CRC REPORT NO. 662

DURABILITY OF AUTOMOTIVE FUEL SYSTEM COMPONENTS EXPOSED TO E20

Coordinating Research Council
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Disclaimers

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List of Acronyms

AVFL............ Advanced Vehicle/Fuel/Lubricants
ASTM .... ASTM International, formerly known as the American Society for Testing and Materials
CAA.............. Clean Air Act
CO................. Carbon monoxide
COA.............. Certificate of Analysis
CRC .... Coordinating Research Council, Inc.
DIPE.............. Diisopropyl ether
EISA.............. Federal Energy Independence and Security Act of 2007
EPA............... United States Environmental Protection Agency
EPAct............ Energy Policy Act of 2005
ETBE .... Ethyl Tertiary Butyl Ether
FDM.............. Fuel delivery module
FBP .... Final Boiling Point
FFV .... Flexible Fuel Vehicle
FLVV .... Fuel Fill Vent Valve
g/s.................. Grams per second
HCl................ Hydrochloric acid
ICP .... Inductively Coupled Plasma
KOH/g........... Potassium Hydroxide / gram
mL/sec........... Milliliters per second
MTBE .... Methyl Tertiary Butyl Ether
MY................ Model Year
NACE TM..... National Association of Corrosion Engineers Test Method
NREL............ National Renewable Energy Laboratory
OBDII .... On Board Diagnostic
OEM.............. Original Equipment Manufacturer
pHe................ pH value in Ethanol
POM.............. polyoxymethylene
ppm,m .... Parts per million, mass
PZEV .... Partial Zero Emissions Vehicle
RFG............... Reformulated gasoline
RFS .... Renewable Fuels Standard
SAE............... Society of Automotive Engineers
TAN .... Total acid number
TAME .... Tertiary Amyl Methyl Ether
TRC Inc......... Transportation Research Center Inc.
USCAR .... United States Council for Automotive Research
XRF .... X-ray fluorescence

Executive Summary

This report describes a scoping study that investigated how a gasoline that contained 20% ethanol by volume (E20) would affect wetted automotive fuel system components such as pumps, dampers, level senders, and injectors. The study was initially discussed in July of 2006 by the Advanced Vehicle/Fuel/Lubricants (AVFL) Committee of the Coordinating Research Council (CRC) in response to the State of Minnesota's legislation mandating that all gasoline sold or offered for sale in the state contain 20% ethanol by volume starting in August 2013. There was clearly a need to determine the effects of E20 on fuel system components that were not intended to be exposed to fuel containing more than 10% ethanol by volume (E10).

In 2007, the CRC AVFL Committee commissioned the AVFL-15 program in cooperation with the National Renewable Energy Laboratory (NREL), with funding from the U.S. Department of Energy, Office of Vehicle Technologies, Fuels and Lubricants Technologies Program, to investigate these effects on various fuel components and systems found on automotive on-road vehicles." The final contract was awarded in 2008 to the Transportation Research Center Inc. (TRC Inc.). The AVFL-15 project originated as a scoping study, and as such is to be used to identify areas where further testing should be performed.

The primary test fuel for the protocols was an aggressive blend of E20 ($E20_A$); E10 and an E0 test fuel were also incorporated into the program. The same base gasoline was used for each of the batches of test fuels consumed during the program.

Automobile manufacturers were contacted in order to develop a candidate list of vehicles for testing. Based on these suggestions, an initial selection of 15 designs from different manufacturers spanning the 1996 to 2009 model years were chosen for this program. It is estimated that these design selections represent at least 37 million vehicles with components and systems similar to the construction and materials found in the components and systems used in this study. The vehicle designs tested in this study are shown in Table E.1.

Table E.1 Initial Vehicle / Design Selections

1996 Toyota Camry 2.2L
1998 Honda Accord 3.0L V6
2000 Jeep Grand Cherokee 4.0L
2001 Chevrolet Cavalier 2.2L
2001 Toyota Tacoma 2.4L
2002 Mitsubishi Galant 2.4L
2002+ Toyota Camry 2.4L
2003 Hyundai Elantra 2.0L
2003 Nissan Maxima 3.5L
2004 Ford Focus 2.0L
2004 Ford Focus 2.3L PZEV
2004 Ford Ranger 3.0L
2005 Dodge Neon 2.0L
2007 Nissan Altima 2.5L (non-PZEV)
2009 Honda Accord 2.4L

Figure E.1 describes the general flow of the project.

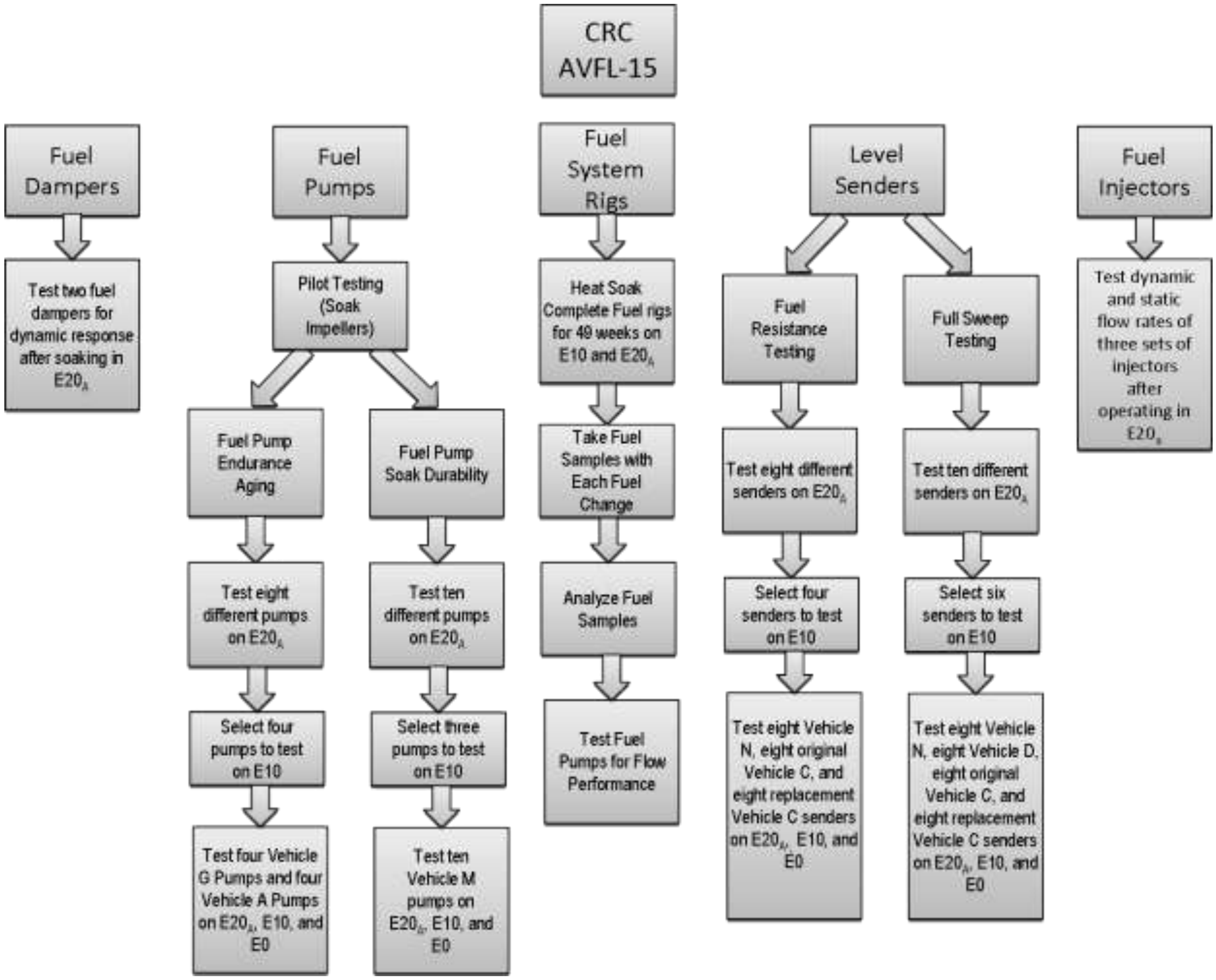

Figure E.1. AVFL-15 Project Flow Chart

Two fuel dampers were tested; both were representative of a design used by one vehicle manufacturer on two vehicle families produced from model year 1994 to 2008. Neither showed any significant difference between pre- and post-aging dynamic response. However, additional testing performed on fuel dampers from different vehicle designs could have different results.

Three 12-hole fuel injector designs from vehicles produced by three different manufacturers during model years 2002-2009 were tested. All of the injectors showed some reduction in flow, but none of the manufacturer representatives deemed the flow reductions significant. While these three injector models did not show any $E20_A$ compatibility issues, compatibility with other designs of fuel injectors is unknown without further testing.

Twelve fuel system rigs were built, two from each of six vehicle models produced during model years 1996 to 2009. One of each rig was aged on $E20_A$, while the other was aged on E10. Several areas of concern were identified, and more testing on fuel rigs would determine the frequency of failures in fuel pump seals, filler hoses, or other components.

Fuel level senders were tested in two different aging protocols, a fuel resistance protocol and a full sweep aging protocol. The fuel resistance aging involved moving the powered level senders in and out of test fuel at one to two seconds per cycle for 250,000 cycles, then soaking unpowered for one week. This process was repeated until one million cycles and four weeks of soak had been accumulated. The full sweep aging protocol involved cycling the powered level senders in and out of fuel at a rate of one to two seconds per cycle for five million cycles. Various level senders from eight different vehicle designs were tested; several were clearly affected by the $E20_A$ test fuel, and more testing is needed to fully characterize the effect.

Two different test methods were used to evaluate fuel pump performance. The soak durability testing evaluated the fuel pump's response to longer term exposure to the $E20_A$ while the pump remained in a static condition. Fuel pumps from ten vehicle designs were tested through the soak durability program. No negative impacts of ethanol on pump performance could be determined from the soak durability test data. None of the pumps tested exhibited a flow decline in excess of the established failure metric.

The endurance aging program investigated potential fuel pump failure mechanisms resulting from continuous operation. The pumps were aged to 3,000 hours of continuous operation at temperatures varying between 40°C and 60°C. Pumps from eight different vehicle designs were tested. The overall trend from this limited data set suggests that additional testing should be conducted and a statistically robust dataset should be developed.

Since this study was designed for scoping purposes, the findings should only be used to identify where additional testing should be performed. This study was never considered to be comprehensive or as an exhaustive determination of fuel system component compatibility. Failing to find an issue in this scoping study does not imply none exist. Further testing would be prudent to better understand the effects of >E10 upon wetted fuel system components.

I. Introduction

I.1 Background and Evolution of the Project

The main objective of the AVFL-15 project was to determine the durability of wetted automotive fuel system components when exposed to E20, including impact on wear and function of fuel pumps, fuel injectors, fuel dampers, fuel tank, fuel lines and fuel level senders used in existing light-duty vehicles. The program was designed as an initial scoping study. Resources were added as needed to continue testing deemed by the project panel as necessary – the study is not to be considered as a comprehensive or exhaustive determination of materials compatibility with E20 for fuel systems components used across the entire spectrum of gasoline-fueled light-duty vehicles currently in operation.

Ethanol has been used as a motor fuel in the United States for more than a century. Prior to the passage of the Clean Air Act (CAA) Amendments of 1977, there were no federal or state regulations controlling the use or properties of motor gasoline containing ethanol. The 1977 CAA Amendments included a provision that unleaded gasoline marketed for use in model year 1974 and newer vehicles must be substantially similar to those fuels used during the federal emissions certification test procedures. In 1978, the Environmental Protection Agency (EPA) failed to act on a request to waive this provision for motor gasoline containing ethanol in concentrations up to 10% by volume (E10) within the time period provided by law, and thus ushered in the use of this blend as a legal motor fuel in the United States.

In the late 1980s, some states and urban areas began to use ethanol and other oxygenates in mandatory oxygenated fuel programs to reduce automobile tailpipe emissions of carbon monoxide (CO). The Clean Air Act Amendments of 1990 also stimulated fuel ethanol production by requiring the implementation of: (a) oxygenated fuels programs to reduce wintertime motor vehicle emissions of carbon monoxide (CO) in many CO nonattainment areas, and (b) reformulated gasoline (RFG) to reduce emissions of ozone precursors and air toxics in certain ozone nonattainment areas. Early on, many oxygenated gasoline blends contained Methyl Tertiary Butyl Ether (MTBE).

However, with the implementation of numerous state-level bans on MTBE due to groundwater contamination concerns in the starting in early 2000, ethanol became the oxygenate most widely used to meet the minimum 2.0% by weight oxygen content requirement for RFG which existed until 2005. This oxygenate requirement was replaced by a Renewable Fuels Standard (RFS) in the federal Energy Policy Act of 2005 (EPAct) which mandated the use of 7.5 billion gallons of renewable fuels by 2012. Together with the subsequent expansion of the mandated renewable fuels volumes to 36 billion gallons by 2022 per the federal Energy Independence and Security Act (EISA) of 2007, these two laws effectively accelerated the growth in the volume of ethanol used in motor gasoline.

Figure I.1 graphically illustrates the trend in US ethanol fuel production over the past 30 years in response to the events described in the previous narrative. Ethanol production remained on a slow but steady increase from 1980 through 2001, with an annual increase of about 70 million gallons per year. From 2001 through 2005, that rate of increase jumped to about 600 million gallons per, and from 2006 through 2010 the rate of increase jumped again to roughly 2,100 million gallons per year. Although this chart does not differentiate between ethanol production for E85 and E10, the E85 market penetration has remained modest over this same time period.

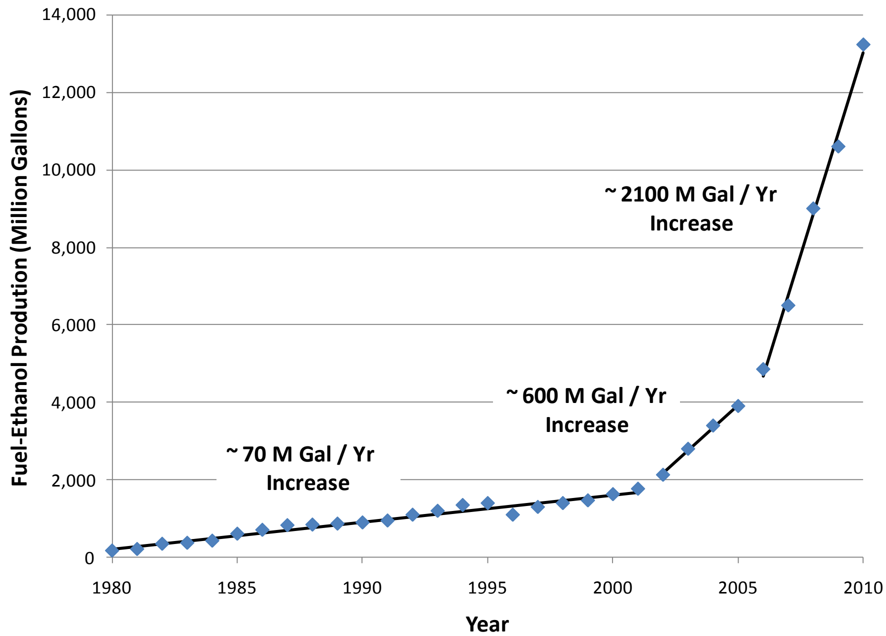

Figure I.1. U.S. Fuel Ethanol Production from 1980 to 2010

In 2005, the State of Minnesota adopted legislation to require all gasoline sold or offered for sale in the state to contain 20% ethanol (E20) starting August 30, 2013. The provision would expire, however, if 20 percent of gasoline sold in Minnesota was already ethanol (e.g., through the expanded use of E10 and E85) or if the EPA had not already approved E20 for general use. At the time, it was anticipated by industry that at least one company producing ethanol or some other coalition/stakeholder would initiate the E20 waiver submission process to the EPA as early as possible; and once an E20 waiver was approved by EPA, E20 would be considered a legal fuel for sale in any other state.

Even though gasoline containing ethanol had been available in the marketplace for many years, the actual and continuous exposure of vehicles to ethanol in fuel had become more of a reality in the 2005 – 2006 calendar year timeframe. Therefore, the prospect of an E20 fuel being used in non-Flexible Fuel Vehicles (FFV)[1] already on the road (so-called "legacy" vehicles) was viewed with concern by many parties. Automotive on-road OEMs offering vehicles for sale in the United States include language in their respective Vehicle Owner Guides discussing the allowance of using "…up to 10% by volume ethanol…". As of 2011MY, no identifiable OEM Vehicle Owner Guide has indicated acceptance beyond E10, aside from those vehicles designed and sold as FFVs. The main concern revolved around the potential for non-FFV vehicles on the road and in current production (as well as for engines and fuel systems found in various non-road equipment) to encounter performance issues when operated with gasoline fuels containing more than 10% ethanol by volume.

To understand how non-FFVs would handle an increase in ethanol concentration, there was a need to determine the effects of gasoline containing more than 10% ethanol by volume on the fuel management system. For example, previous CRC projects had shown elevated diurnal permeation emissions from some vehicles when fueled with gasoline containing ethanol concentrations up to 20% by volume relative to when those same vehicles operated on hydrocarbon-only gasoline.[2] [3] Furthermore, there was a concern

[1] FFVs are not a concern as the engine and fuel systems on these applications are specifically designed to accommodate and perform on gasoline fuels containing up to a maximum of 85% ethanol (E85) by volume.
[2] Haskew, H. M., et al., *Fuel Permeation from Automotive Systems*, CRC Project E-65, Final Report, September 2004

that the ability of the oxygen contained in the ethanol molecule to induce a lean shift in air:fuel ratio control during the combustion process may have a deleterious effect in vehicles not equipped to handle such fuels (via a lack of calibration capability). This effect was demonstrated in a study conducted by Orbital Engine Co for the Australian government in 2003.[4]

Additionally, engine control system fuel volume demand is a main design requirement for fuel pump performance and capability. As ethanol concentration increases, inherently overall fuel energy density (on a volumetric basis) decreases and thus the ability of the fuel pump to provide sufficient fuel is reduced. Flow less than that demanded by the engine control system can result in an enleanment effect and a loss of control over the fuel:air mixture to the engine. This loss of control could have negative impacts on engine and emissions control equipment functionality and durability. This is a concern during high-load engine operating conditions – such as wide-open throttle – and especially when exhaust gas oxygen feedback control may not be designed to function.

At a meeting of the CRC AVFL Committee in July 2006, the team decided to engage in an effort to provide initial engineering data to regulatory agencies. There was clearly a need to understand the effects of ethanol at concentrations beyond E10. Goals for this project centered on the concept of completing an initial scoping study which, pending the outcome, would determine whether further investigations would be needed.

As mentioned earlier, the 2007 EISA significantly expanded the mandated volumes of renewable fuels required to be blended into the transportation fuel pool by 2022. These requirements, together with available projections of motor gasoline demand, implied that unless there was a huge increase in the numbers of FFVs in operation coincident with a dramatic expansion in the consumption of E85, there would continue to be pressures for mid-level ethanol blends in the future.

In 2007, the CRC AVFL Committee commissioned the AVFL-15 program to investigate various fuel systems and fuel system components (fuel pump, fuel level senders, fuel injectors, fuel dampers and fuel tank and lines) found on automotive on-road vehicles. OEMs were asked to suggest model candidates and model years based on their internal engineering assessments. Based on these recommendations and/or sales volumes, the AVFL-15 panel made an initial selection of 15 designs from eight different manufacturers spanning model years 1996 through 2009. It is estimated that these design selections represent at least 37 million vehicles with components and systems similar to the construction and materials found in the components and systems used in this study.

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[3] Haskew, H.M., et al., *Fuel Permeation from Automotive Systems: E0,E6, E10, E20 and E85*, CRC Project E-65-3, Final Report, December 2006

[4] Orbital Engine Co., *Market Barriers to the Uptake of Biofuels Study: A Testing Based Assessment to Determine Impacts of a 20% Ethanol Gasoline Fuel Blend on the Australian Passenger Vehicle Fleet*, Report to Environment Australia, March 2003

The vehicle designs tested in this study were:

Table I.1 Initial Vehicle / Design Selections

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2004 Ford Focus 2.3L PZEV
2004 Ford Ranger 3.0L
2005 Dodge Neon 2.0L
2007 Nissan Altima 2.5L (non-PZEV)
2009 Honda Accord 2.4L

These applications were incorporated in the AVFL-15 program at various stages to investigate specific components or entire fuel systems. Complete fuel system rigs were commissioned to soak and operate with $E20_A$ fuel for an extended period of time while other individual components such as the Fuel Pump, Fuel Level Senders, Fuel Injectors and Fuel Damper experienced a variety of testing. In all, a total of 120 pieces were subjected to functional testing, durability aging and evaluations using protocols developed by CRC, SAE, ASTM and TRC Inc. (For examples, see the list of ASTM and SAE protocols in Table I.2. – these standards were used for evaluation and guidance, but were not performed on every part if it was not deemed necessary) These protocols were considered to sufficiently represent component in-use field durability as best determined by the AVFL-15 panel and based on recommendations and guidance from the OEMs involved. Some of these standards were incorporated into portions of this study, while others were modified or simply reviewed for consideration.

