sample C

WEAR METALS AND ADDITIVES [ppm by weight]	CYCLE [h] 0	50	100	150	200	250	300	350	400	450	500
IRON	4	17	18	21	19	18	17	26	18	16	16
COPPER	<1	<1	<1	<1	<1	<1	<1	5	<1	1	<1
CHROMIUM	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
LEAD	2	<1	<1	<1	<1	<1	1	1	<1	<1	1
ALUMINUM	1	3	3	3	2	1	2	3	3	3	2
TIN	14	8	11	14	13	7	7	8	10	10	10
SILICON	3	5	6	6	5	7	7	8	8	7	7
ZINC	845	746	898	888	948	1013	936	959	1028	994	978
MAGNESIUM	12	12	14	14	14	15	15	15	16	15	15
CALCIUM	1300	1265	1515	1557	1545	1638	1610	1559	1705	1636	1626
PHOSPHORUS	979	795	1014	1084	1067	898	895	808	953	901	906
BARIUM	<1	<1	<1	<1	<1	<1	<1	<1	1	<1	<1
BORON	60	20	21	21	22	22	24	23	25	3	24
SODIUM	119	119	113	104	104	164	176	157	174	197	200
MOLYBDENUM	114	108	125	120	122	123	126	123	132	129	133
SILVER	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
NICKEL	<1	<1	1	1	1	3	3	2	3	5	4
TITANIUM	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
MANGANESE	<1	<1	1	1	<1	<1	<1	<1	<1	<1	<1
ANTIMONY	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
CST @ 100C	9.1	8.7	8.9	8.9	9.1	9	8.9	8.9	9	9	9
TAN	1.23	1.96	2.07	2.1	2.16	2.17	2.34	2.4	2.44	2.46	2.4

Sample D

WEAR METALS AND ADDITIVES [ppm by weight]	CYCLE [h] 0	50	100	150	200	250	300	350	400	450	500
IRON	-	14	12	15	16	14	15	14	14	15	18
COPPER	-	1	<1	33	35	<1	33	23	28	28	<1
CHROMIUM	-	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
LEAD	-	1	1	2	4	1	<1	1	2	1	2
ALUMINUM	-	1	1	1	1	1	1	1	1	2	1
TIN	-	<1	<1	<1	6	<1	<1	<1	<1	<1	<1
SILICON	-	44	12	7	6	4	4	4	4	4	3
ZINC	-	877	903	915	968	901	1007	950	953	942	990
MAGNESIUM	-	16	16	16	17	15	17	16	16	17	17
CALCIUM	-	1903	2105	2076	2205	2049	2240	2141	2181	2221	2242
PHOSPHORUS	-	761	813	786	870	791	900	823	823	850	866
BARIUM	-	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
BORON	-	7	3	2	2	1	1	1	1	1	<1
SODIUM	-	143	112	95	94	89	85	94	89	96	90
MOLYBDENUM	-	48	41	36	42	35	40	38	37	41	38
SILVER	-	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
NICKEL	-	<1	2	1	2	<1	<1	<1	<1	<1	2
TITANIUM	-	4	5	5	5	4	5	5	5	5	5
MANGANESE	-	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
ANTIMONY	-	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
CST @ 100C	-	8.4	8.6	8.6	8.6	8.6	8.5	8.6	8.6	8.7	8.5
TAN	-	2.1	2.62	2.73	2.93	2.97	3.02	2.96	3.04	3.02	3.03

Vehicle 3

Sample C

WEAR METALS AND ADDITIVES [ppm by weight]