In order to eliminate the inherent variability associated with testing individual fuel system components removed from in-use vehicles with varying levels of accumulated mileage, this part of the study focused on new components sold as service parts and purchased from local OEM dealerships. However, as the program progressed, the panel discovered that design changes had occurred on some OEM replacement parts offered for sale at dealerships (a normal practice throughout the life span of a replacement part); these changes, in effect, resulted in the testing of parts from more recent model years than indicated. This complicated the evaluation process, which was intended to represent the specific original part that was used on that particular vehicle model.

Table I.2. List of ASTM and SAE Documents

ASTM:	
D412:	Vulcanized Rubber and Thermoplastic Elastomers – Tension
D471:	Rubber Property – Effect of Liquids
D543:	Evaluating the Resistance of Plastics to Chemical Reagents
D618:	Conditioning Plastics for Testing
D638:	Tensile Properties of Plastics
D2240:	Rubber Property – Durometer Hardness
D3183:	Rubber – Preparation of Product Pieces for Test Purposes from Products
D4806:	Denatured Fuel Ethanol for Blending with Gasolines for Use as Automotive Spark-Ignition Engine Fuel
D4814:	Automotive Spark-Ignition Engine Fuel
D4815:	Determination of MTBE, ETBE, TAME, DIPE, tertiary-Amyl Alcohol and C_1 to C_4 Alcohols in Gasoline by Gas Chromatography
D5500:	Vehicle Evaluation of Unleaded Automotive Spark-Ignition Engine Fuel for Intake Valve Deposit Formation
G1:	Preparing, Cleaning, and Evaluating Corrosion Test Specimens
G31:	Laboratory Immersion Corrosion Testing of Metals
SAE:	
J905:	Fuel Filter Test Methods
J1537:	Validation Testing of Electric Fuel Pumps for Gasoline Fuel Injection Systems
J1681:	Gasoline, Alcohol, and Diesel Fuel Surrogates for Materials Testing
J1747:	Recommended Methods for Conducting Corrosion Tests in Hydrocarbon Fuels or Their Surrogates and Their Mixtures with Oxygenated Additives
J1748:	Methods for Determining Physical Properties of Polymeric Materials Exposed to Gasoline/oxygenate Fuel Mixtures
J1832:	Low Pressure Gasoline Fuel Injector
J1862:	Fuel Injection System Fuel Pressure Regulator and Pressure Damper
J2260:	Nonmetallic Fuel System Tubing with One or More Layers

I.2 General Testing Overview

Figure I.1 presents the general flow of the project and the five main pathways.

The first pathway dealt with the fuel pump: the intention of the initial pilot phase testing of the impeller was to provide guidance regarding which specific designs would be eligible for further fuel pump testing for the endurance and soak portions.

In the second pathway, the complete fuel system was reproduced from replacement parts available at the OEM dealership for the specific model. The entire configuration experienced exposure in a temperature-controlled environment for nearly one year.

The third pathway investigated the compatibility of fuel dampers found in a design.

Fuel injectors were included in the fourth pathway.

The fifth and final pathway of the durability program investigated fuel level senders found in vehicles. Fuel level senders are used to inform the instrument panel and fuel gauge of the actual fuel level in the fuel tank.

In addition, at the end of the pathway for each of the components, a postmortem analysis was conducted where applicable and as determined by the AVFL-15 project panel, with support by the Tier 1 parts suppliers as appropriate. Some components experienced more postmortem analyses than others due to need and resource constraints. Examples of the rigs and fuel system components tested in each of the pathways are illustrated in the photographs in Section I.4.

Further details and more specific information for each of the testing protocols and the data collected can be found in the subsequent sections of the report.

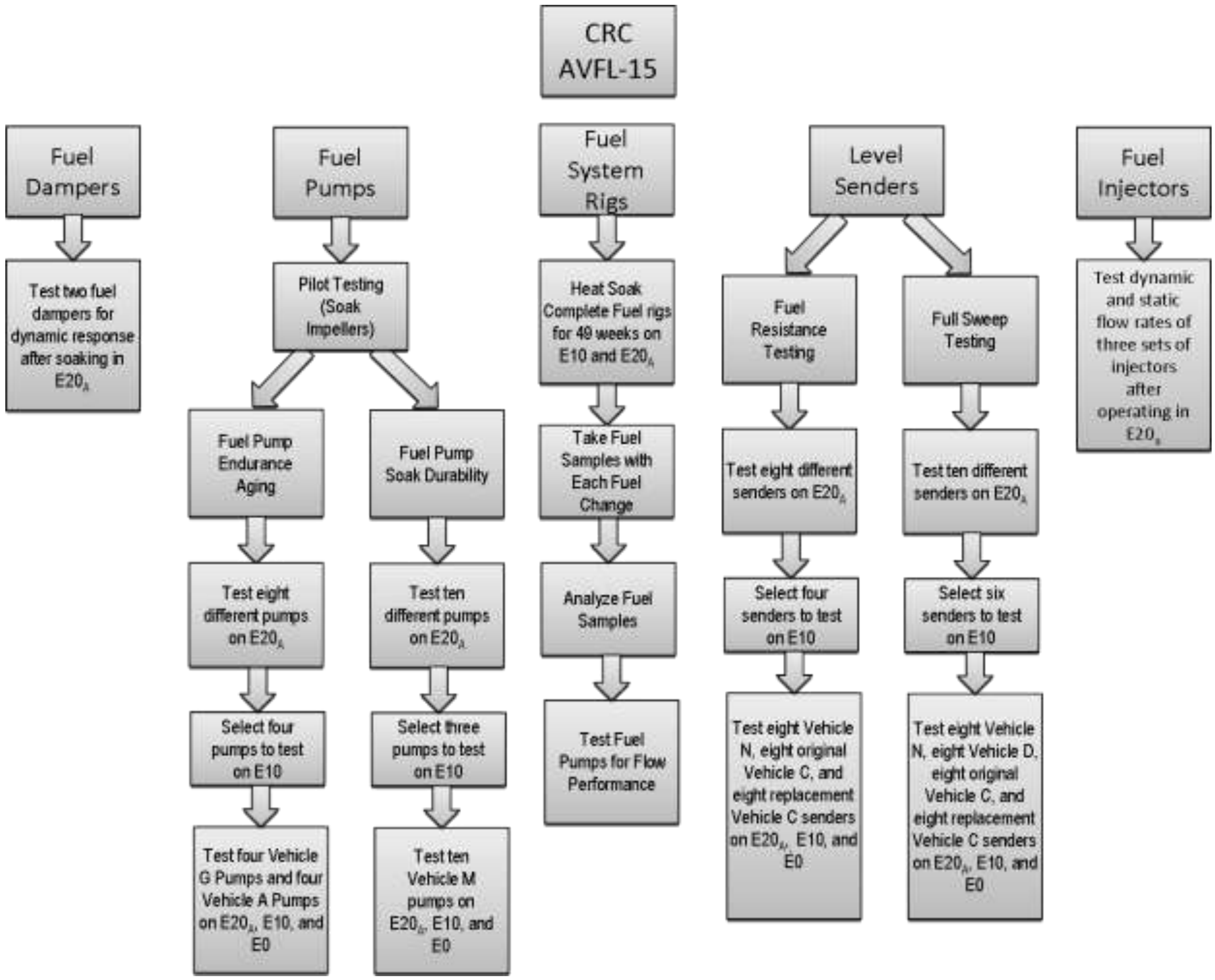

Figure I.2. AVFL-15 Project Flow Chart

In March of 2009, while the CRC study was ongoing, Growth Energy (a coalition of U.S. ethanol supporters), along with 54 ethanol manufacturers, applied for a waiver to increase the allowable amount of ethanol in gasoline from E10 to E15. The waiver application included data on the impact of E15 on vehicle emissions, fuel system materials, and driveability.

In September 2010, the CRC released initial findings on the effects of ethanol greater than 10% by volume that included select portions of this AVFL-15 study. In October 2010, EPA partially granted Growth Energy's waiver request application. The partial grant allowed the use of gasoline containing up to 15 percent by volume ethanol in model year (MY) 2007 and newer light-duty vehicles, provided that certain conditions were met. Three months later, in January 2011, EPA took additional action on Growth Energy's waiver request application and expanded the model years covered to include MY 2001 through 2006 light-duty vehicles.

In order to maximize testing and optimize use of the available resources, the project oversight panel chose to initiate testing with components and fuel systems exposed to test gasoline containing 20% ethanol by volume. (In addition, after EPA issued its E15 waivers, priority was placed on testing those designs found on MY 2001 and newer vehicles.) Those component designs that were found to exhibit functional degradation would then be considered for further evaluation on test fuels containing lower levels of ethanol. Moreover, they would also be considered for inclusion in a more focused program to be conducted as a follow-on to the present screening study.

I.3 Additional Project Introductory Comments

Fuel Pump Volumetric Demand – The effect of increased ethanol on fuel pump volumetric flow demand is well understood as this is simply related to the energy density of the fuel – essentially fuel pump and fuel injector sizing for FFV vehicles must include fuel volume delivery capability greater than that necessary for non-FFV applications using a maximum of 10% by volume ethanol. Ethanol has about 67% of the volumetric energy density of gasoline (E0) without oxygenates. Engine volumetric fuel demand will increase with increasing concentrations of ethanol present in gasoline-ethanol blends in order to maintain an equivalent level of engine power. For example, engine volumetric fuel demand for E20 is roughly 7% greater than that required for E0, and roughly 3.5% greater than that required for E10. This increased fuel flow demand on the fuel pump to maintain engine power is in addition to any loss in fuel flow associated with fuel pump deterioration over the life of a vehicle caused by operating with a fuel not originally intended.

Fuel Level Sender – The fuel level sender determines how the fuel gauge on the instrument panel displays the fuel tank level for the vehicle. Each OEM may have different criteria and tolerances for the translation of signals measured from the fuel level sender; however, a lack of a signal or a signal that does not vary with fuel level will be a concern, especially when the signal is used by the On-Board Diagnostic (OBD) system. If the gauge shows full when empty, this is more of a concern for consumer safety than if the fuel causes a stuck signal resulting in the gauge on the instrument panel illustrating a false empty state.

Fuel Specification – The AVFL-15 panel decided to use an 'aggressive ethanol' for blending an E20 (referred to in this report as $E20_A$). The goal was to prepare an ethanol blend that would represent a worst case denatured ethanol from the field. This approach is similar to that taken in some of the studies cited in the Growth Energy E15 waiver request[5,6]. The panel felt that a worst case fuel was critical for a scoping trial such as AVFL-15 in that if a fuel system component was susceptible to E20, it would more likely be indentified with a worst case fuel. The intention of the committee is to incorporate safeguards, via a more aggressive ethanol-gasoline blend, to offer a level of protection given that fuels are used under a variety of driving conditions. The framework for such an aggressive blend was found in the SAE specification J1681, adjusted accordingly to focus on E20. To more closely match the gasoline in the marketplace, the AVFL panel chose to modify the J1681 to use a commercially available gasoline. The aggressive nature of the fuel included increased concentration of water, lowered pH (increased acidity), inclusion of chlorides and sulfates, with careful attention to avoid any one fuel parameter overwhelming the test results – the study is intended to be an E20 Durability study (for example, the study is not a chloride test). ASTM specifications for individual fuel parameter limits provide guidance on the maximum potential value achievable by any of the fuel parameters. E0 and / or E10 were used as a baseline aging fuel for comparisons to $E20_A$ while component functional tests were conducted using E0 on all pieces.

Vehicle Design and Connected Data Identification within the Report – Each component or rig system tested represented a single model year; however, that particular fuel system design may also have experienced testing in multiple aspects of AVFL-15, but it is not the case that all designs were tested in all phases. The model years that experienced the bulk of testing focused on model years 2001 and beyond, in

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

[6] *Minnesota Compatibility Studies*, Bruce Jones, Gary Mead, Paul Steevens and Chris Connors, http://www.mda.state.mn.us/en/renewable/ethanol/e20testresults.aspx

alignment with the approved EPA E15 waiver. Because AVFL-15 was initiated before the E15 waiver submission and approval process, the project focuses on E20. The assigned vehicle design label for each section is arbitrary and thus, no connection from section to section is possible as the same design evaluated in different sections may have a different label. However, for a given component, such as the fuel pump, where a specific design may have undergone pilot, soak and endurance testing, that particular design will have a similar label format to identify that the specific component was evaluated across multiple protocols within the component section, in this case the Fuel Pump Section.

Contract History and Period of Performance – The CRC and its members identified a need for mid-level ethanol fuel system durability research and partnered with the National Renewable Energy Laboratory (NREL) to conduct this study. TRC Inc. (Transportation Research Center Inc.) was awarded the contract for this program and conducted the testing sequences. The contract began May 20, 2008, and the first test sequence of the Pilot Study ran on September 8, 2008. The final test sequence for the last (fuel level sender) portion of this program was completed in mid-September 2011. Weekly or bi-weekly conference calls were made during the course of this three-year program, and TRC provided monthly progress reports to the AVFL-15 Panel.

I.4 Example Photographs of Fuel System and Components

Figure I.3 is an example of the complete fuel system rig assembly for one design. Attempts were made to position the system into a layout similar layout as would be found on that particular vehicle. Where needed, fuel lines were adjusted to fit within the confines of the cart with the best attempts to maximize the diameter for any radius not found on the vehicle. As shown, the full fuel system included the fuel injectors, fuel rails, fuel lines, fuel filter, fuel inlet, fuel tank, the fuel pump and any other internals to the fuel tank.

Figure I.3. Example of Fuel System Rig Assembly

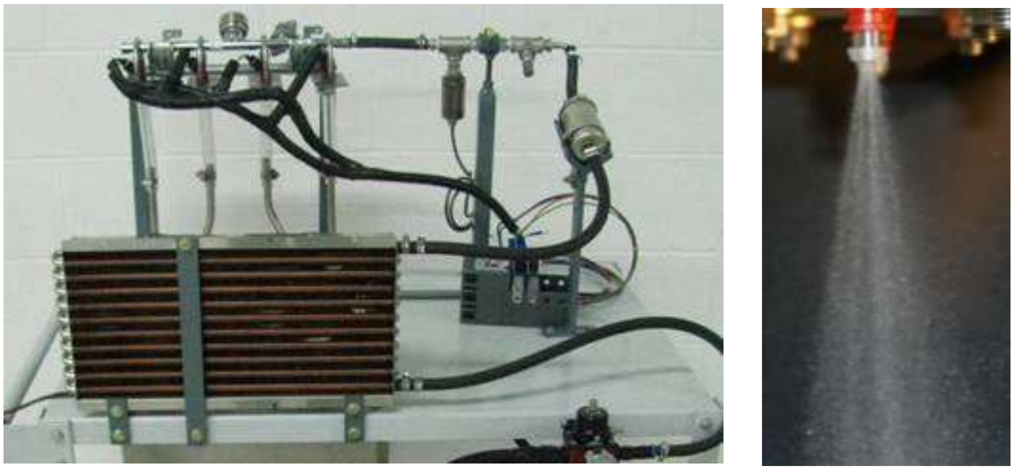

Figure I.4. Example of Fuel Injector Aging Assembly.

Figure I.4 shows an example of the fuel injector aging assembly on the left. The injectors were positioned such that the flow could be observed through the clear tubing. On the right is an example of a spray pattern from one of the designs.

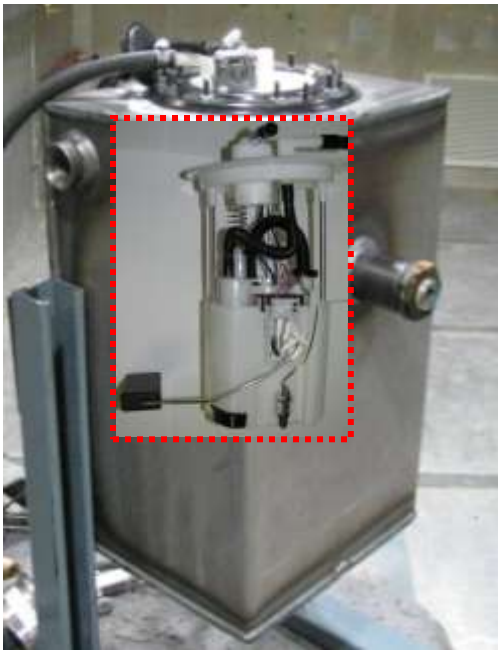

Figure I.5. Example of fuel pump durability fixture

Figure I.5 shows an example of the fuel pump durability fixture. The fuel pump assembly was lowered into the top access and sealed; inlet and outlet hose connections were made to the OEM positions.

Figure I.6. Example of fuel level sender

Figure I.6 is an example of the fuel level sender. The sender is mounted to the actuator which is then programmed to move up and down allowing full range of motion. This piece fits atop a cylindrical reservoir containing approximately three gallons of fuel.

I.5 Organization of the Report

The procedures used to develop the test fuels for this program are described in Section II. Section III discusses the complete fuel system component test rigs evaluated for the study. The fuel pump investigations are presented in Section IV. Section V describes the fuel level sender assessment. Fuel dampers and fuel injectors are discussed in Section VI and VII, respectively. Overall conclusions from this program are presented in Section VIII.

II. Test Fuel Preparation

This section discusses the rationale underlying the formulas for the fuels selected for the test program, outlines the blending procedures employed, and presents analyses of the properties of the test fuel blending components and final test fuel blends.

II.1. Formulation Discussion

The Advanced Vehicle/Fuel/Lubricants (AVFL) panel chose to use three fuels for the AVFL-15 project: a gasoline with no ethanol, an E10, and an E20.

The AVFL-15 panel decided to use an 'aggressive ethanol' for the blending of an E20. The goal was to prepare an ethanol blend that would represent a worst case denatured ethanol from the field. The panel felt that a worst case fuel was critical for a scoping trial such as AVFL-15, in that if a fuel system component was susceptible to E20, it would more likely be identified with a worst case fuel. The framework for this aggressive blend was found in the SAE specification J1681, and the formula to blend the SAE aggressive ethanol is shown in Table II.1.

Table II.1. SAE J1681 Formula for Aggressive Ethanol.

Component	Units	1.0 liter	1.0 gallon
Ethanol, Synthetic	Grams	816.0	3084.5
Deionized Water	Grams	8.103	30.631
Sodium Chloride	Grams	0.004	0.014
Sulfuric Acid	Grams	0.021	0.080
Glacial Acetic Acid	Grams	0.061	0.230

Following this recipe would result in 2.73 ppm,m chloride ions, 25.15 ppm,m sulfate ions, and 9832 ppm,m of water.

However, the AVFL panel decided to deviate from this specification for several reasons. While synthetic ethanol was available, the panel decided to use ethanol generated from a fermentation process in an effort to more closely represent ethanol from a field application.

Comparing the SAE J1681 formula to the ASTM specification for ethanol pending at the time of project planning [ASTM D4806-08a], it was noted that the SAE J1681 formula would not provide enough chlorides to achieve the maximum limit of 10 ppm,m chloride limit in D4806-08a, and that the sulfuric acid content of J1681 would result in the sulfate content exceeding the maximum limit of 4 ppm,m in D4806-08a. As noted above, if the J1681 formula was used, the sulfate level would have been approximately 25 ppm sulfate, and sulfates are known to have a detrimental effect on fuel system components. To ensure that the AVFL-15 project was not influenced by excessive sulfate levels, only enough sulfuric acid was used to achieve the maximum limit of 4 ppm,m according to ASTM D4806-08a.

If the full amount of sulfuric acid and acetic acid from SAE J1681 was used, the resulting pHe of the ethanol would have been ~2.8. This low pHe was felt to be an important aspect of the aggressive ethanol, and other means were sought to lower the pHe. The sodium chloride addition in the SAE J1681 specification was substituted by hydrochloric acid as a means to introduce the required chloride ions and reduce the pHe closer to the goal of ~2.8. However, its impact on pHe was minimal, and nitric acid was used instead to lower the pHe to the desired goal of 2.8.

The resulting final formula used for aggressive ethanol blending is shown in Table II.2.

Table II.2. Modified Formula for Aggressive Ethanol.

Component	Units	Mass per gallon of ethanol
Deionized Water	Grams	Based on existing water content of ethanol
Hydrochloric Acid	Grams	0.031
Sulfuric Acid	Grams	0.012
Glacial Acetic Acid	Grams	0.230
Nitric Acid	Grams	0.0568

The ethanol used for this study had a specific gravity of approximately 0.79 or 6.579 lbs / gallon (or 2984.184 grams / gallon). This density required 0.0298 grams of 'pure' HCl to achieve the desired 10 ppm chloride limit; if 10 N Hydrochloric acid was used, then 0.82 g HCl was needed to achieve 10 ppm. (10 N HCl is 36% HCl by weight)

After adding these components, the expected properties of the aggressive ethanol were estimated to be as shown in Table II.3.

Table II.3. Expected Properties of Aggressive Ethanol Using Modified Formula.

Property	Test Method	Units	ASTM D 4806-09 Limits	Expected Properties of Aggressive Ethanol
Water	E203 or E1064	vol%	1, max	1
Chloride	D7319 or D7328	ppm,m	10, max	10
pHe	D6423	--	6.5 to 9.0	2.8
Sulfate	D7318,7319, or 7328	ppm,m	4, max	4

II.2. Blending Procedure

Increase Aromatic Content of Base Fuel

The project oversight panel specified the aromatic level of the base gasoline (prior to ethanol blending) to be approximately 40 vol%. Gasoline fuels with aromatic levels this high were commercially available, but if needed, the aromatic content could have been increased to a level between 38-40 vol. % using Sunoco Aromatic 100 solvent (or equivalent.)

Blending of Aggressive Ethanol

Prior to making the blend, a small batch of ethanol (~5 gallons) with the required salts and acids for addition to the total ethanol volume was prepared. This small batch of concentrated aggressive ethanol was prepared and used on the same day as the E20 blending.

Blending of Aggressive E20

1. Add all of the ethanol to the tank except for the five gallons that will be used to blend in the aggressive components. Verify that the tank has the correct volume of ethanol.
2. Slowly pour the ethanol with acid into the blend tank.
3. Once all acid has been added, flush the inlet line with a small volume of neat ethanol. Close the cap on the inlet of the blending tank, apply the nitrogen blanket, mix.
4. Take a sample for certification purposes
5. Once the correct volume of gasoline has been loaded, seal the inlet, apply nitrogen blanket and mix.
6. Take a sample for certification purposes.
7. The analysis below should be performed on the samples as part of the Certificate of Analysis.

Blending of E0 and E10

The same base gasoline (with adjusted aromatic level) was used for the E10 blend and the gasoline with no ethanol (E0).

II.3 Production and Analysis of Test Fuels

Changes in scope that evolved throughout the duration of the program necessitated the supply of three different batches of test fuels. The first two batches were supplied by BP Global Fuels Technology. The third (and final) batch was supplied by Gage Products. The same blend recipes and procedures were used for all three batches, and all included an E0, E10, and aggressive E20 fuel. Fuel system component evaluations were scheduled such that all fuel system components and their controls were evaluated using the same batch; this was done to eliminate the influence of batch-to-batch variability in fuel properties on the results.

While the base gasoline and ethanol for each batch originated from different lots, inspections of the blend components and final fuels (as described and presented in the text below) demonstrate that there were no significant differences among the three batches of fuels used for this study.

II.3.1. First Batch of Fuels – Produced by BP Global Fuels Technology

Analysis of Blending Components

Table II.4. Analysis of Denatured Ethanol.

Property	Test Method	Units	ASTM D4806-11a Limits	Base Denatured Ethanol
Water	E1064	ppm,m	12600 ppm,m max	6093 ppm,m
Specific Gravity	D1298	--	N/A	0.7905
Flash	D93	°C	N/A	4
Gum (solvent washed)	D381	mg / 100 ml	5.0, max	0.40 before wash and 0.00 after wash
Sulfur	D5453	ppm,m	30, max	2
Sulfate	D7328	ppm,m	4, max	0.75
Nitrate	D7328	ppm,m	N/A	0.01
Chloride	D7328	ppm,m	10, max	0.08
Copper content	D1688 or ICP	mg/kg	0.1, max	<0.01
Total Acid Number	D664	mg KOH / g	N/A	0.00
pHe	D6423	--	6.5 to 9.0	7.4
Sodium	ICP	ppm,m	N/A	1.37
Calcium	ICP	ppm,m	N/A	0.749
Potassium	ICP	ppm,m	N/A	0.02

Please note that Total Acid Number, ASTM D664, was used to measure acidity of the base ethanol instead of ASTM D1613.

Table II.5. Analysis of Aggressive Ethanol (LN # 22376-57)

Property	Test Method	Units	ASTM D4806-11a Limits	Aggressive Denatured Ethanol
Total Acid Number	D664	mg KOH / g	N/A	0.08
Water	E1064	ppm,m	12600 ppm,m max	5694 ppm,m
pHe	D6423	N/A	6.5 to 9.0	1.91
Sulfate	D7328	ppm,m	4, max	5.4
Nitrate	D7328	ppm,m	N/A	4.98
Chloride	D7328	ppm,m	10, max	Measured result not valid

Pilot blending work performed by BP Global Fuels Technology determined that ASTM D7328 could not detect the chlorides added through the use of hydrochloric acid. However, use of an x-ray fluorescence (XRF) method was able to measure a value close to the calculated value of chlorides.

Table II.6. Analysis of Gasoline (Prior to Adjustment of Aromatic Level).

Property		Test Method	Units	ASTM D4814-11 Limits	Base Gasoline
Research Octane Number		D2699	N/A	N/A	92.8
Motor Octane Number		D2700	N/A	N/A	83.7
Specific Gravity		D1298	N/A	N/A	0.7382
Reid Vapor Pressure		D5191	psi	Varies by region and time of year	8.59
Sulfur		D5453	ppm,m	80	33
Oxidation Stability		D525	minutes	240	>1440
Total Aromatics		D6293	vol. %	N/A	30.2
Olefins		D6293	vol. %	N/A	9.3
Saturates (Paraffins and Naphthenes)		D6293	vol. %	N/A	60.5
Benzene		D6293	vol. %	N/A	1.32
Toluene		D6293	vol. %	N/A	5.6
Distillation	IBP	D86	°F		90.9
	5%		°F		114.7
	10%		°F	Varies	122.8
	20		°F		133.1
	30%		°F		145.1
	40		°F		161.8
	50%		°F	Varies	183.6
	60%		°F		211.9
	70%		°F		253.5
	80%		°F		308.8
	90%		°F	Varies	337.9
	95%		°F		351.0
	FBP		°F	Varies	388.8
	Recovery		ml		97.6
	Residue		ml		1
Nitrogen		D4629	ppm,m	N/A	9
Mercaptan Sulfur		D3227	ppm,m	N/A	4.0
Silver Strip Corrosion		D130	N/A	1, max	0 (no tarnish)

Analysis of $E20_A$ Fuel

Tables II.7 and II.8 summarize and compare fuel property inspections for the $E20_A$ fuel made from a sample collected when the fuel was shipped to TRC and from a sample drawn after several months of storage at TRC.

Table II.7. $E20_A$ (LN # 22376-101) – Retain from Truckload Shipped to TRC.

Property	Test Methods	Units	$E20_A$
Water	E1064	ppm,m	1198
Peroxide Number	D3703	ppm,m	6
Total Acid Number	D664	mg KOH / g	0.01
Reid Vapor Pressure	D5191	psi	8.85
Sulfur	D5453	ppm,m	22
Ethanol	D6293	vol. %	19.52
Nitrate	D7328	ppm,m	2.06
Sulfate	D7328	ppm,m	0.67
Specific Gravity	D1298	N/A	0.7619
Total Aromatics	D6293	vol. %	30.4
Olefins	D6293	vol. %	6.5
Saturates (P & N)	D6293	vol. %	42.3
Benzene	D6293	vol. %	0.91
Toluene	D6293	vol. %	3.72

Table II.8. Analysis of TRC Retain Sent Back to BP in Q2 2009

Property	Test Methods	Units	$E20_A$
Water	E1064	ppm,m	2136
Chloride	XRF	ppm,m	2.5

The water level of the $E20_A$ increased from 1198 ppm,m at the time of shipment from BP to 2136 ppm,m when the $E20_A$ tank sample was taken at TRC. This was probably due to absorbance of water during storage, e.g., absorbance of water bottoms.

II.3.2. Second Batch of Fuels – Produced by BP Global Fuels Technology (April 2010)

Analysis of Blending Components

Table II.9. Analysis of Denatured Ethanol from Second Fuel Batch.

Property	Test Method	Units	ASTM D4806-11a Limits	Base Denatured Ethanol
Water	E1064	ppm,m	12600 ppm,m, max	7656 ppm,m
Specific Gravity	D1298	--	N/A	0.7919
Gum (solvent washed)	D381	mg / 100 ml	5.0, max	0.40 before wash and 0.0 after wash
Sulfate	D7328	ppm,m	4, max	0.22
Chloride	XRF	ppm,m	10, max	0.37
Total Acid Number	D664	mg KOH / g	N/A	<0.01
pHe	D6423	--	6.5 to 9.0	7.8

The formula for the aggressive ethanol was the same as the original batch, and the water level was adjusted to reach ASTM D4806-11a upper limit for water, 12600 ppm,m water. However, the results in Table 10 show that while the water was added, the incremental amount was not sufficient to reach the desired level of 12600 ppm,m.

Table II.10. Analysis of Aggressive Ethanol (LN # 22538-4) from Second Fuel Batch.

Property	Test Method	Units	ASTM D4806-11a Limits	Aggressive Denatured Ethanol
Total Acid Number	D664	mg KOH / g	N/A	Not measured
Water	E1064	ppm,m	12600 ppm,m max	10928
pHe	D6423	N/A	6.5 to 9.0	2.26

Table II.11. Analysis of Gasoline (Prior to Adjustment of Aromatic Level) from Second Fuel Batch.

Property		Test Method	Units	ASTM D4814-11 Limits	Base Gasoline
Research Octane Number		D2699	N/A	N/A	85.1
Motor Octane Number		D2700	N/A	N/A	80.4
Specific Gravity		D1298	N/A	N/A	0.7375
Reid Vapor Pressure		D5191	Psi	Varies by region and time of year	5.7
Sulfur		D5453	ppm,m	80	37
Oxidation Stability		D525	Minutes	240	>1440
Oxidation Stability of Aviation Fuels		D873			
Insoluble Gum			mg / 100 ml		0.3
Soluble Gum			mg / 100 ml		4.3
Total Potential Gum			mg / 100 ml		4.6
Gum Content of Fuels by Jet Evaporation		D381			
Existent Gum			mg / 100 ml		0.20
Solvent Washed Gum			mg / 100 ml		0.20
Total Aromatics		D6293	vol. %	N/A	20.7
Olefins		D6293	vol. %	N/A	5.6
Saturates (Paraffins and Naphthenes)		D6293	vol. %	N/A	73.7
Benzene		D6293	vol. %	N/A	0.59
Toluene		D6293	vol. %	N/A	2.39
Distillation	IBP	D86	°F		95.6
	5%		°F		139.3
	10%		°F	Varies	150.6
	20		°F		167.6
	30%		°F		185.7
	40		°F		203.6
	50%		°F	Varies	219.9
	60%		°F		236.2
	70%		°F		258.7
	80%		°F		295.6
	90%		°F	Varies	348.5
	95%		°F		382.9
	FBP		°F	Varies	430.5
	Recovery		Ml		98.2
	Residue		Ml		1.0
Nitrogen		D4629	ppm,m		21
Mercaptan Sulfur		D3227	ppm,m	N/A	6
Silver Strip Corrosion		D130	N/A	1, max	0, no tarnish

At the end of component testing at TRC, a sample of each of the E0, E10, and $E20_A$ test fuels were sent back to BP to inspect and evaluate their condition. The inspection analysis results are illustrated in Tables II.1 through II.3. Table II.1 shows that the soluble gums by ASTM D873 and existent gums by ASTM D381 are slightly elevated for the E0 fuel compared to the base gasoline used for blending. This is most probably due to the fact that the fuel was stored for over a year at TRC.

As with the E0 fuel, the soluble and existent gums results are slightly elevated for the E10 fuel compared to the base gasoline used for blending. (See Table II.2.) In addition, the solvent washed gums by ASTM D381 are higher for E10 compared to E0. Again, this is most probably due to storage of the fuel for over a year at TRC.

The gum results for the $E20_A$ sample (shown in Table II.3) are also elevated in comparison to the base gasoline blendstock, but to a greater extent than the E10 sample.

The low detect level of peroxides for the $E20_A$ sample is an unusual result, especially compared to the E0 and E10 samples, which both had measurable levels of peroxides after storage.

Table II.12. Analysis of TRC Retain Sample of E0 Test Fuel

Property		Test Method	Units	ASTM D4814-11 Limits	E0
Specific Gravity		D1298	N/A	N/A	0.7689
Reid Vapor Pressure		D5191	psi	Varies by region and time of year	4.66
Oxidation Stability		D525	minutes	240	>1440
Oxidation Stability of Aviation Fuels		D873			
Insoluble Gum			mg / 100 ml		0.3
Soluble Gum			mg / 100 ml		24.5
Total Potential Gum			mg / 100 ml		24.8
Gum Content of Fuels by Jet Evaporation		D381			
Existent Gum			mg / 100 ml		9.00
Solvent Washed Gum			mg / 100 ml		0.00
Total Aromatics		D6293	vol. %	N/A	38.2
Olefins		D6293	vol. %	N/A	4.2
Saturates (Paraffins and Naphthenes)		D6293	vol. %	N/A	57.6
Benzene		D6293	vol. %	N/A	0.44
Toluene		D6293	vol. %	N/A	1.81
Distillation	IBP	D86	°F		102.5
	5%		°F		147.0
	10%		°F	Varies	162.9
	20		°F		186.9
	30%		°F		211.6
	40		°F		235.2
	50%		°F	Varies	259.7
	60%		°F		286.7
	70%		°F		313.0
	80%		°F		329.3
	90%		°F	Varies	343.3
	95%		°F		359.9
	FBP		°F	Varies	415.9
	Recovery		ml		98.4
	Residue		ml		1.0
Peroxide Number		D3703	ppm,m		20.7
Ferrous Corrosion		NACE TM-0172-01	N/A		B+
Silver Strip Corrosion		D130	N/A	1, max	0
Sulfur		D5453	ppm,m		30
Water		E1064	ppm,m		73
Total Acid Number		D664	mg KOH/g		0.0216

Table II.13. Analysis of TRC Retain Sample of E10 Test Fuel

Property		Test Method	Units	ASTM D4814-11 Limits	E10
Specific Gravity		D1298	N/A	N/A	0.7700
Reid Vapor Pressure		D5191	psi	Varies by region and time of year	6.00
Oxidation Stability		D525	minutes	240	>1440
Oxidation Stability of Aviation Fuels		D873			
Insoluble Gum			mg / 100 ml		0.1
Soluble Gum			mg / 100 ml		9.7
Total Potential Gum			mg / 100 ml		9.8
Gum Content of Fuels by Jet Evaporation		D381			
Existent Gum			mg / 100 ml		12.80
Solvent Washed Gum			mg / 100 ml		3.20
Distillation	IBP	D86	°F		103.1
	5%		°F		139.2
	10%		°F	Varies	144.0
	20		°F		151.4
	30%		°F		157.5
	40		°F		212.3
	50%		°F	Varies	247.0
	60%		°F		275.3
	70%		°F		306.6
	80%		°F		327.4
	90%		°F	Varies	342.0
	95%		°F		359.0
	FBP		°F	Varies	407.8
	Recovery		ml		99.0
	Residue		ml		1.0
Peroxide Number		D3703	ppm,m		20.5
Ferrous Corrosion		NACE TM-0172-01	N/A		C
Silver Strip Corrosion		D130	N/A	1, max	0
Sulfur		D5453	ppm,m		25
Water		E1064	ppm,m		894
Total Acid Number		D664	mg KOH / g		0.0061
Ethanol		D4815	wt%		9.77

Table II.14. Analysis of TRC Retain Sample of $E20_A$ Test Fuel

Property	Test Methods	Units	$E20_A$
Reid Vapor Pressure	D5191	psi	5.95
Oxidation Stability	D525	minutes	>1440
Oxidation Stability of Aviation Fuels	D873		
Insoluble Gum		mg / 100 ml	0.3
Soluble Gum		mg / 100 ml	8.8
Total Potential Gum		mg / 100 ml	9.1
Gum Content of Fuels by Jet Evaporation	D381		
Existent Gum		mg / 100 ml	18.00
Solvent Washed Gum		mg / 100 ml	7.60
Water	E1064	ppm,m	2745 (Volumetric)
Peroxide Number	D3703	ppm,m	<2.0 (measured twice, same result)
Total Acid Number	D664	mg KOH / g	0.0111
Ethanol	D4815	vol. %	18.86
Chloride	XRF	ppm,m	2.7
Nitrate	D7328	ppm,m	1.41
Sulfate	D7328	ppm,m	0.48
Specific Gravity	D1298	N/A	0.7724
Ferrous Corrosion	NACE TM-0172-01	N/A	B
Silver Strip Corrosion	D130	N/A	0
Sulfur	D5453	ppm,m	22

II.3.3. Third Batch of Fuels – Produced by Gage Products

The properties for the blending components as well as the three final test fuels produced and supplied by Gage Products are provided in the Certificates of Analysis presented in Appendix A.1. To confirm the fuel property results reported by Gage, BP Global Fuels Technology conducted selected analyses of the blend components and the aggressive E20 ($E20_A$) fuel. These analyses, reported in the tables which follow, confirm that the use of different fuel suppliers had no significant impact on test fuel properties.

Analysis of Gage's Blending Components Select Methods by BP Global Fuels Technology

Table II.15. Analysis of Base Gasoline (Gage Products BPF0031-55F)

Property		Test Method	Units	ASTM D4814-11 Limits	Base Gasoline
Research Octane Number		D2699	N/A	N/A	92.7
Motor Octane Number		D2700	N/A	N/A	84.3
Specific Gravity		D1298	N/A	N/A	0.7502
Reid Vapor Pressure		D5191	psi	Varies by region and time of year	11.47
Sulfur		D5453	ppm,m	80	15
Oxidation Stability		D525	Minutes	240	>1440
Total Aromatics		D6293	vol. %	N/A	37.7
Olefins		D6293	vol. %	N/A	5.3
Saturates (Paraffins and Naphthenes)		D6293	vol. %	N/A	56.8
Benzene		D6293	vol. %	N/A	0.58
Toluene		D6293	vol. %	N/A	10.4
Distillation	IBP	D86	°F		70.5
	5%		°F		98.2
	10%		°F	Varies	111.9
	20		°F		137.2
	30%		°F		165.4
	40		°F		195.8
	50%		°F	Varies	224.5
	60%		°F		249.3
	70%		°F		274.1
	80%		°F		313.0
	90%		°F	Varies	334.2
	95%		°F		352.9
	FBP		°F	Varies	407.5
	Recovery		ml		98.1
	Residue		ml		1.1
Nitrogen		D4629	ppm,m		11
Mercaptan Sulfur		D3227	ppm,m	N/A	<2.0
Silver Strip Corrosion		D130	N/A	1, max	0 (no tarnish)

Table II.16. BP Analysis of Aggressive Ethanol ($E98_A$) Produced by Gage

Property	Test Method	Units	ASTM D4806-11a Limits	Aggressive Denatured Ethanol $E98_A$
Total Acid Number	D664	mg KOH / g	N/A	0.07
Sulfate	D7328	ppm,m	4, max	3.01
Nitrate	D7328	ppm,m	N/A	1.50
Specific Gravity	D1298	N/A	N/A	0.7947

The only significant deviation in results between those measured by BP Global Fuels Technology and those reported on the Certificate of Analysis (COA) from Gage Products was for the Total Acid Number (TAN) of the aggressive ethanol ($E98_A$). BP measured a TAN value of 0.07 mg KOH / g using ASTM D664, whereas Gage Products reported a value of 140 mg KOH / g using ASTM D974. BP's result for this sample is consistent with TAN measurements for the previous batches of aggressive ethanol ($E98_A$) and the pilot blending work to develop an aggressive ethanol.

Table II.17. BP Analysis of $E20_A$ Produced by Gage (Gage Products 'BPF0033-55C')

Property	Test Methods	Units	$E20_A$
Water	E1064	ppm,m	2408 (volumetric)
Peroxide Number	D3703	ppm,m	24.11
Total Acid Number	D664	mg KOH / g	0.04
Reid Vapor Pressure	D5191	Psi	11.62
Sulfur	D5453	ppm,m	12
Ethanol	D6293	vol. %	20.09
Nitrate	D7328	ppm,m	1.45
Sulfate	D7328	ppm,m	0.08
Specific Gravity	D1298	N/A	0.7595
Total Aromatics	D6293	vol. %	31.5
Olefins	D6293	vol. %	4.1
Saturates (P & N)	D6293	vol. %	44.3
Benzene	D6293	vol. %	0.47
Toluene	D6293	vol. %	8.04

III. Fuel System Rig Tests

III.1. Test Set Up

Rig tests allow evaluation of fuel mediated interactions between components of the fuel system that might not be observed in component tests. Thirteen test rigs were created using OEM service parts to completely replicate the fuel system of each candidate vehicle. Twelve of the rigs were assembled in pairs to represent six different light-duty vehicle models to be evaluated on both E10 and $E20_A$ test fuel. The thirteenth rig was acquired from a previous CRC program. This rig represented a seventh light-duty vehicle model and was tested on $E20_A$ fuel only. The seven vehicle models are listed in Table III.1.