	CYCLE [h]										
	0	50	100	150	200	250	300	350	400	450	500
IRON	6	19	15	13	13	10	-	13	17	15	-
COPPER	<1	5	8	1	9	<1	-	5	<1	6	-
CHROMIUM	<1	<1	<1	<1	<1	<1	-	<1	<1	<1	-
LEAD	2	7	11	3	2	2	-	6	5	3	-
ALUMINUM	3	2	2	1	2	2	-	1	1	2	-
TIN	11	8	10	10	10	10	-	9	8	8	-
SILICON	8	12	15	19	20	20	-	18	19	19	-
ZINC	892	825	839	873	950	930	-	895	924	937	-
MAGNESIUM	15	12	12	13	14	15	-	14	15	15	-
CALCIUM	2440	2133	2162	2240	2432	2517	-	2311	2432	2471	-
PHOSPHORUS	1233	886	885	917	1052	1088	-	719	778	787	-
BARIUM	<1	<1	<1	<1	<1	<1	-	<1	1	<1	-
BORON	100	60	60	61	64	69	-	62	69	68	-
SODIUM	14	19	29	20	9	11	-	10	10	10	-
MOLYBDENUM	120	104	109	108	116	123	-	107	115	117	-
SILVER	<1	<1	<1	<1	<1	<1	-	<1	<1	<1	-
NICKEL	<1	1	2	<1	3	1	-	1	1	1	-
TITANIUM	<1	<1	<1	<1	<1	<1	-	<1	<1	<1	-
MANGANESE	1	1	1	1	1	1	-	<1	1	1	-
ANTIMONY	<1	<1	<1	<1	<1	<1	-	<1	<1	<1	-
CST @ 100C	8.5	7.8	8.2	8.4	8.3	8.3	-	8.2	8.2	8.1	-
TAN	1.53	2.17	2.01	2.24	2.16	2.17	-	2.39	2.6	2.64	-

Sample D

WEAR METALS AND ADDITIVES [ppm by weight]

	CYCLE [h]										
	0	50	100	150	200	250	300	350	400	450	500
IRON	-	23	14	13	13	12	13	14	12	14	15
COPPER	-	1	35	34	26	<1	31	36	37	39	5
CHROMIUM	-	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
LEAD	-	4	2	4	4	4	1	3	3	2	5
ALUMINUM	-	2	2	1	1	1	1	1	1	1	2
TIN	-	8	8	8	7	7	7	8	6	7	8
SILICON	-	21	19	15	14	13	12	12	11	12	14
ZINC	-	803	854	802	760	777	795	799	796	816	862
MAGNESIUM	-	14	15	15	13	15	15	15	15	15	16
CALCIUM	-	2117	2330	2147	2008	2152	2251	2223	2242	2223	2442
PHOSPHORUS	-	966	1095	1056	890	981	1043	1034	951	1081	1183
BARIUM	-	<1	1	<1	<1	<1	<1	<1	<1	<1	<1
BORON		53	56	54	50	51	53	53	53	53	56
SODIUM	-	12	10	12	12	11	12	11	10	13	14
MOLYBDENUM	-	98	102	104	98	103	107	105	105	106	111
SILVER	-	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
NICKEL	-	3	4	<1	1	2	2	4	<1	3	2
TITANIUM		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
MANGANESE	-	2	1	1	1	<1	1	<1	<1	<1	<1
ANTIMONY	-	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
CST @ 100C	-	8.07	8.02	8.1	8.2	8.2	8.2	8.3	8.2	8.1	8.1
TAN	-	2.17	2.23	2.39	2.41	2.53	2.04	2.13	2.52	2.6	2.49