Table III.1. Vehicle Models Used in Fuel System Rig Tests

Vehicle M
Vehicle A
Vehicle C
Vehicle F
Vehicle J
Vehicle K
Vehicle G

Parts for the rig assemblies were purchased from local automotive dealers and included items such as, but not limited to: fuel lines, tank, pump, fuel injection rail, injectors, return lines, pressure regulators, etc. Evaporative system components were excluded as these are designed typically to be only exposed to vapor and not wetted with fuel. However, the venting valves in the fuel tank assemblies were exposed to an ethanol/gasoline vapor blend. During rig assembly, bending of the fuel lines were added only as needed to fit within the dimensions of the test cart. Where bends were added, the radius was kept to as large a diameter as was possible, with a minimum radius of 12” maintained on all non-OEM bends. If the fuel system of the vehicle was return-less, a stainless steel return line was plumbed in from the injector rail to the vehicle fill hose. This allowed for the fuel to circulate through the entire rig when the in-tank fuel pump was operated. A sample fuel system rig is shown in Figure III-1.

Figure III.1. Vehicle Fuel Rig

III.2. Test Plan

Following rig construction, any evaporative ports and/or vents were sealed and the fuel caps were sealed with epoxy in order to prevent fuel evaporation during soak. The rigs were then pressurized and checked for the presence of evaporative leaks. Each rig was then filled to 100% capacity with its respective test fuel and soaked overnight at approximately 23°C. Near the beginning of this initial soak, the pump on each rig was energized for ten minutes to circulate fuel. The next day, the rigs were drained using an automatic draining system.

The automatic drain system was operated by energizing the onboard rig fuel pump. Once energized, the fuel pump sent fuel toward the fuel rail just as it would when installed in a vehicle. A valve and quick connect fitting were used on each rig to allow the fuel to be diverted to a drain line. During the drain, the fuel pressure of the drain line was maintained at the OEM fuel pump specified pressure for each rig. Once the pressure dropped below another preset value, usually 10 psi, the system would automatically turn off the fuel pump. This permitted the tank to be drained as much as the pump would allow while eliminating the possibility of the pump running without fuel.

After draining, each rig was filled to 80% capacity with its respective test fuel and placed in a soak chamber at 40°C. For the first 24 hours, the rigs were allowed to vent by removing the fuel cap or a vent line plug after which the rigs were sealed. Throughout the program on week days, each rig fuel pump was operated for ten minutes to circulate fuel. Old fuel was drained and fresh fuel added for each rig once per week for the first fourteen weeks, and then every other week until another fourteen weeks had been accumulated. From week twenty-eight to the end of the program, week sixty-one, the fuel was changed every third week.

III.3. Evaluation Process

At each fuel change, fuel samples were retained for chemical analysis. The objective of these analyses was to determine if rig test temperatures were causing fuel degradation and/or whether any metals from the test rigs were dissolving into the fuel. Not all samples were sent for analysis, and different tests were performed on each fuel sample set. The types of measurement tests included analyses for pHe, water content, inorganic chlorides, peroxides, total acid number, and metals. The entire list of the sample schedule, tests performed, and the analytical results can be found in Appendix A.2. The results are briefly summarized below.

- Total Acid Number (TAN) – Total Acid Number (TAN) at Week 1 was higher for the $E20_A$ test rigs than it was for the E10 test rigs, but this was expected since the $E20_A$ test fuel contained aggressive components. However, the TANs of the samples taken from fuels that had soaked in the rigs both for two weeks between fuel change intervals (e.g., Week 16 sample) and for three weeks between fuel change intervals (e.g., Week 37 sample) were similar, i.e. the E10 and $E20_A$ rigs had similar TANs.
- Peroxides - The peroxide numbers of the samples from the $E20_A$ rigs were generally higher than those measured from the rigs soaked with E10 at Week 1. However, at Weeks 4, 16, and 37, the peroxide numbers of fuel samples drawn from the E10 and $E20_A$ rigs were generally comparable. The Week 4 sample and Week 1 sample were both in the rigs for only one week (due to weekly fuel change outs), yet the Week 4 samples had higher peroxide numbers for the E10 blends. One possible explanation is the E10 fuel in bulk storage had an increase in peroxide number.
- pHe - The pHe of the fuel varied from week to week and from rig to rig, but all of the samples were relatively “neutral” throughout the trial. However, it must be stated that this test method for pHe, ASTM D6423, is intended for denatured ethanol, and not $E20_A$.
- Water content - The water content at Week 13 (after one week in rigs) was lower for the E10 than it was on Week 3 (also after one week in the rigs). The lower amount of water can also be seen in the Week 24 and 28, both of which were in the rigs for two weeks. The most probable cause for this change is a temperature change in the bulk fuel storage that allowed more or less water to dissolve in the fuel depending on the ambient storage conditions.
- Inorganic Chlorides - The inorganic chloride levels measured in the fuel samples drawn from the $E20_A$ rigs was always higher than those obtained from the E10 rigs, but this was expected since chlorides were purposely added to the $E20_A$ fuel to make it aggressive.
- Metal content - The measurements for select metals by (ICP) analysis showed no remarkable results.

At the conclusion of the sixty-one week soak period, a meeting was held to disassemble and inspect the rigs. OEM representatives, fuel tank and fuel system supplier representatives, and members of the AVFL-15 Panel attended this meeting. Each fuel system rig was pressurized to 28 inches of water and then the pressure level was monitored in order to discover any leaks in the system. Valves were checked for sticking and free movement. Fuel delivery modules were checked for suspension travel capability (related to the reservoir and pump assembly’s ability to maintain a reference to the bottom of the fuel tank) and overall tube and wiring condition. All components were inspected, and materials were evaluated for fuel-associated deterioration and visible fuel effects. Photographs were taken of all components, subsystems and systems. Complete details of the rig tear down procedures are documented in Appendix A.3.

III.4. Results

The results for the rigs representing each of the seven vehicle models are discussed below. The discussion for each model/rig is presented for each of five categories of fuel system components evaluated:

- Fuel Tank Assembly and Component Attachments, Interfaces and Seals
- Fuel Delivery Module (FDM)
- Fuel Vapor Venting Valves
- Fuel Hoses, Lines and Tubes
- Fuel Rail and Injectors

III.4.1. Vehicle A: Rig #4 – E10 and # 3 – $E20_A$

III.4.1.1 Fuel Tank Assembly and Component Attachments, Interfaces and Seals

E10 – No unusual findings were detected. All observed material condition indicated no degradation or predictable performance loss. No defects were noted and no significant issues were observed in the attachment interface.

The FDM fuel tank seal did not leak when pressurized to 28" of water. There was some visible swelling of the seal but not to an amount which would be considered significant. When the FDM retaining nut was checked for proper torque, it was measured to be approximately 60 % of production specification. This can be attributed to the test facility assembly procedures, but it is possible that thermal cycling and differential swell between the tank and nut were a factor.

$E20_A$ - The test rig exhibited leaks around the fuel delivery module area.

These leaks were attributed to a loosening of the retaining plastic nut on the fuel pump module. The torque on the nut was checked before the unit was disassembled. There was visible swell of the seal similar to the E10 seal. The torque applied to install the nut at the time the rig was assembled could not be verified. Debris was visually seen on the sealing surface of the fuel tank. After the nut on the fuel FDM was cleaned and re-tightened, the leak was eliminated.

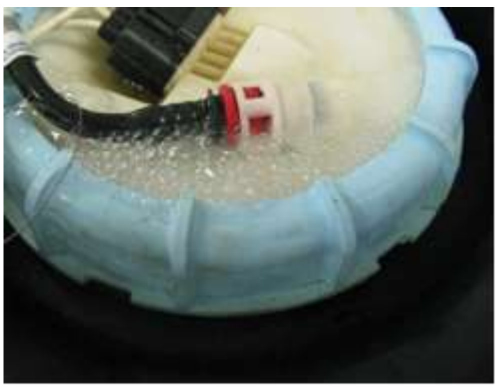

Figure III.2. Fuel Delivery Module and Retaining Nut

Vehicle A fuel tank rig also had a leak at the pressure sensor seal due to mechanical damage, most likely during installation of the pressure sensor onto the fuel tank at the test facility when the rigs were assembled. No other leaks were evident.

Figure III.3. Fuel Tank Opening and Seal - Plastic

Figure III.4. Fuel Tank Pressure Sensor

III.4.1.2. Fuel Delivery Module (FDM)

E10 and E20$_A$ – No unusual findings were detected. All observed material condition indicated no degradation or predictable performance loss. No defects were noted and no significant issues were observed in the FDM connections and components within to the fuel delivery module.

III.4.1.3. Fuel Vapor Venting Valves

E10 - No unusual findings were detected. All observed material condition indicated no performance loss.

E20$_A$ - The fuel tank filler tube inlet check valve was stuck in the slightly open position. The pressure in the fuel tank (as measured by fuel tank bleed down from 28" of water to 0") was four seconds when the fuel cap was removed. Typically, fuel tank bleed down is significantly slower if the component is performing correctly.

II.4.1.4. Fuel Hoses, Lines and Tubes

E10 - There did not appear to be any significant difference in the fuel filler hoses, filler tube, and fuel lines between the E10 and E20$_A$ rigs. The fuel delivery module materials seemed similar and unaffected.

E20$_A$ - The fuel filler hoses appeared to be stiffer and have some inner wall discoloration as compared to E10 Test Rig.

Figure III.5. Fuel Filler Hose – Interior Section

III.4.1.5. Fuel Rail and Injectors

E10 and E20$_A$ - No unusual findings were detected. All observed material condition indicated no degradation or predictable performance loss. No defects were noted and no significant issues were observed in the attachment interface.

III.4.2. Vehicle G: Rig #13 – E10 and Rig #11 - $E20_A$

III.4.2.1. Fuel Tank Assembly and Component Attachments, Interfaces and Seals

E10 and $E20_A$ - There was a substantial amount of debris in the fuel tanks. The origin and composition of this debris is not known.

The E10 and $E20_A$ rigs both exhibited leaks that were due to loose FDM lock-nuts attaching the fuel delivery module. This can be attributed to the test facility assembly procedures, but it is possible that thermal cycling and differential swell between the tank and nut were a factor. Both seals had visible swelling.

Figure III.6. Fuel Tank – Interior Surface - Plastic

$E20_A$ – The seal had appeared to have changed physical properties and was very soft and pliable. There was a build-up of black soft material around the FDM area (notice arrows pointing to black material between the module flange and retaining interface). It was believed to be leaching of a rubber polymer from the compound. Analysis was not completed on the sample.

Figure III.7. Fuel Delivery Module and Retaining Nut

III.4.2.2. Fuel Delivery Module (FDM)

E10 – E20$_A$ - Both E10 and E20$_A$ FDMs were stuck in the compressed condition and did not travel freely. The E10 and E20$_A$ FDMs electrical connectors also had visible leak on the FDM flange surface.

Figure III.8. Fuel Delivery Module and Retaining Nut – Wire Terminal

III.4.2.3. Fuel Vapor Venting Valves

E10 and E20$_A$ - No unusual findings were detected. All observed material condition indicated no degradation or predictable performance loss. No defects were noted and no significant issues were observed in the valve performance.

III.4.2.4. Fuel Hoses, Lines and Tubes

E10 and E20$_A$ - No unusual findings were detected. All observed material condition indicated no degradation or predictable performance loss. No defects were noted and no significant issues were observed.

III.4.2.5. Fuel Rail and Injectors

E10 and E20$_A$ - No unusual findings were detected. All observed material condition indicated no degradation or predictable performance loss. No defects were noted and no significant issues were observed in the attachment interface.

III.4.3. Vehicle M: Rig #1 – E10 and Rig #2 - $E20_A$

III.4.3.1. Fuel Tank Assembly and Component Attachments, Interfaces and Seals

E10 - $E20_A$ – The FDM seals had characteristics typical of being under the pressure / force of the retaining lock ring system. No unusual findings were detected. All observed material condition indicated no degradation or predictable performance loss.

III.4.3.2. Fuel Delivery Module

E10 - $E20_A$ - No defects were noted and no significant issues were observed in the FDM connections and components within to the fuel delivery module

III.4.3.3. Fuel Vapor Venting Valves

E10 - $E20_A$ - There did not appear to be any significant differences in the conditions of the fuel filler inlet check valve, fuel tank welded valve and components.

III.4.3.4. Fuel Hoses, Lines and Tubes

E10 - $E20_A$ – There did not appear to be any significant differences in the condition of the fuel lines, and tubes between the E10 and $E20_A$ rigs.

E10 - The fuel filler hose inner wall was shiny. The material did not appear compromised and no degradation or predictable performance loss is expected.

Figure III.9. Fuel Filler Hose – Interior Section

$E20_A$ - The inner wall of the fuel filler hose was shiny and seemed somewhat sticky. The material of the inner wall could be removed with a finger. Analysis of the hoses indicated no fuel-related concerns, however. No significant material degradation was observed.

Figure III.10. Fuel Filler Hose – Interior Section

Figure III.11. Fuel Filler Hose – Interior Section

III.4.3.5. Fuel Rail and Injectors

E10 - E20$_A$ - No unusual findings were detected. All observed material condition indicated no degradation or predictable performance loss. No defects were noted, and no significant issues were observed in the attachment interface.

III.4.4. Vehicle C: Rig #7 – E10 and Rig #5 - E20,

III.4.4.1. Fuel Tank Assembly and Component Attachments, Interfaces and Seals

E10 - $E20_A$ – There were black particles of unknown origin in both fuel tanks. No unusual findings were detected. All observed material conditions indicated no degradation or predictable performance loss. There were no notable differences between E10 and E20A test rigs.

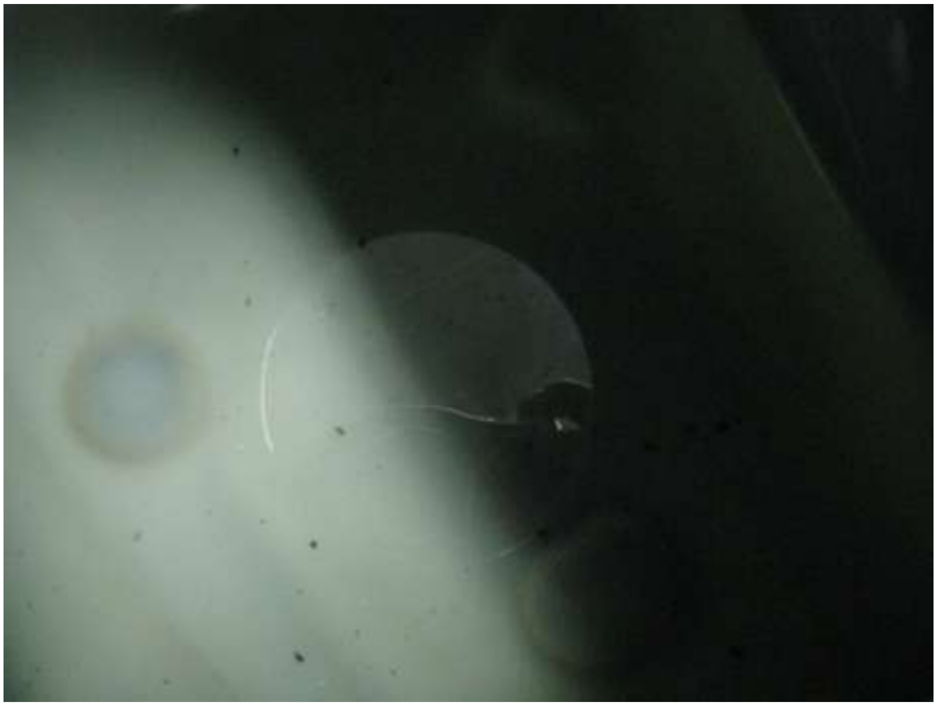

Figure III.12. Fuel Tank Interior Surface - Steel

III.4.4.2. Fuel Delivery Module

E10 - $E20_A$ – No unusual findings were detected. All observed material condition indicated no degradation or predictable performance loss. No defects were noted, and no significant issues were observed in the FDM connections and components within to the fuel delivery module.

III.4.4.3. Fuel Vapor Venting Valves

E10 - $E20_A$ – There did not appear to be any significant differences in the conditions of the fuel filler inlet check valve, fuel tank welded valve and components.

III.4.4.4. Fuel Hoses, Lines and Tubes

E10 -$E20_A$ – No unusual findings were detected. All observed material condition indicated no degradation or predictable performance loss.

III.4.4.5. Fuel Rail and Injectors

E10 - $E20_A$ - No unusual findings were detected. All observed material condition indicated no degradation or predictable performance loss. No defects were noted, and no significant issues were observed in the attachment interface.

III.4.5. Vehicle K: Rig #12 – E10 and Rig #10 - $E20_A$

III.4.5.1. Fuel Tank Assembly and Component Attachments, Interfaces and Seals

E10 - No unusual findings were detected. No corrosion was seen inside the fuel tank. All observed material condition indicated no degradation or predictable performance loss

$E20_A$ – The seal for the Fuel Fill Vent Valve (FLVV) was swollen but did not leak.

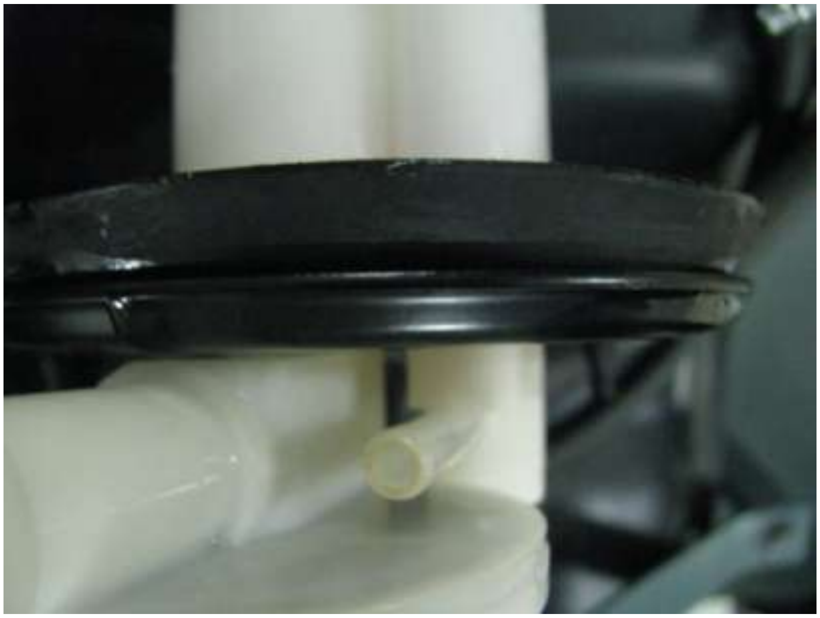

Figure III.13. Fuel Fill Vent Valve with Seal

There was white corrosion noted on the inner surface of the metal fuel tank coating.

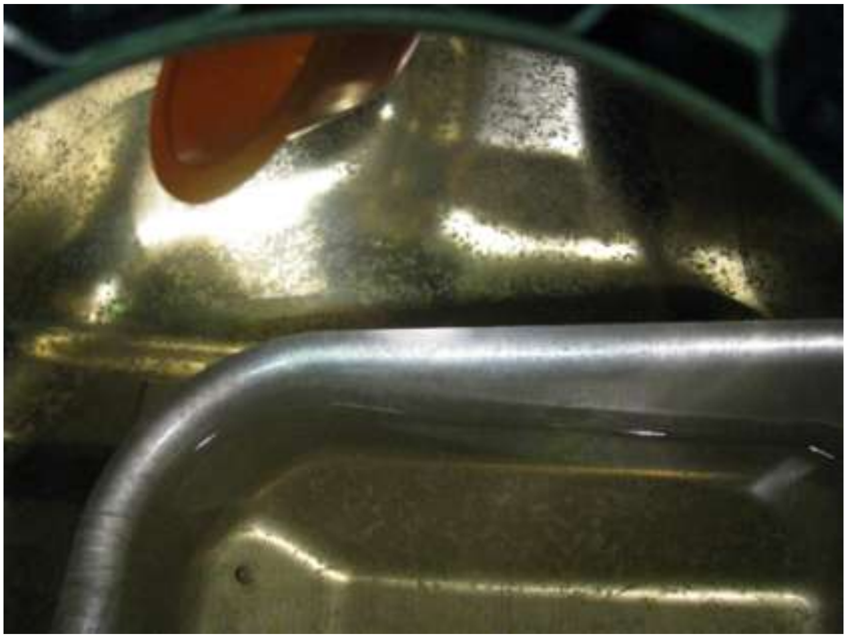

Figure III.14. Fuel Tank Interior Surface - Steel

Figure III.15. Fuel Tank Interior Surface - Steel

III.4.5.2. Fuel Delivery Module

E10 - $E20_A$ - No unusual findings were detected. All observed material condition indicated no degradation or predictable performance loss. No defects were noted and no significant issues were observed in the FDM connections and components within to the fuel delivery module.

III.4.5.3. Fuel Vapor Venting Valves

E10 and $E20_A$ - No unusual findings were detected with the fuel vapor valves. All observed material condition indicated no degradation or predictable performance loss. No defects were noted, and no significant issues were observed in the valve performance.

III.4.5.4. Fuel Hoses, Lines and Tubes

E10 and $E20_A$ - No unusual findings were detected. All observed material condition indicated no degradation or predictable performance loss. No defects were noted, and no significant issues were observed.

III.4.5.5. Fuel Rail and Injectors

E10 and $E20_A$ - No unusual findings were detected. All observed material condition indicated no degradation or predictable performance loss. No defects were noted, and no significant issues were observed in the attachment interface.

III.4.6. Vehicle F: Rig #6 – E10 and Rig #8 – $E20_A$

III.4.6.1. Fuel Tank Assembly and Component Attachments, Interfaces and Seals

E10 - No unusual findings were detected. All observed material condition indicated no degradation, corrosion or predictable performance loss. There were no notable differences between E10 and E20 test rigs. No leaks were noted.

$E20_A$ – The FDM seal had signs of cracking around the outside edge of the seal. Over-compression due to swell can lead to cracking on the inside or outside edge. There were no leaks when the fuel tank assembly was pressurized. There seemed to have been a change of physical properties as compared to the E10 Rig.

Figure III.16. Fuel Delivery Assembly with Seal – Fuel Tank Opening – Steel Tank

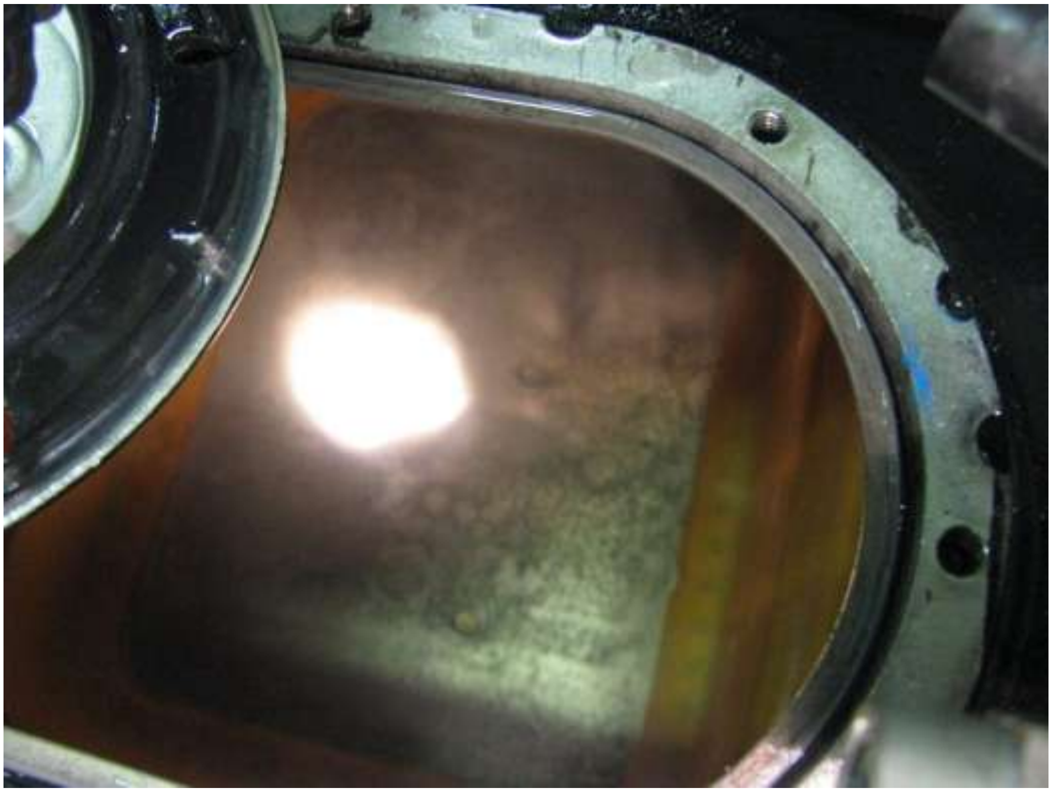

Figure III.17. Fuel Delivery Assembly with Seal – Fuel Tank Opening – Steel Tank

III.4.6.2. Fuel Delivery Module

E10 - $E20_A$ – No unusual findings were detected. All observed material condition indicated no degradation or predictable performance loss. No defects were noted, and no significant issues were observed in the FDM connections and components within to the fuel delivery module. No leaks were noted.

III.4.6.3. Fuel Vapor Venting Valves

E10 and $E20_A$ - No unusual findings were detected with the fuel vapor valves. All observed material condition indicated no degradation or predictable performance loss. No defects were noted, and no significant issues were observed in the valve performance.

III.4.6.4. Fuel Hoses, Lines and Tubes

E10 and $E20_A$ - No unusual findings were detected. All observed material condition indicated no degradation or predictable performance loss. No defects were noted, and no significant issues were observed.

III.4.6.5. Fuel Rail and Injectors

E10 and $E20_A$ - No unusual findings were detected. All observed material condition indicated no degradation or predictable performance loss. No defects were noted, and no significant issues were observed in the attachment interface.

III.4.7. Vehicle J: Rig #9 - $E20_A$

III.4.7.1. Fuel Tank Assembly and Component Attachments, Interfaces and Seals

$E20_A$ - There was corrosion noted on the inner surface of the metal fuel tank coating. The fuel tank held pressure when testing. No leaks were noted. The FDM seal showed signs of deterioration and polymer bleed out.

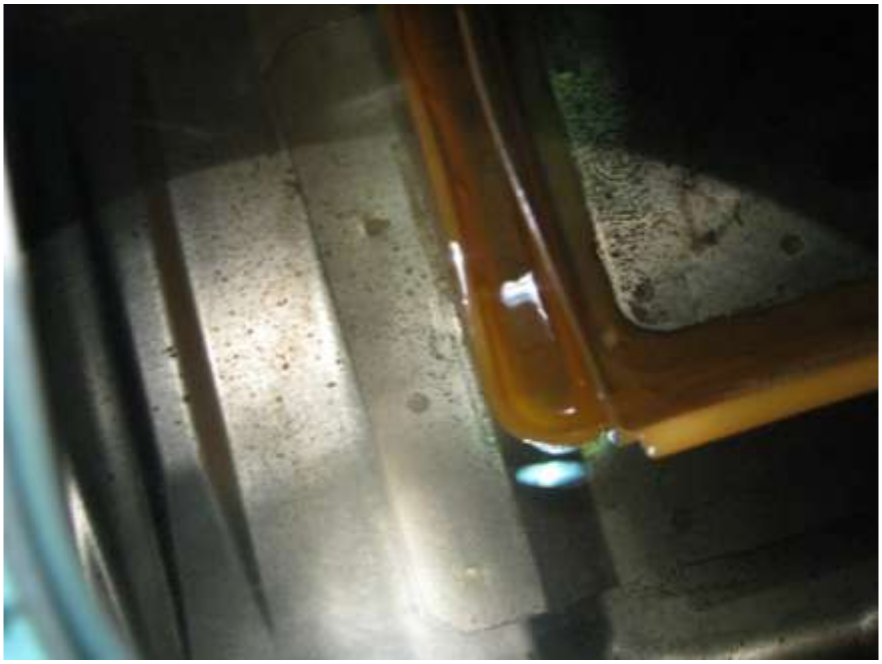

Figure III.18. Fuel Tank Interior Surface - Steel

Figure III.19. Fuel Tank Interior Surface - Steel

III.4.7.2. Fuel Delivery Module

$E20_A$ – Corrosion was seen on the underside of the metal fuel pump hanger flange.

Figure III.20. Fuel Delivery Assembly with Seal - Steel

III.4.7.3. Fuel Vapor Venting Valves

$E20_A$ - No unusual findings were detected with the fuel vapor valves. All observed material condition indicated no degradation or predictable performance loss. No defects were noted, and no significant issues were observed in the valve performance.

III.4.7.4. Fuel Hoses, Lines and Tubes

$E20_A$ - No unusual findings were detected. All observed material condition indicated no degradation or predictable performance loss. No defects were noted, and no significant issues were observed.

III.4.7.5. Fuel Rail and Injectors

$E20_A$ - No unusual findings were detected. All observed material condition indicated no degradation or predictable performance loss. No defects were noted, and no significant issues were observed in the attachment interface.

IV. Fuel Pump Tests

IV.1. Fuel Pump Pilot Program

In the fuel pump pilot program, nine impeller types were soaked in $E20_A$ test fuel (fully submerged) at a temperature of 60°C for a duration of 12 weeks. A tenth design was chosen initially, but after discovering it was a gerotor pump with gears (no impeller), it was dropped from the pilot program. Impellers were selected by the AVFL-15 Panel using information gathered from auto manufacturers. Selected impellers were from high sales volume vehicles in the 1996 through 2009 model year range with suspected sensitivity to increased ethanol in fuel. The intent was to screen the designs and decide which would be tested in the Soak Durability and Endurance Aging test programs.

Several impellers were supplied directly by the OEMs, while others were harvested from new fuel pumps purchased from dealer stock. In all cases, the impellers were current replacement part quality and may have had upgrades to their design and/or materials since the time the original equipment was produced (i.e., parts in the field that have not been replaced). The purchased fuel pumps were disassembled, and the impellers were removed and placed into their respective soak containers. An example impeller and container are shown in Figure IV.1. Of the five impeller types that were supplied by manufacturers, ten copies of each type were acquired and tested. Of the four impeller types that were acquired through local automotive dealers, three copies of each type were tested. This gave a total of sixty-two impellers in the program. The vehicles chosen are listed in Table IV.1.

Table IV.1. Vehicles Used in Impeller Testing.

	Impeller obtained from:	
	Manufacturer	Dealership
Vehicle C	X*	
Vehicle A	X	
Vehicle N	X	
Vehicle L	X*	
Vehicle H		X
Vehicle D		X
Vehicle M	X	
Vehicle K		X
Vehicle F		X

** Full pump module supplied*

Figure IV.1. Example of Fuel Pump Impeller in Soak Container

At every measurement cycle, each impeller was measured at three random locations for thickness and diameter. At the beginning of the test, the micrometer being used was only accurate to 0.0005" (12.7 μm). Because no change in thickness was observed for several of the impellers after the start of testing (suggesting that the amount of swelling or shrinkage was below the accuracy of the micrometer), this tool was replaced during the third week of soak with a new micrometer with an accuracy of 0.00005" (1.27 μm). Impellers were measured three times per week for the first nine weeks and then twice per week until the end of soak. Results of impeller thickness measurements are shown in the appendix. An example is shown in Figure IV.2.

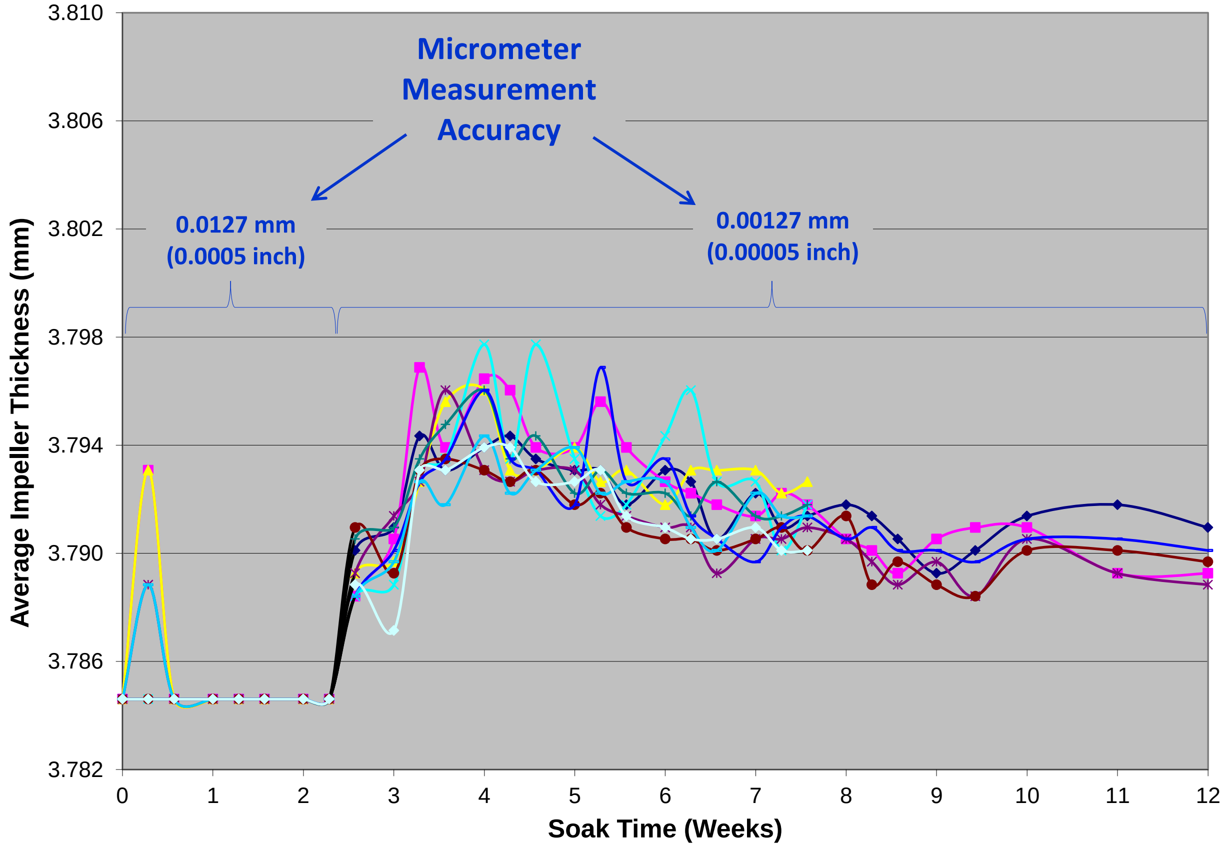

Figure IV.2. Impeller Swell during Soak – Vehicle C

Although the less accurate micrometer used to measure impeller thickness for the first two and a half weeks of testing did not show any change in thickness from the initial thickness measurement, the measurements from the more accurate micrometer did reach a maximum at Week Three to Four. Some impellers appeared to stabilize at this maximum thickness for several weeks. The majority of impellers exhibited a decline in thickness after this initial swell. The maximum thickness change for any individual impeller was 25µm (0.001 inch) and the average measured thickness change across all impellers was 15µm (0.0006 inch).

It was not possible to screen the designs to decide which would be tested in the Soak Durability and Endurance test programs due to the lower accuracy of the initial measurements, so no designs were eliminated. Along with the lower accuracy of the first two and a half weeks of measurements, pump-impeller clearance specifications are proprietary to the manufacturers. This meant that no Pass/Fail determinations were made. As a result, testing proceeded to the Soak Durability and Endurance Aging programs with all designs as options.

IV.2. Fuel Pump Main Program

IV.2.1. Background

Fuel pump capacity is affected by numerous environmental variables over the life of a vehicle. Two variables known to influence fuel pump capacity are fuel quality and fuel chemistry. Increasing ethanol may affect fuel pump capacity through its effect on fuel chemistry. Fuel chemistry concerns are a likely increase in water absorption (because ethanol is hydrophilic) and associated increases in chlorides and sulfates. Chlorides and sulfates may adversely affect fuel system components by increasing deposit formation and potential for corrosion. Ethanol may also affect elastomeric components through either dimensional changes or changes in mechanical properties. Yuen, et al.[7] provides a good overview of these concerns as well as an extensive bibliography of the relevant literature.

IV.2.2. Evaluation Metrics

Fuel pump testing was performed in two general areas; soak durability testing and endurance aging testing. Soak durability testing evaluated each fuel pump's response to long term exposure in gasoline containing ethanol while the pump was in a static condition. Endurance aging testing evaluated each fuel pump's response to long term exposure in gasoline containing ethanol while the pump was in operation. In both test protocols, elevated temperatures and aggressive fuel formulations were used to accelerate pump response to increased ethanol in gasoline with the objective to allow prediction to full-useful life effects. These aggressive approaches are typical of those used in the industry to predict new product life and are based on existing SAE and USCAR protocols.[8,9] Many OEMs use more aggressive protocols – including longer test durations – than those used here, however those protocols are proprietary and could not be fully incorporated in this study. Detailed test protocols used for fuel pump evaluations are contained in Appendix B. Aggressive test fuel formulations are described in Section II of this report.

Ten fuel pump models were evaluated by the soak durability protocol while eight pump models were evaluated by the endurance aging protocol. A summary list of pump models used in each test protocol is contained in Table IV.1. An explanation of the selection criteria for these pumps is included in Section I of this report.

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7 P.K. Yuen, J. Beckett and W. Villaire, "Automotive Materials Engineering Challenges and Solutions for the Use of Ethanol and Methanol Blended Fuels," SAE Technical Paper 2010-01-0729, April 2010.

8 Standard for In-Tank Electric Fuel Pumps, SAE/USCAR13, August 1999.

9 Validation Testing of Electric Fuel Pumps for Gasoline Fuel Injection Systems, SAE J1537, June 1990.

Table IV.1. Fuel Pump Models Included in Test Protocol

Soak Durability:	Endurance Aging:
➢ Vehicle K	➢ Vehicle K
➢ Vehicle C	➢ Vehicle C
➢ Vehicle F	➢ Vehicle F
➢ Vehicle M	➢ Vehicle M
➢ Vehicle G	➢ Vehicle G
➢ Vehicle H	➢ Vehicle A
➢ Vehicle A	➢ Vehicle L
➢ Vehicle D	➢ Vehicle N
➢ Vehicle L	
➢ Vehicle N	

Fuel Pump Soak Durability

The objective of the soak durability test protocol was to evaluate potential mechanisms of fuel pump failure resulting from static soak. Nominally, each pump was soaked for 8 to 12 weeks in 60°C fuel with pump performance evaluated every week for the first 8 weeks. Selected pumps were soaked for an additional four weeks in 60°C fuel with pump performance evaluated after 12 weeks of soak. Pump operation was minimized prior to test and at each flow test interval so that long term exposure without operation could be evaluated. Failure modes evaluated by this protocol included commutator/brush interface film buildup, impeller or elastomer swell and materials degradation. Because this test protocol included limited break-in time for pump operation, minor changes in flow are not significant. Pumps included in this test series were first operated for one hour at OEM specified flow, pressure and voltage using retail-grade E0 fuel. By comparison, a typical break-in procedure prior to pump validation test would be between 12 and 24 hours. Flow changes on the order of 10 to 12% are common during pump break-in and are not an indication of significant fuel effects. There were two metrics for pump failure in the soak durability test, a rapid and sustained[10] loss in flow capacity on the order of 30% or an observation of significant material degradation from post-test teardown inspection.

Fuel Pump Endurance Aging

The objective of the endurance aging test protocol was to evaluate potential mechanisms of fuel pump failure resulting from continuous operation. Nominally, each pump was aged to 3000 hours of continuous operation at temperatures varying between 40°C and 60°C. This testing protocol was based on the SAE/USCAR13 protocol referenced above. Performance evaluations were conducted at aging intervals of 0, 700, 1000, 2700, and 3000 hours. Failure modes evaluated by this protocol included galling or scoring at the impeller/casing interface, wear of the brush/commutator interface, armature shaft bearing failure, and materials degradation. For this test, flow loss in excess of that observed for the E10 baseline test fuel is assumed to indicate a failure.

[10] Soak durability testing is expected to result in temporary flow loss due to film build-up at the brush/commutator interface. However, if flow loss persists with continued operation, the affected pump is at risk of not meeting fuel system demand and may be considered to have failed.

Failure modes described above do not account for loss of energy content of the ethanol-containing fuels. Volumetric energy loss for E20 is expected to be on the order of 3.5% compared to the baseline E10 and nearly 7% compared to E0.

Figure IV.3 shows a typical cross-section of a fuel pump with significant features identified.