FEV

Vehicle 8

Sample C

WEAR METALS AND ADDITIVES [ppm by weight]	CYCLE [h] 0	50	100	150	200	250	300	350	400	450	500
IRON	-	28	22	22	22	21	23	17	-	-	-
COPPER	-	<1	<1	<1	<1	<1	6	<1	-	-	-
CHROMIUM	-	<1	<1	<1	<1	<1	<1	<1	-	-	-
LEAD	-	<1	<1	<1	<1	<1	1	<1	-	-	-
ALUMINUM	-	5	5	7	9	8	5	3	-	-	-
TIN	-	11	12	11	12	13	13	13	-	-	-
SILICON	-	2	1	2	2	2	2	1	-	-	-
ZINC	-	976	974	982	956	929	935	939	-	-	-
MAGNESIUM	-	25	15	14	16	14	14	14	-	-	-
CALCIUM	-	2310	2107	2130	2120	2063	2130	2119	-	-	-
PHOSPHORUS	-	892	902	936	914	867	950	909	-	-	-
BARIUM	-	<1	<1	<1	<1	<1	<1	<1	-	-	-
BORON	-	9	24	24	24	23	23	21	-	-	-
SODIUM	-	138	208	213	211	215	221	223	-	-	-
MOLYBDENUM	-	146	143	146	145	148	158	156	-	-	-
SILVER	-	<1	<1	<1	<1	<1	<1	<1	-	-	-
NICKEL	-	<1	<1	2	1	1	1	<1	-	-	-
TITANIUM	-	<1	<1	<1	<1	<1	<1	<1	-	-	-
MANGANESE	-	<1	<1	<1	<1	<1	<1	<1	-	-	-
ANTIMONY	-	<1	<1	<1	<1	<1	<1	<1	-	-	-
CST @ 100C	-	7.8	7.62	7.74	7.65	7.7	7.71	7.71	-	-	-
TAN	-	2.15	2.19	2.24	2.21	2.54	2.4	2.26	-	-	-

Sample D

WEAR METALS AND ADDITIVES [ppm by weight]	CYCLE [h] 0	50	100	150	200	250	300	350	400	450	500
IRON	-	-	-	14	15	12	-	-	-	-	-
COPPER	-	-	-	5	6	7	-	-	-	-	-
CHROMIUM	-	-	-	<1	<1	<1	-	-	-	-	-
LEAD	-	-	-	1	3	<1	-	-	-	-	-
ALUMINUM	-	-	-	2	2	1	-	-	-	-	-
TIN	-	-	-	10	9	11	-	-	-	-	-
SILICON	-	-	-	1	3	1	-	-	-	-	-
ZINC	-	-	-	954	917	993	-	-	-	-	-
MAGNESIUM	-	-	-	13	449	101	-	-	-	-	-
CALCIUM	-	-	-	2012	1293	1983	-	-	-	-	-
PHOSPHORUS	-	-	-	917	886	958	-	-	-	-	-
BARIUM	-	-	-	<1	<1	<1	-	-	-	-	-
BORON				26	52	30					
SODIUM	-	-	-	202	94	201	-	-	-	-	-
MOLYBDENUM	-	-	-	143	98	143	-	-	-	-	-
SILVER	-	-	-	<1	<1	<1	-	-	-	-	-
NICKEL	-	-	-	2	<1	1	-	-	-	-	-
TITANIUM				<1	<1	<1					
MANGANESE	-	-	-	<1	<1	<1	-	-	-	-	-
ANTIMONY	-	-	-	<1	<1	<1	-	-	-	-	-
CST @ 100C	-	-	-	7.73	7.61	7.77	-	-	-	-	-
TAN	-	-	-	1.76	1.9	2.05	-	-	-	-	-

Oil Analysis Results of Engines tested with E0

Vehicle 2

Sample F

WEAR METALS AND ADDITIVES [ppm by weight]

	CYCLE [h]										
	0	50	100	150	200	250	300	350	400	450	500
IRON	-	-	-	-	-	-	-	6	8	5	7
COPPER	-	-	-	-	-	-	-	<1	<1	<1	<1
CHROMIUM	-	-	-	-	-	-	-	<1	<1	<1	<1
LEAD	-	-	-	-	-	-	-	1	<1	2	2
ALUMINUM	-	-	-	-	-	-	-	<1	1	<1	<1
TIN	-	-	-	-	-	-	-	<1	<1	<1	<1
SILICON								4	4	3	4
ZINC	-	-	-	-	-	-	-	603	617	634	661
MAGNESIUM	-	-	-	-	-	-	-	8	8	8	9
CALCIUM	-	-	-	-	-	-	-	1402	1487	1471	1645
PHOSPHORUS	-	-	-	-	-	-	-	710	717	739	795
BARIUM	-	-	-	-	-	-	-	<1	<1	<1	<1
BORON	-	-	-	-	-	-	-	5	4	4	4
SODIUM	-	-	-	-	-	-	-	158	163	158	167
MOLYBDENUM	-	-	-	-	-	-	-	12	15	14	16
SILVER	-	-	-	-	-	-	-	<1	<1	<1	<1
NICKEL	-	-	-	-	-	-	-	<1	<1	<1	<1
TITANIUM	-	-	-	-	-	-	-	105	16	15	17
MANGANESE	-	-	-	-	-	-	-	<1	<1	<1	<1
ANTIMONY	-	-	-	-	-	-	-	<1	<1	<1	<1
CST @ 100C	-	-	-	-	-	-	-	8.4	8.1	8.6	8.5
TAN	-	-	-	-	-	-	-	1.91	2.02	2.07	2.1