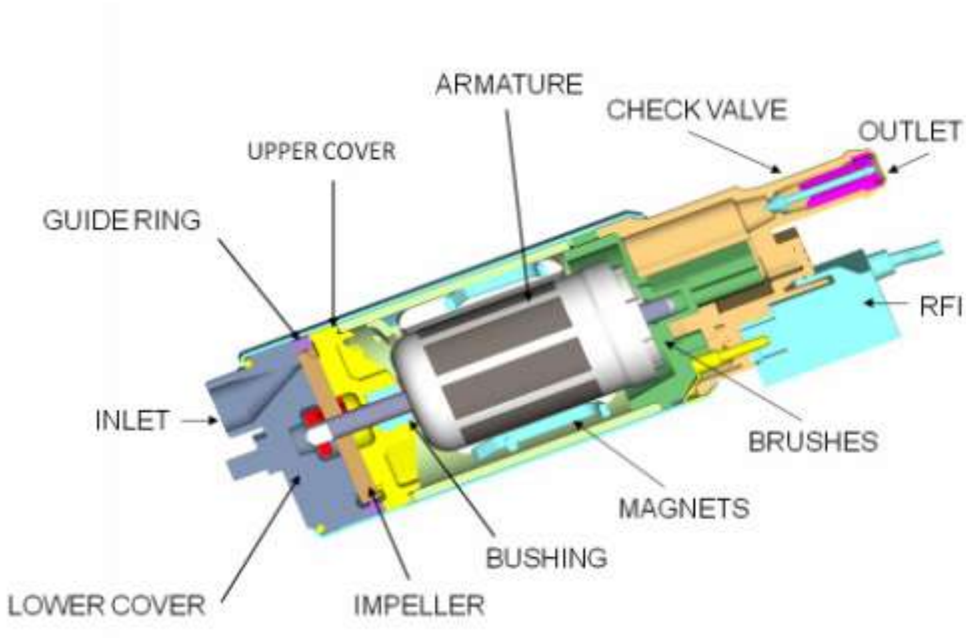

Figure IV.3. Fuel Pump Cross-Section, Typical Turbine Pump

IV.2.3. Results

Fuel pump tests for both protocols were conducted in three separate phases:

Phase 1: All pumps evaluated using $E20_A$ test fuel

Phase 2: Selected pumps evaluated using E10 test fuel

Phase 3: Selected pumps evaluated using E0, E10, and $E20_A$ test fuels

Each successive phase built upon the results of the earlier phase. Pumps selected for E10 evaluation in Phase 2 were those observed to have the greatest deterioration in Phase 1. Additional pumps evaluated in Phase 3 were those determined to show the greatest differentiation in fuel effect from Phase 2. Phase 3 also added E0 as a baseline test fuel.

Soak Durability Results

Table IV.2 provides a summary of the results from the soak durability test protocol. Percent flow loss data are shown for each fuel averaged over the number of pumps tested in that fuel. The ten pump types included in the soak durability protocol were all tested in Phase 1 using $E20_A$ test fuel. Three of those pump types were additionally tested in Phase 2 using E10 test fuel, and one pump type was further tested in Phase 3 using $E20_A$, E10 and E0 test fuels. Total numbers of test articles for each test fuel are shown in the table.

Table IV.2. Percent Flow Loss – Soak Durability Test Protocol

Vehicle	Evaluation Phase	Test Fuel E20A	E10	E0
Vehicle K	1	- 2.8% (1 pump)	N/A	N/A
Vehicle C	1	+ 7.5% (1 pump)	N/A	N/A
Vehicle F	1	- 3.2% (1 pump)	N/A	N/A
Vehicle M	1, 2, 3	- 15% (5 pumps)	- 14% (4 pumps)	- 18% (3 pumps)
Vehicle G	1, 2	- 3% (1 pump)	- 0.5% (1 pump)	N/A
Vehicle H	1	+ 2.9% (1 pump)	N/A	N/A
Vehicle A	1	- 11.5% (1 pump)	N/A	N/A
Vehicle D	1	+ 1.2% (1 pump)	N/A	N/A
Vehicle L	1	+ 0.5% (1 pump)	N/A	N/A
Vehicle N	1, 2	- 12% (1 pump)	- 18% (1 pump)	N/A

Percent flow loss for each pump was calculated based on the initial flow measurement at the start of test and the final flow measurement at the 8 or 12 week test point.[11] Percent flow change data did not consider flow recovery resulting from continuous operation. Flow recovery following the 12 week test interval is described further below.

Figure IV.3 shows the data contained in Table IV.2 in a graphical format. Percent change in pump flow over the 8 or 12 week test interval is charted for each pump model. Because the Vehicle M pump is the only pump type tested with multiple samples in each test fuel, it is the only dataset with maximum and minimum error bars included. All other data in this chart represent results from only one test article per test fuel.

No negative impacts of ethanol on pump performance could be determined from the soak durability test data. The Vehicle M pump model, which included multiple test articles per fuel, exhibited considerable scatter. The average flow-loss value for each fuel fell nearly within the scatter from the other fuels. The E0 pumps showed the greatest average flow decline, however, maximum and minimum values overlapped with data from both the E10 and $E20_A$ pump samples. None of the pumps tested exhibited a

[11] Pumps tested in Phase 1 were all soaked for 8 weeks in $E20_A$ test fuel. Those pumps selected for Phase 2 and Phase 3 testing were soaked for 12 weeks in their respective test fuels in an attempt to capture any additional deterioration.

flow decline in excess of the failure metric, a loss in flow capacity on the order of 30%. Post-test teardown analysis of selected pumps showed no differentiation among fuels to suggest that the aggressive ethanol-blended fuel had any additional negative impacts on fuel pump integrity.

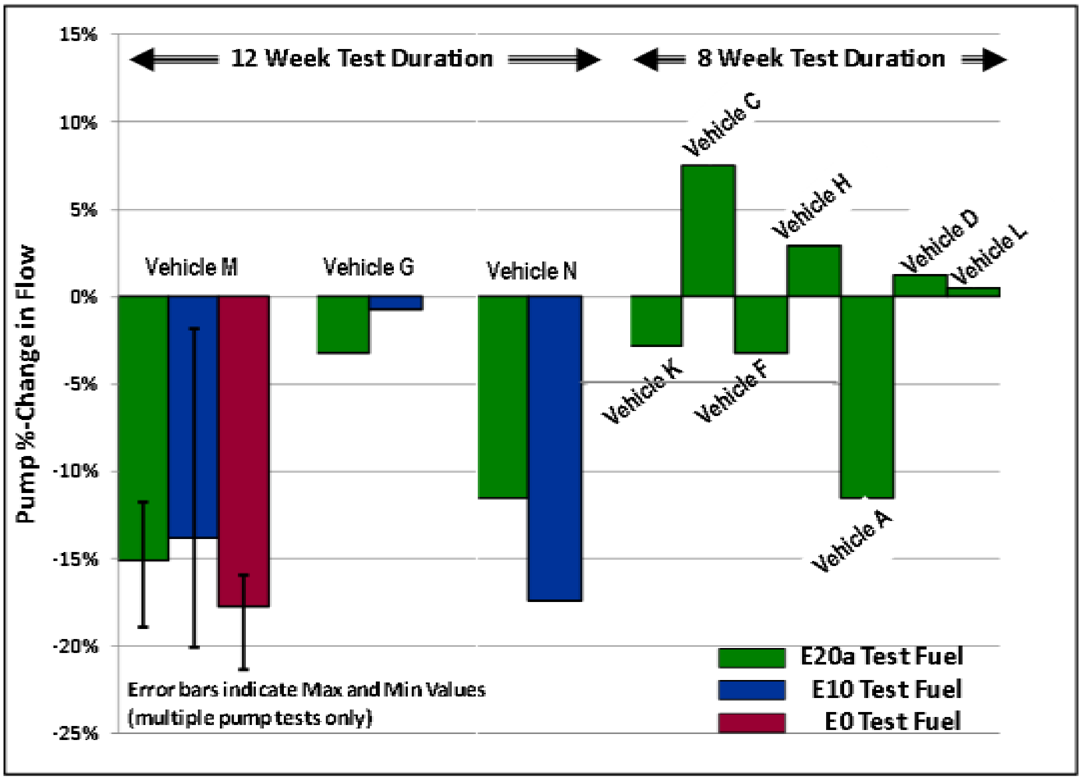

Figure IV.4. Soak Durability Summary Results - All Pumps

The soak durability protocol was designed to specifically investigate effects of long-term static soak on fuel pump flow performance. Brush/commutator film build-up was anticipated to be one of the more likely causes of flow degradation. To further evaluate this potential failure mechanism – and to further differentiate among fuels – it was decided to additionally test each of the Vehicle M pumps tested under Phase 3, but with continuous operation to determine if the observed flow losses were permanent or could be recovered. The ten test pumps were removed from their post-test storage containers[12] and immersed in E0 test fuel. Each pump was then connected to the flow test stand and energized. Flow was recorded after 30 minutes of operation and then periodically thereafter for six hours of continuous operation. Three of the pumps were further tested to ten hours of continuous operation; one from each of the test fuels. Results of these flow tests are shown in Figure IV.4.

[12] Following their last flow test on E0 (at week 12), pumps were stored in sealed plastic bags in a fuel-wet condition and placed in room temperature storage. Pumps remained in storage for about 1 week before being flow tested as described.

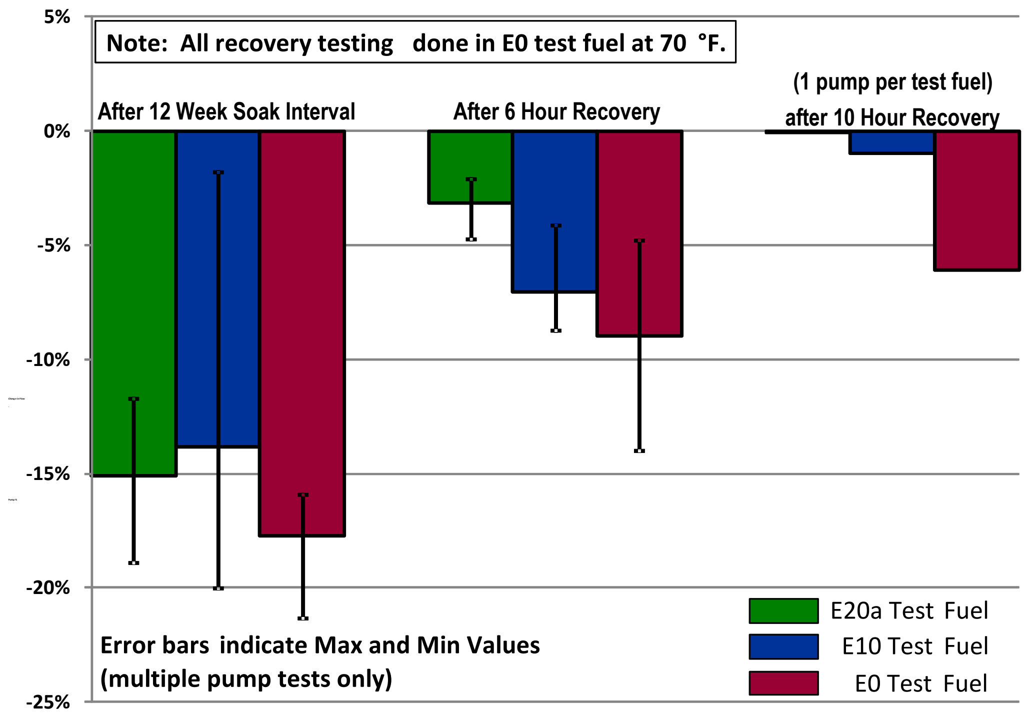

Figure IV.5. Flow Recovery from Soak Durability – Vehicle M

The three bars on the left side of Figure IV.5 are identical to those from Figure IV.4; they show the flow loss for the 12 Vehicle M pumps at the end of the 12 week soak test. The three bars in the middle of the figure depict flow loss from the ten pumps tested in Phase 3 after six hours of continuous flow with E0 test fuel. Bars on the right side of Figure IV.5 show data from the three pumps tested to ten hours of continuous operation. The data show a trend of continuous flow improvement with increasing run time following extended soak. After ten hours of continuous operation, the $E20_A$ pump recovered to very nearly its original flow value. The E10 pump finished with only a 1% flow loss. The E0 test pump finished the ten-hour recovery test with a 6% flow loss. Flow recovery is assumed to have resulted from the cleaning of the film build-up at the brush/commutator interface which occurred during extended fuel soak. The better flow recovery for the pumps soaked in ethanol-containing fuels suggests that the solvency effect of ethanol may have been beneficial to the cleaning of this film.

Endurance Aging Results:

Table IV.3 provides a summary of the results from the endurance aging test protocol. Percent loss data are shown for each fuel averaged over the number of pumps tested in that fuel.

Table IV.3. Summary Results – Endurance Aging Test Protocol

Vehicle	Evaluation Phase	Test Fuel		
		$E20_A$	E10	E0
Vehicle K	1,2	- 5.4% (1 pump)	+ 0.3 % (1 pump)	N/A
Vehicle C	1	- 2.2% (1 pump)	N/A	N/A
Vehicle F	1	- 1.6% (1 pump)	N/A	N/A
Vehicle M	1	- 3.2% (1 pump)	N/A	N/A
Vehicle G	1, 2, 3	- 15.1% [a] (2 pumps)	- 3.9% [b] (1 pump)	- 2.8% (1 pump)
Vehicle A	1, 2, 3	- 58.8% [c] (2 pumps)	- 43.3% (2 pump)	- 21.9% (1 pump)
Vehicle L	1, 2	- 12.8% (1 pump)	Incomplete [d] (1 pump)	N/A
Vehicle N	1	- 12.7% (1 pump)	N/A	N/A

[a] Phase 1 $E20_A$ pump failed due to procedural error. Post-test analysis showed melted impeller and charring suggesting pump had run dry. Failure not considered fuel related.
[b] Phase 2 E10 pump failed due to excessive debris in test fuel. Post-test analysis showed melting in brush/commutator section - most likely due to clogged inlet screen. Failure not considered fuel related.
[c] Although three pumps were tested in $E20_A$ fuel, one pump failed during test due to high resistance at the brush-commutator interface caused by formation of brush deposits – either chloride or sulfate – consistent with addition of ethanol to gasoline. This observation is based on post-mortem analysis in the vehicle manufacturer's fuel pump lab.
[d] Phase 2 E10 pump failed due to handling error. Plastic piece from fuel pump module flange entered fuel line during flow testing.

The eight pump types tested using the endurance aging protocol were all tested in Phase 1 using $E20_A$ test fuel. Four pump types were additionally tested in Phase 2 using E10 test fuel, and two pump types were further tested in Phase 3 using $E20_A$, E10 and E0 test fuels. The total numbers of test articles for each test fuel are shown in the table. Percent flow loss for each pump was calculated based on the initial flow measurement at the start of testing and the final flow measurement after completing the 3000 hour endurance aging test procedure.

Figure IV.6 shows the endurance aging results with percent change in flow charted from start-of-test to end-of-test for each of the eight pumps. As the figure shows, both the Vehicle G and Vehicle A pumps were tested in all three test fuels ($E20_A$, E10 and E0), with multiple samples tested in $E20_A$ (Vehicle G and Vehicle A) and E10 (Vehicle A only). The Vehicle K and Vehicle L pumps were both tested in $E20_A$ and E10 test fuels; however, because the E10 Vehicle L pump failed prior to completing the test (non-fuel related) only the $E20_A$ data is shown in the chart. The remaining four pumps were tested only in Phase 1 using $E20_A$ test fuel. Error bars depicting maximum and minimum flow loss values are shown for the three pump types with multiple samples per test fuel at the completion of testing. The $E20_A$ Vehicle G, the $E20_A$ Vehicle A and E10 Vehicle A data were all based on sample populations of two data points each.

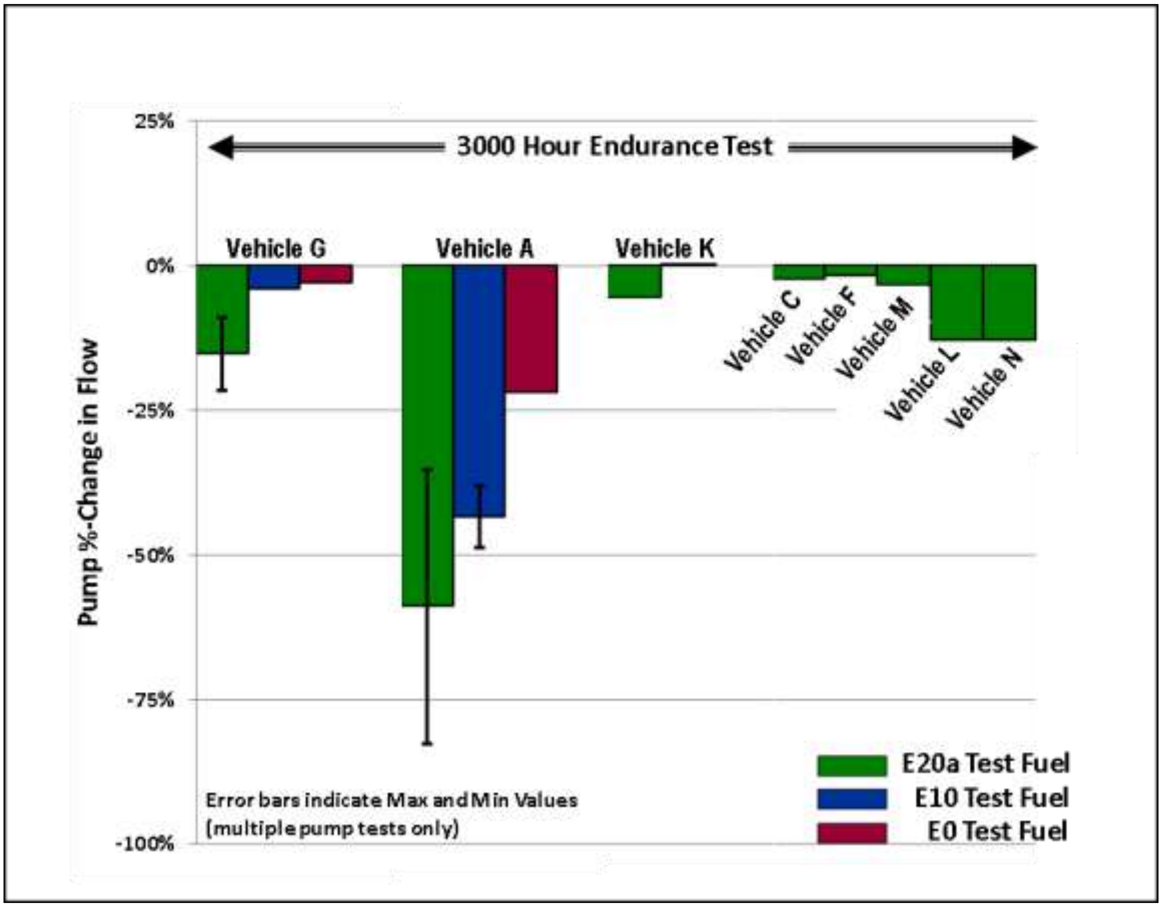

Figure IV.6. Endurance Aging Summary Results – All Pumps

Four pumps failed during the endurance aging test. The two Vehicle G pumps tested in Phases 1 and 2 ($E20_A$ and E10 respectively) both failed due to errors in testing procedure. One appeared to have been run dry while the other had a clogged inlet screen due to excess debris in the test vessel. Neither failure was considered to be fuel-related. The E10 Vehicle L pump also failed due to errors in testing procedure after a plastic piece from the fuel pump module flange fell into the fuel line during one of the flow test cycles. The fourth failed pump, a Vehicle A pump tested in $E20_A$, failed during Phase 3 testing due to high resistance at the brush-commutator interface. This failure was believed to have been caused by excessive deposits on the brush contact face (see Figure IV.7). The observed deposits, believed to be either chloride or sulfate, are consistent with experience from similar pumps exposed to higher levels of ethanol blends in gasoline (e.g., E85, which is expected to contain higher levels of chlorides and sulfates). Based on analysis from the vehicle manufacturer's fuel pump lab, this failure was believed to be fuel-related and caused by the higher ethanol content in the $E20_A$ test fuel.

New brush contact face showing finishing lines from final machining

Brush contact face from failed $E20_A$ Vehicle A pump. Deposits are assumed to be either chloride or sulfate, consistent with experience from E85 fuel pump development experience

Figure IV.7. Fuel Pump Brush Contact Faces – New and Failed Endurance Sample

The two $E20_A$ Vehicle G pumps which completed the endurance aging test both showed flow loss at the end of the test in excess of that measured for either the E10 or E0 test fuels. The two $E20_A$ test pumps exhibited percent loss values of 8.8% and 21.4%, while the E10 and E0 test pumps had final loss values of 3.9% and 2.8% respectively. The two Vehicle A pumps tested in $E20_A$ test fuel also showed greater average flow loss compared with the E10 and E0 test pumps, however, individual data for the $E20_A$ test pumps overlapped with data from the E10 test pumps. The $E20_A$ Vehicle A pump which exhibited the highest flow loss (82.5%) was determined to have suffered a fuel-related failure at the anti-siphon mechanism, believed to be caused by swelling of the polyoxymethylene (POM) material which retained the anti-siphon valve in place. This observation is based on post-mortem analysis in the vehicle manufacturer's fuel pump lab. The single E0 Vehicle A pump tested exhibited the least flow loss among the three test fuels. Percent flow loss values for the Vehicle A pumps were 82.5% and 35.1% for $E20_A$, 48.7% and 37.8% for E10, and 21.9% for E0. The single Vehicle K pump tested in $E20_A$ test fuel exhibited greater flow loss than that found for the E10 test fuel.

Average data from the endurance aging test showed a trend of increased flow loss with $E20_A$ test fuel when compared with E10 and E0 test fuels. This observation is based on a small sample size (one or two test articles per test fuel) and a limited variety of pump types (three vehicle models). Several non-fuel related failures (not shown in Figure IV.6 above) caused by test set-up and test procedure also suggest caution in interpretation of the results. The observed trends, however, do suggest that additional testing be conducted on the pump models identified as having potential sensitivity to ethanol.

V. Fuel Level Sender Tests

V.1. Background

The fuel level sender is used to send a signal to indicate the amount of fuel remaining in the fuel tank. This signal is used for several purposes. The basic purpose is to provide a voltage to the gauge driver that is related to the volume of fuel in the tank so that the vehicle operator can be made aware of the amount of fuel remaining in the tank. The secondary purpose of the fuel level sender is to provide the fuel level information (on OBDII vehicles) to the diagnostic system. Many OBDII functions use the fuel level either as part of the enable criteria, or as a component of the leak diagnostic calculation. The voltage supplied to the card varies among vehicle manufacturers and ranges from 5 to 13.5 volts.

A typical fuel level sender consists of a float, constructed of a fuel resistant material, mounted on a lever arm. The lever arm is constructed to allow a range of motion to measure the fill level over the entire range of the fuel volume. The lever arm is connected to a wiper assembly with a set of contacts. Common styles for the contacts are ribbon (Figure V.1) or button (Figure V.2.). The contacts slide on a conductive ink which is deposited on a printed circuit board with a ceramic substrate. Both the contacts and ink may be made of various blends of metals such as silver, platinum, palladium, and gold. The ink also may have glass beads for strength. The formula for the ink as well as the contacts are chosen to be resistant to corrosion, wear, and attack by fuel impurities, such as free (elemental) sulfur.

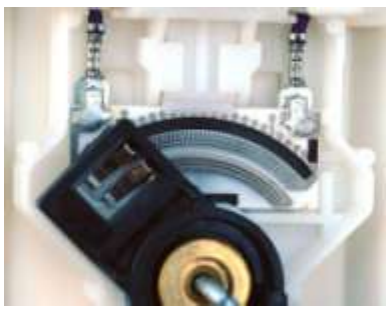

Figure V.1. Level Sender Contacts: Ribbon Style System

Figure V.2. Level Sender Contacts: Button Style System

Figure V.3. Typical Circuit Board

The level indication and OBDII systems must have some level of "cleanliness" in their signal without spikes or open circuits in the resistance level otherwise false diagnostic messages may occur. Each vehicle manufacturer determines the level of "cleanliness" needed for the signal depending on the software and hardware filtering. Typically the fuel level instrument panel gauge is sufficiently damped so that the limiting factor for signal noise is the OBDII system requirement.

Many vehicle manufacturers use a visual indication of the signal output to determine the pass fail criteria after a fuel level sender test.

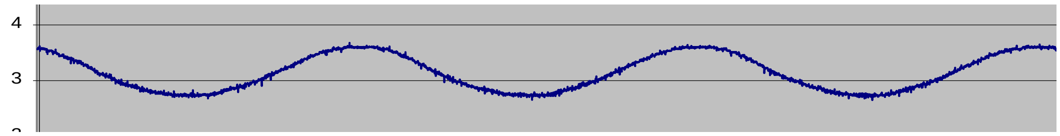

Figure V.4. Example of "Clean", Acceptable Signal

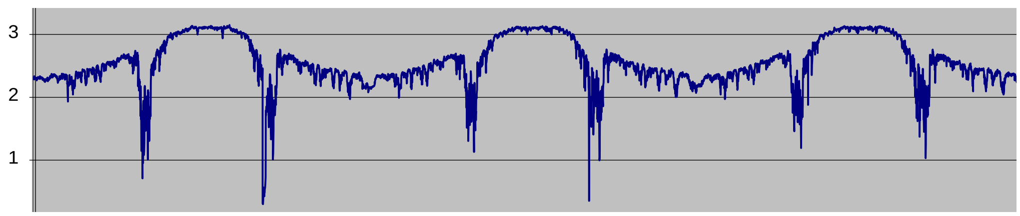

Figure V.5. Example of "Dirty", Unacceptable Signal

Other methods to determine the suitability of a level sender signal are quantitative. Depending on the filtering of the receiving electronics, a certain number of defects from the ideal signal are allowed. An example of a quantitative pass/fail criterion is included in the appendix to this section. As the number and frequency of the excursions allowed are proprietary and highly dependent on the individual manufacturer's system, the visual indication and analysis of the output signal will be used to discuss the results of the tests in this project.

V.2. Test Plan

The level senders were tested in fuel using two protocols:

Fuel Resistance: The level senders were cycled, unpowered, for 250,000 cycles in fuel and soaked for one week. The cycle was then repeated three additional times for a total of 1,000,000 cycles. The fuel resistance test protocol is designed to simulate the effect of changes which may occur to the fuel level sender while the sender is not powered. Changes which may be expected include the electrical characteristics of the interface between the conductive surfaces in the level sender.

Full Sweep: The level senders were cycled for 5,000,000 cycles at one cycle per second. The level sender circuit is powered during the cycles. The full sweep test protocol is designed to simulate the operation of the fuel level sender during vehicle operation. The contacts are kept powered to ensure a flow of current across the surfaces in order to evaluate any electrochemical effects and the float arm is kept in motion to evaluate any mechanical effects on the float arm and contact mechanism. Five million cycles is a typical validation cycle used in the industry.

Functional tests of the fuel level signal were performed during the test sequence and will be discussed in the following sections. Complete details of the test procedure are included in Appendix D.

V.3. Results

V.3.1. Summary

Table V.1 summarizes the results. In the table, "N" indicates noise in the signal at end of test, "F" indicates a failure which prevented test completion, "O" indicates an open in the sender circuit, and "S" indicates a steady state signal shift.

Table V.1. Summary of Results

Summary of Results

Vehicle	Test Mode	Results E20a	E10	E0	Comments
Vehicle A	Fuel Resistance	Noise N	OK	Not Tested	Bad resistance data in E20a fuel
	Full Sweep	Noise, opens	Noise N		
Vehicle N	Fuel Resistance	Signal Shift Repeats OK S	Minor Noise Repeats OK	OK	
	Full Sweep	Signal Shift, Noise N Opens, O	Noise, Opens, Repeats OK		
Vehicle M	Fuel Resistance	OK	Not Tested	Not Tested	
	Full Sweep	OK	OK		
Vehicle C	Fuel Resistance	Opens, Noise on repeats O N	OK, OK on repeats	OK	
	Full Sweep	Noise, Opens O N	Noise N		
Vehicle L	Fuel Resistance	OK	Not Tested	Not Tested	
	Full Sweep	Failed Repeats OK F	OK Repeats OK	OK	Failure due to burned resistor
Vehicle K	Fuel Resistance	Failed Open F	Failed Open F	Not Tested	Failures due to burned/shorted section of card
	Full Sweep	Minor Noise	OK		
Vehicle F	Fuel Resistance	Open at top end O	OK	Not Tested	Full Sweep EOT data missing due to broken arm
	Full Sweep	OK at midpoint	Not Tested		
Vehicle G	Fuel Resistance	OK	Not Tested	Not Tested	
	Full Sweep	OK			

V.3.2. Fuel Resistance

Level senders from the following eight vehicles were chosen to undergo a level sender fuel resistance test. The eight designs chosen were:

1. Vehicle A
2. Vehicle N
3. Vehicle M
4. Vehicle C
5. Vehicle L
6. Vehicle K
7. Vehicle F
8. Vehicle G

The fuel resistance test consisted of an initial baseline level sender performance test where the resistance through the level sender circuit was recorded at the empty stop, full stop, and midpoint of float travel. In addition, five sweeps were performed while recording float height and level sender circuit resistance. Each level sender was powered by an OEM-specified voltage, and each circuit contained an OEM-specified resistor. An example of the first sweep of the five sweep test can be seen in Figure V.6 below. Each level sender was then placed into an individual stainless steel container. The level senders were mounted to a pneumatic cylinder that had built-in positional feedback. This feedback signal was used to cycle the cylinders up and down so that the level senders were moved into and out of the test fuel. The strokes were made sufficiently long so that the float was fully removed from the test fuel and then fully submerged in the test fuel.

After the baseline performance test, the senders were cycled for 250,000 cycles while being powered and then soaked fully submerged in the $E20_A$ test fuel for one week while unpowered. This cycle was repeated until one million cycles had been accumulated along with four weeks of soak. After the final week of soak, the level senders underwent another performance test identical to the first.

Complete graphs of the results are shown in Appendix D.

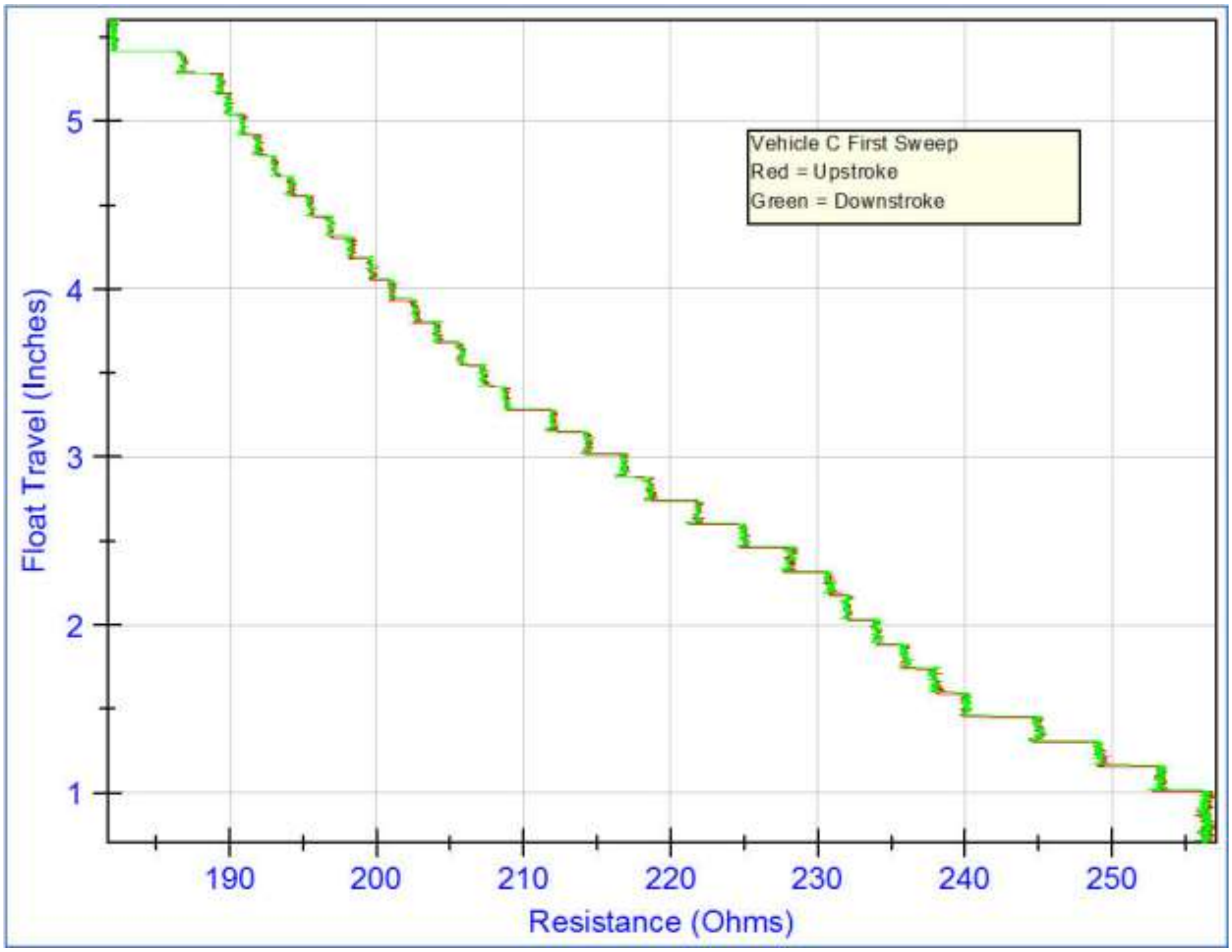

Figure V.6. Vehicle C Level Sender Fuel Resistance Pre-aging First Sweep

V.3.2.1. Vehicle A

Vehicle A was tested on $E20_A$, and E10 fuel. On $E20_A$, the Vehicle A sender showed noise in the signal, with noise levels of 25 to 50 ohms. The Vehicle A sender initially showed slight noise when tested in the E10 fuel; however, it was later determined that the test setup was introducing noise. After retesting on the E10 fuel, the results did not show any noise in the signal. An example of the results with $E20_A$ is shown in Figure V.7.

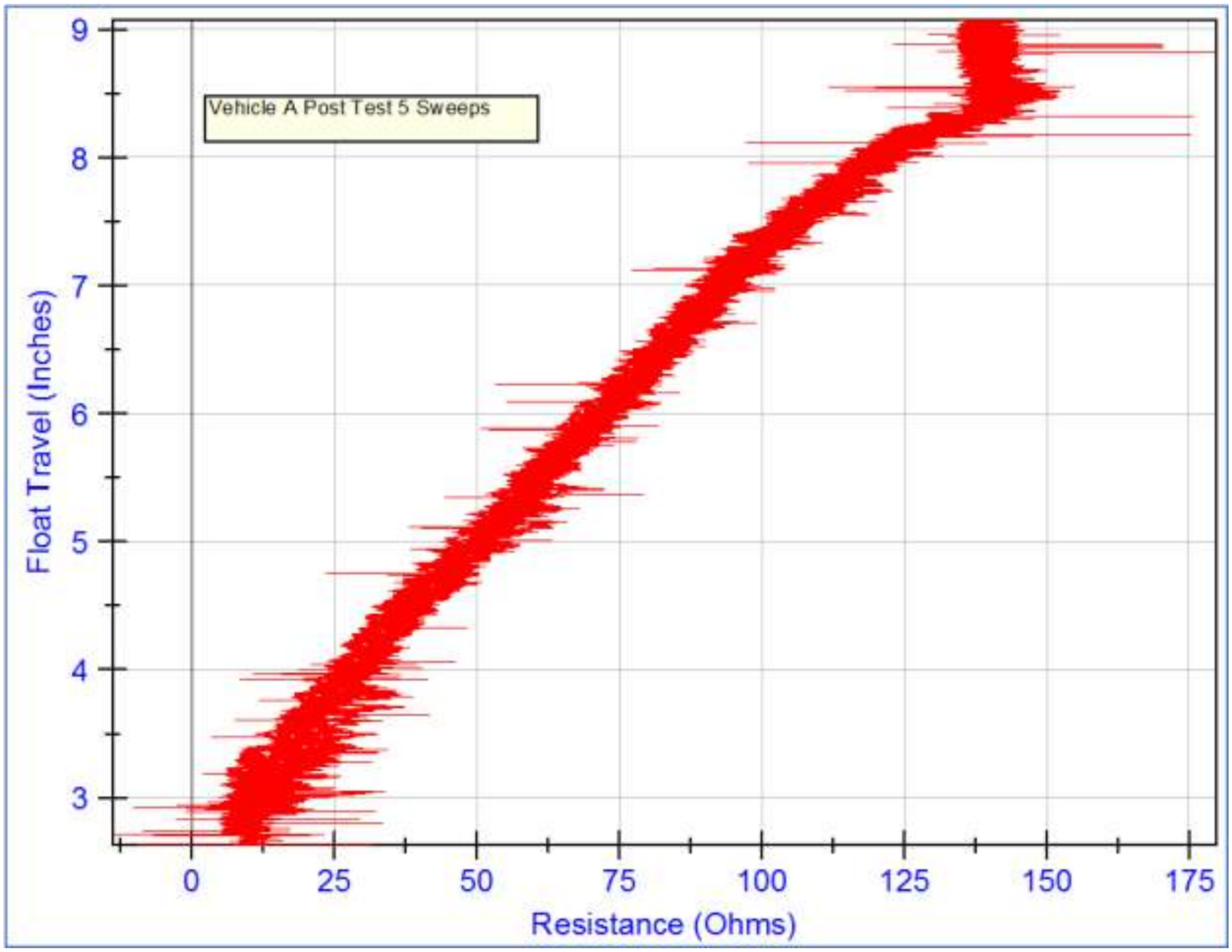

Figure V.7. Vehicle A Post Test 5 Sweeps on $E20_A$

V.3.2.2. Vehicle N

Vehicle N showed a signal shift (hysteresis) when initially tested with $E20_A$ in the fuel resistance portion of the program, shown in Figure V.3. This test showed a shift in the resistance values from the initial to the post test and a change in the range of values observed. Subsequent testing, however, was free from any signal defects after the measurement apparatus was changed. The fuel resistance testing with E10 showed minor noise initially, but also produced clean results when retested. Vehicle N was also tested on E0 using the fuel resistance protocol and showed no issues.

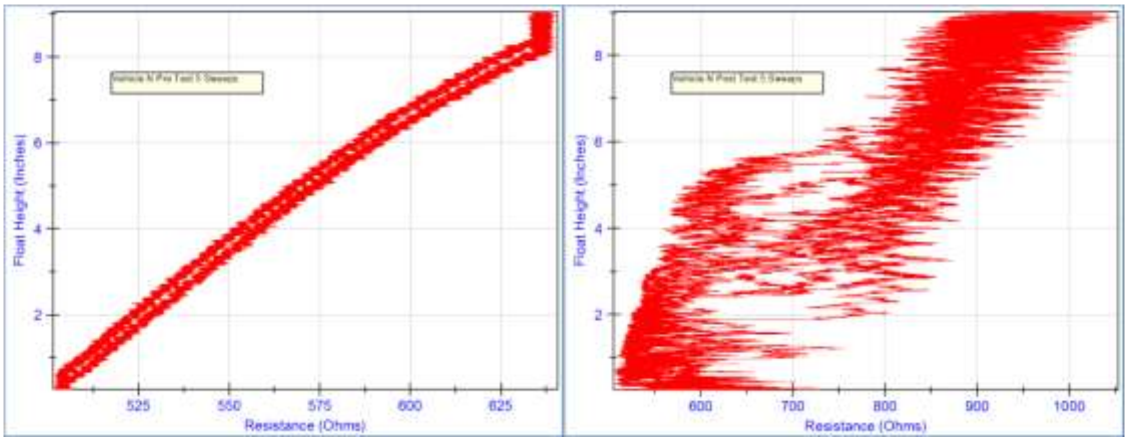

Figure V.8. Vehicle N $E20_A$ Level Sender Fuel Resistance Pre-aging & Post-aging test (initial)

V.3.2.3. Vehicle M

Vehicle M was tested in the fuel resistance portion with $E20_A$ fuel and did not have any signal defects.

V.3.2.4. Vehicle C

Vehicle C was tested on all three fuels in the fuel resistance portion of the test. On $E20_A$, the initial tests had opens and noise. On the repeats, there were no opens observed, but the signal did have noise. On E10 and E0, there were no significant issues. The test results with $E20_A$ are shown in Figure V.9.

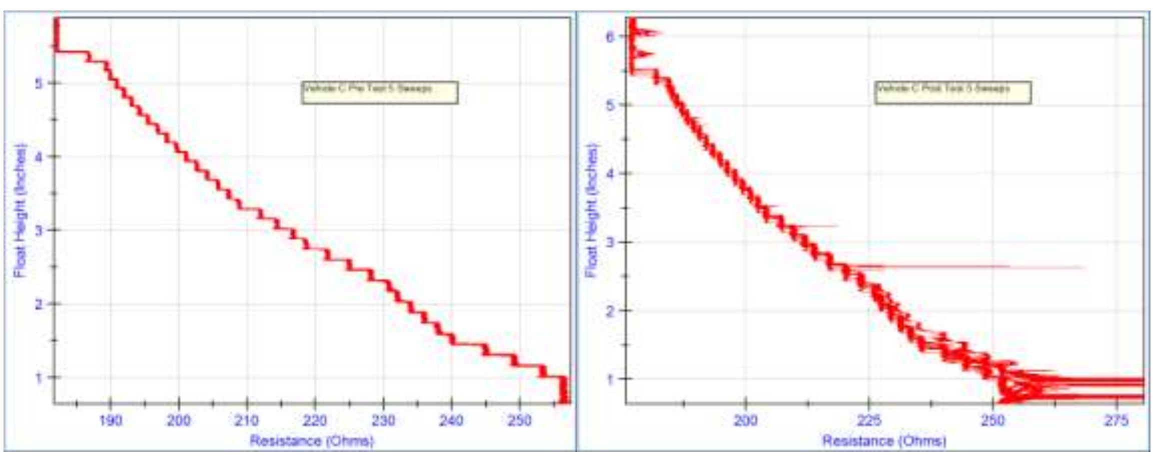

Figure V.9. Vehicle C $E20_A$ Level Sender Fuel Resistance Pre-aging & Post-aging Test

V.3.2.5. Vehicle L

Vehicle L was tested in the fuel resistance portion with $E20_A$ fuel and did not have any signal defects.