Vehicle 3

Sample E

WEAR METALS AND ADDITIVES [ppm by weight]

	CYCLE [h]										
	0	50	100	150	200	250	300	350	400	450	500
IRON	-	31	28	20	17	14	15	13	14	12	11
COPPER	-	<1	<1	<1	<1	<1	<1	<1	2	11	8
CHROMIUM	-	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
LEAD	-	2	4	3	2	3	6	2	5	4	3
ALUMINUM	-	2	3	1	2	3	2	1	3	1	1
TIN	-	8	11	12	11	12	13	11	11	10	9
SILICON	-	13	12	11	11	12	15	11	12	12	14
ZINC	-	846	848	889	941	904	990	883	865	865	869
MAGNESIUM	-	14	13	14	15	15	16	14	14	13	13
CALCIUM	-	2917	2850	3009	3187	3131	3492	2997	2948	2849	2780
PHOSPHORUS	-	798	744	810	878	853	953	809	784	783	763
BARIUM	-	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
BORON	-	60	57	57	62	62	67	58	57	61	58
SODIUM	-	11	10	10	11	13	12	9	10	8	7
MOLYBDENUM	-	127	122	128	133	137	149	124	128	123	119
SILVER		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
NICKEL	-	<1	<1	<1	<1	2	<1	<1	1	<1	<1
TITANIUM	-	3	<1	<1	<1	<1	<1	<1	<1	<1	<1
MANGANESE	-	2	1	1	1	1	1	<1	1	1	1
ANTIMONY	-	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
CST @ 100C	-	7.77	8.16	8.21	8.32	8.16	8.27	8.18	8.17	8.39	8.32
TAN	-	2.09	2.27	2.2	2.25	2.13	2.35	2.4	2.4	2.61	2.41

Vehicle 8

Sample E

WEAR METALS AND ADDITIVES [ppm by weight]

	CYCLE [h]										
	0	50	100	150	200	250	300	350	400	450	500
IRON	-	14	11	12	10	9	8	16	17	11	12
COPPER	-	<1	<1	5	11	2	5	<1	<1	<1	<1
CHROMIUM	-	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
LEAD	-	<1	<1	<1	<1	<1	118	<1	<1	<1	<1
ALUMINUM	-	2	2	<1	<1	1	<1	<1	1	<1	<1
TIN	-	7	7	7	8	7	<1	<1	7	<1	7
SILICON	-	2	2	2	2	1	1	4	3	4	3
ZINC	-	714	799	754	789	708	659	675	751	757	783
MAGNESIUM	-	16	13	12	12	11	11	363	63	19	14
CALCIUM	-	1485	1650	1557	580	1470	<1	1317	1552	1471	1528
PHOSPHORUS	-	805	930	817	909	777	704	756	864	892	897
BARIUM	-	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
BORON	-	26	26	26	25	25	23	37	27	24	22
SODIUM	-	196	204	203	204	203	<1	110	202	188	189
MOLYBDENUM	-	128	139	135	136	131	195	88	135	123	124
SILVER		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
NICKEL	-	<1	<1	<1	<1	<1	1338	<1	<1	1	<1
TITANIUM	-	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
MANGANESE	-	<1	<1	1	5	2	1	1	<1	<1	1
ANTIMONY	-	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
CST @ 100C	-	7.4	7.6	7.4	7.4	7.5	7.5	7	7.5	7.6	7.4
TAN	-	1.66	1.69	1.68	1.67	1.74	1.58	1.71	1.89	1.94	1.9