V.3.2.6. Vehicle K

Vehicle K, when tested both with $E20_A$ and with E10, had hardware failures on the sender card. Both failures were similar, with burned and shorted areas on the card. (See Figures V.10 and V.11.)

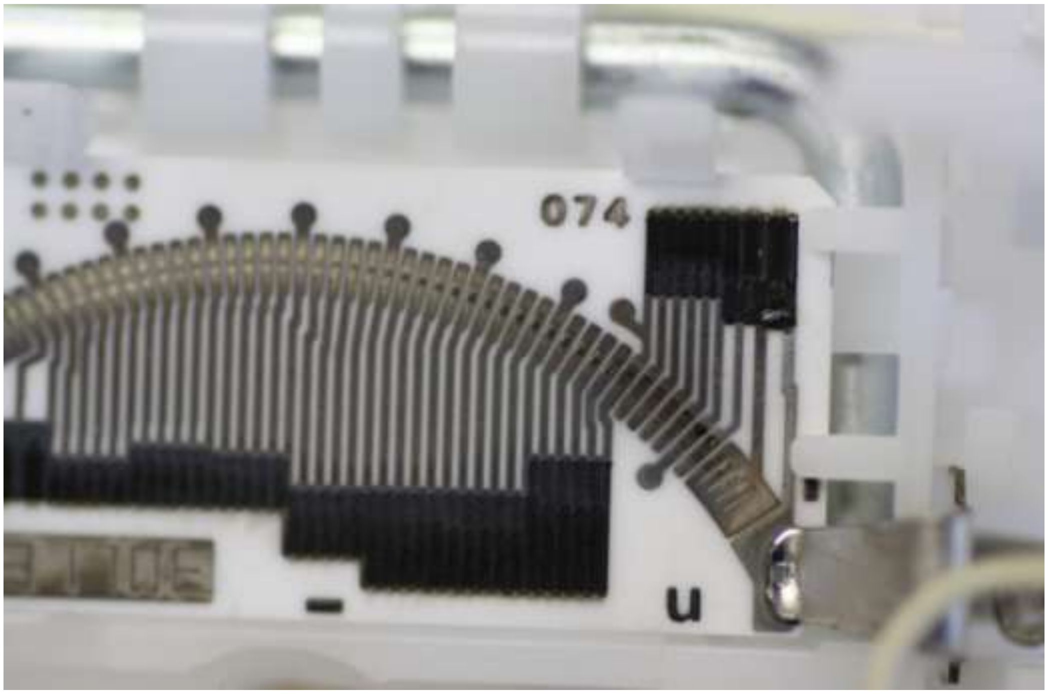

Figure V.10 Vehicle K $E20_A$ Level Sender (shorted area in upper right corner of card)

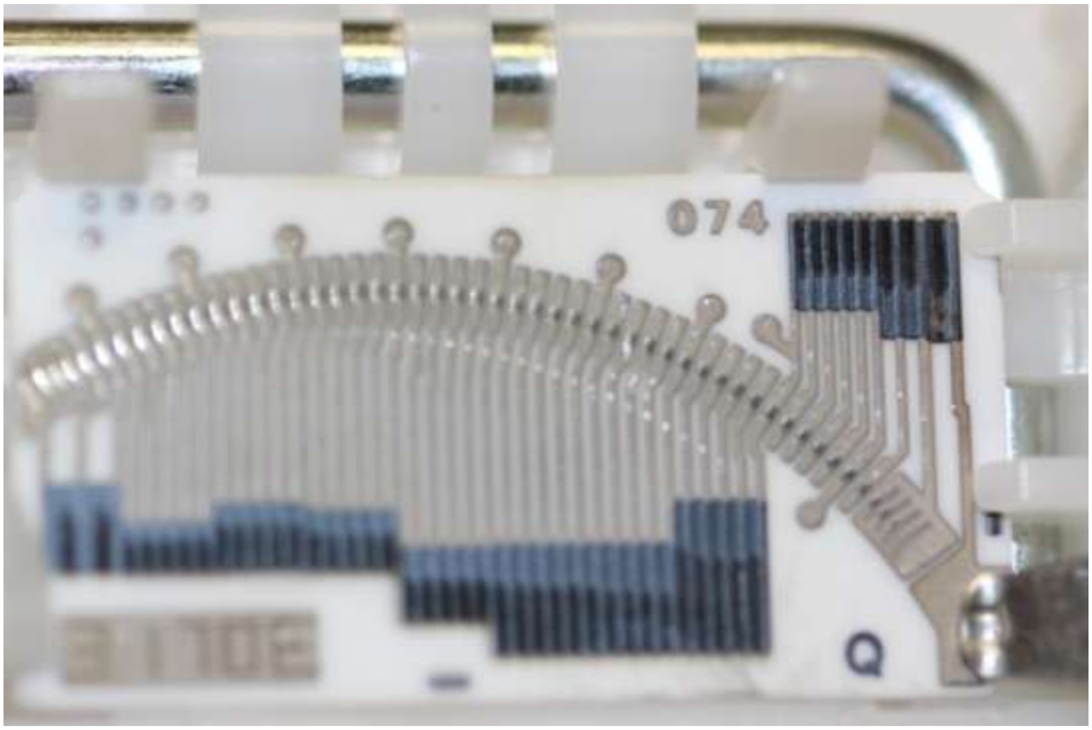

Figure V.11. Vehicle K E10 Level Sender (shorted area in upper right corner of card)

V.3.2.7. Vehicle F

When tested with $E20_A$, Vehicle F had a section of the signal sweep with an open. When tested with E10, the signal had no defects.

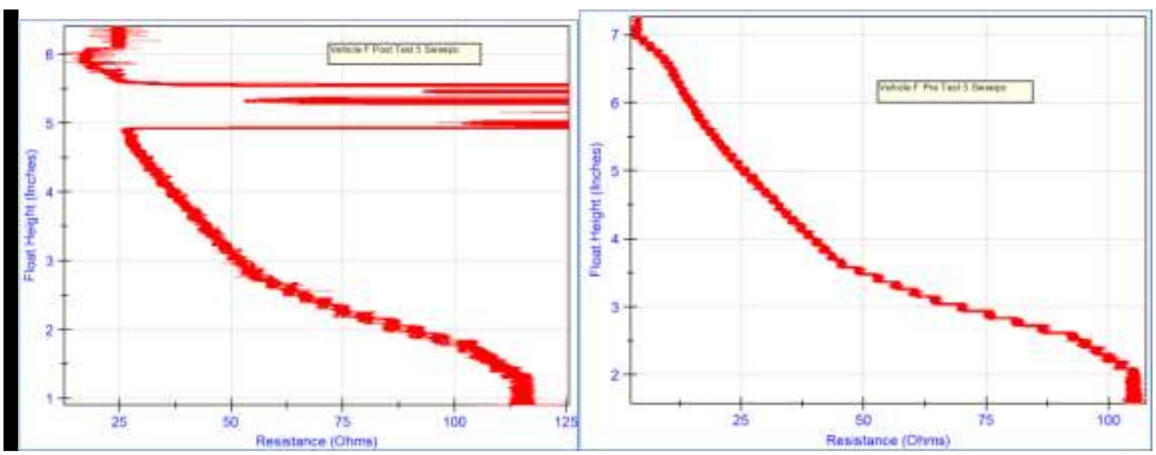

Figure V.12. Vehicle F $E20_A$ Level Sender Fuel Resistance Pre-aging and Post-aging Test

V.3.2.8. Vehicle G

Vehicle G was tested in the fuel resistance portion with $E20_A$ fuel and did not have any signal defects. It was not tested with E10 fuel.

V.3.3. Full Sweep

All eight level senders were also tested through a full sweep test, where they were baseline-tested and then cycled through 5 million full sweeps using the same actuation apparatus described above. A mid-point test was performed as well as a post test.

V.3.3.1 Vehicle A

Vehicle A was tested with $E20_A$ and E10 fuel in the full sweep portion of the test. In the $E20_A$ test fuel, Vehicle A showed an open circuit and noise on the first sweep at the end of the test. When additional sweeps were done, the open circuits did not appear, but the signal remained noisy. Figure V.13 shows the sweeps at end of the $E20_A$ test.

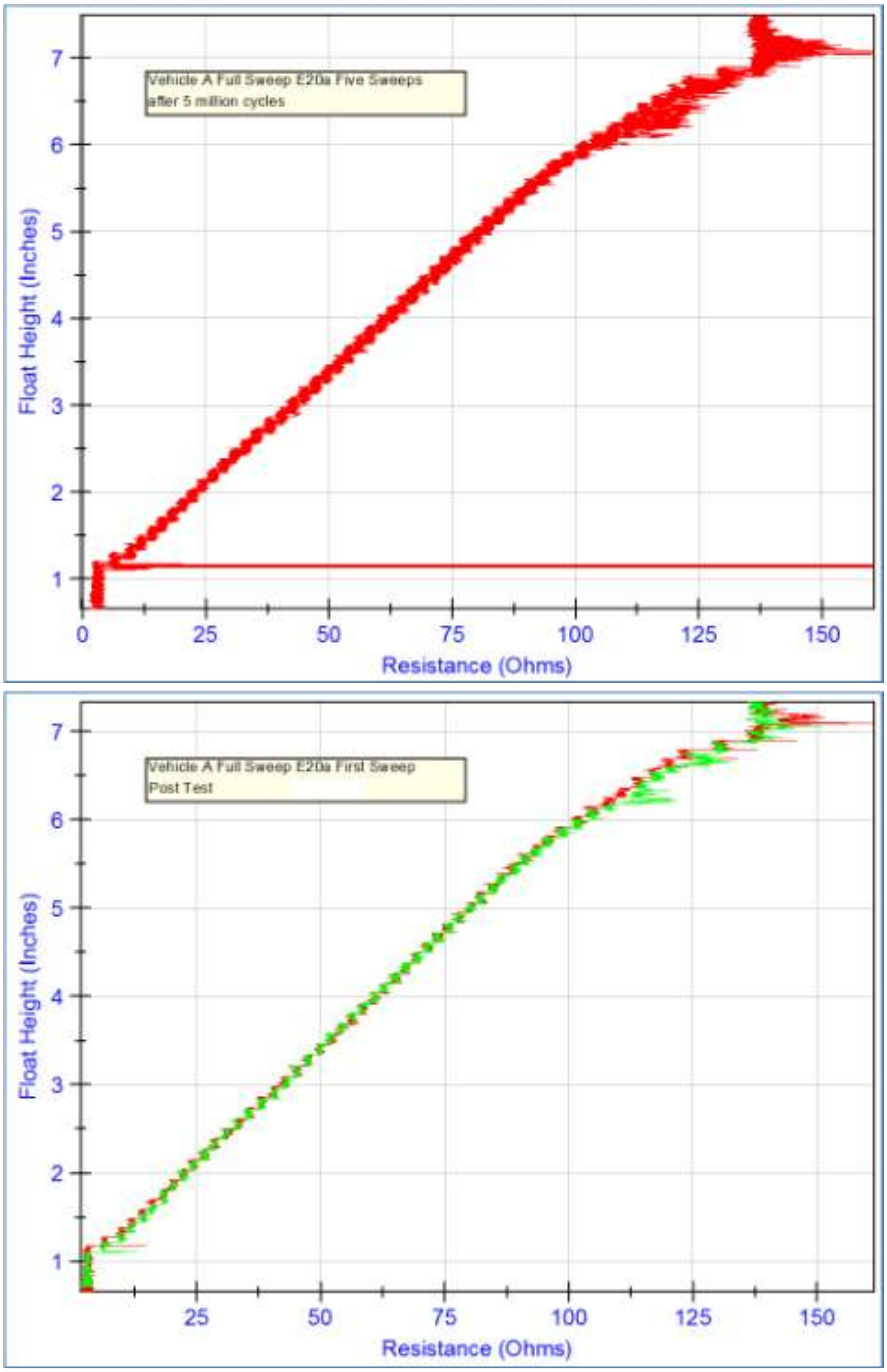

Figure V.13. Vehicle A Full Sweep $E20_A$ Endpoint

Vehicle A's test with E10 fuel showed some noise in the signal, illustrated in Figure V.14.

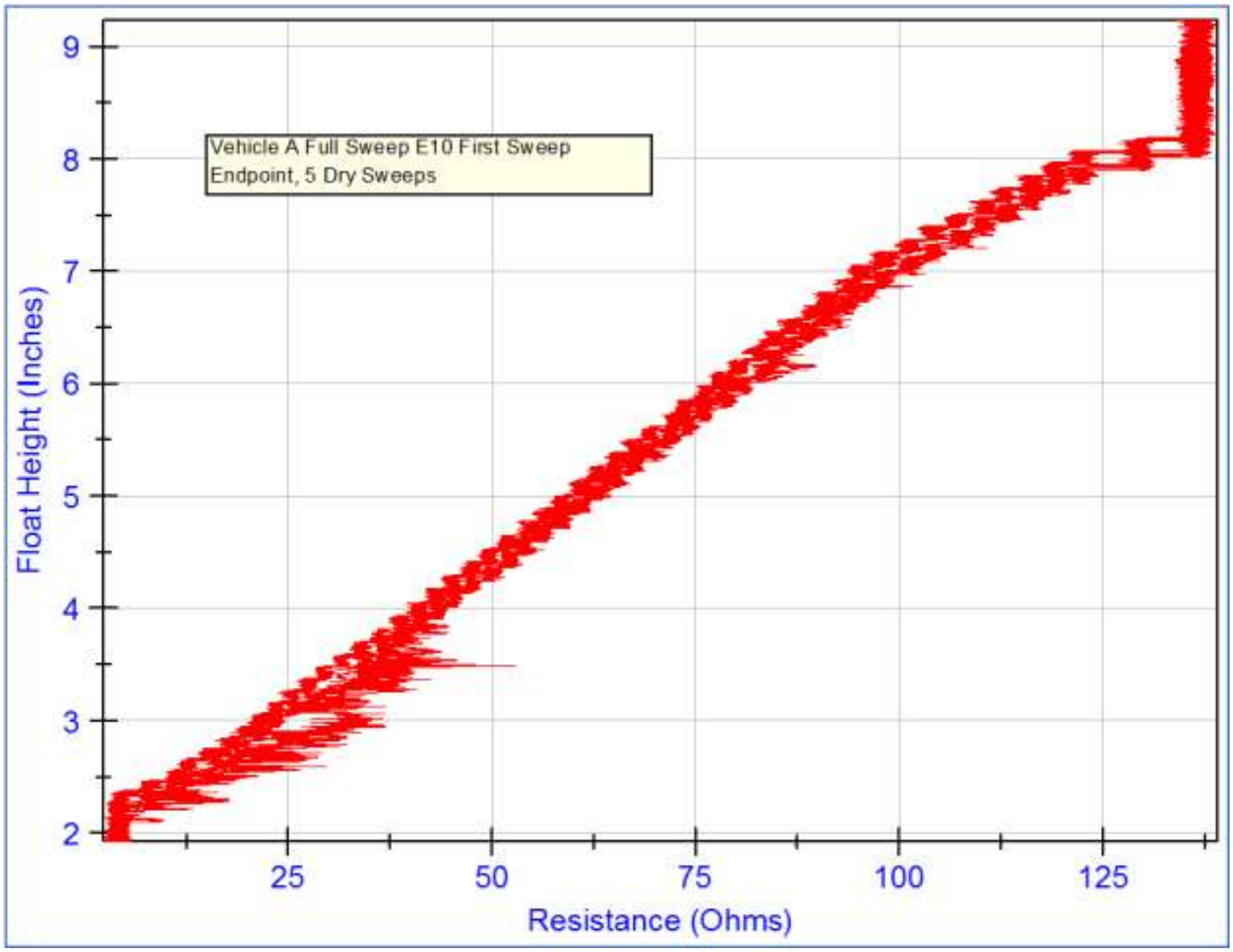

Figure V.14. Vehicle A Full Sweep E10 Endpoint

V.3.3.2. Vehicle N

Vehicle N was tested with $E20_A$ in the full sweep portion of the test. The initial tests showed a noisy signal, with a shift in the resistance value in the midpoint of the sweep. Figure V.15 shows the results at the end of the test for five test sweeps.

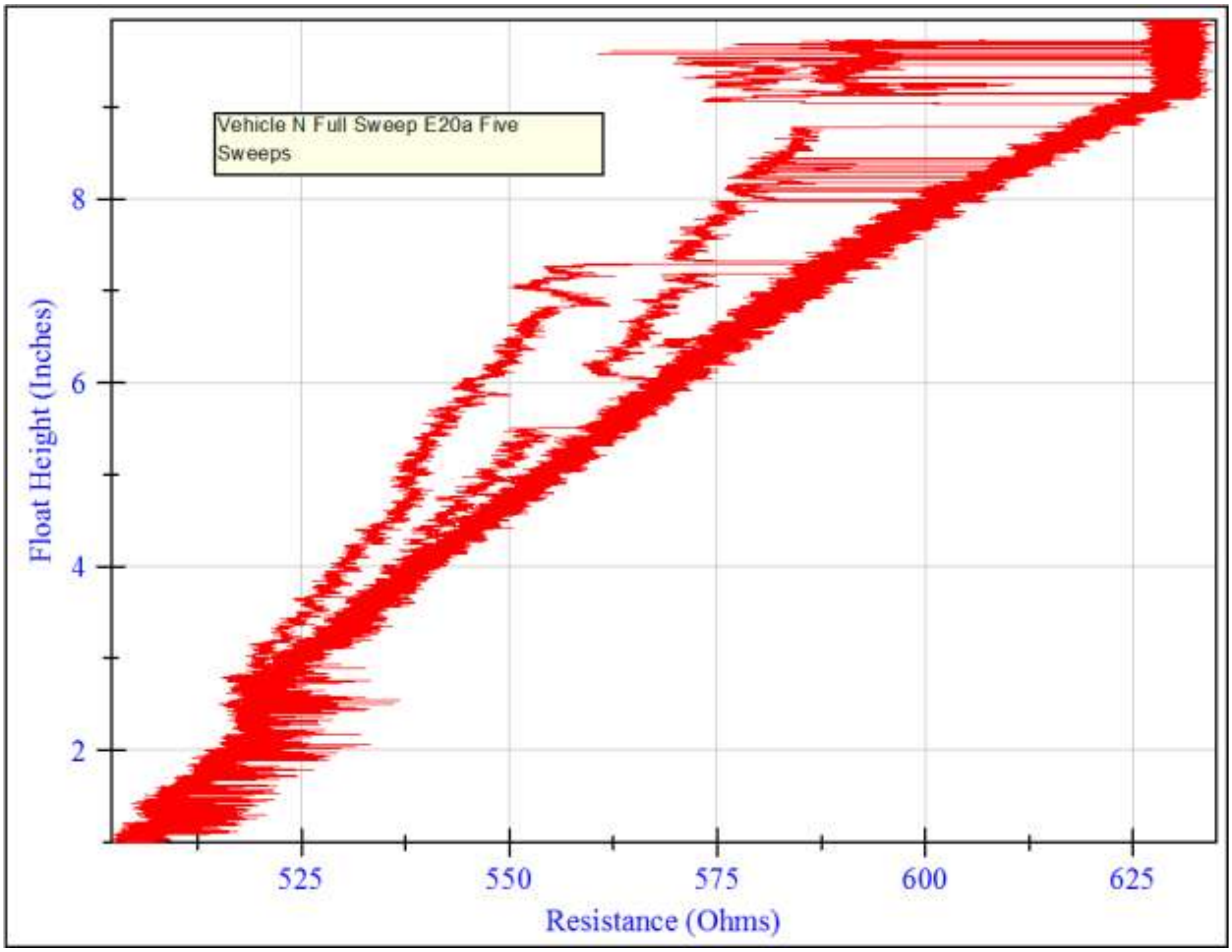

Figure V.15. Vehicle N Full Sweep E20A Endpoint (initial test series)

The initial Vehicle N tests with E10 had a noisy signal, with open circuits at the end of the test. Results are shown in Figure V.16.

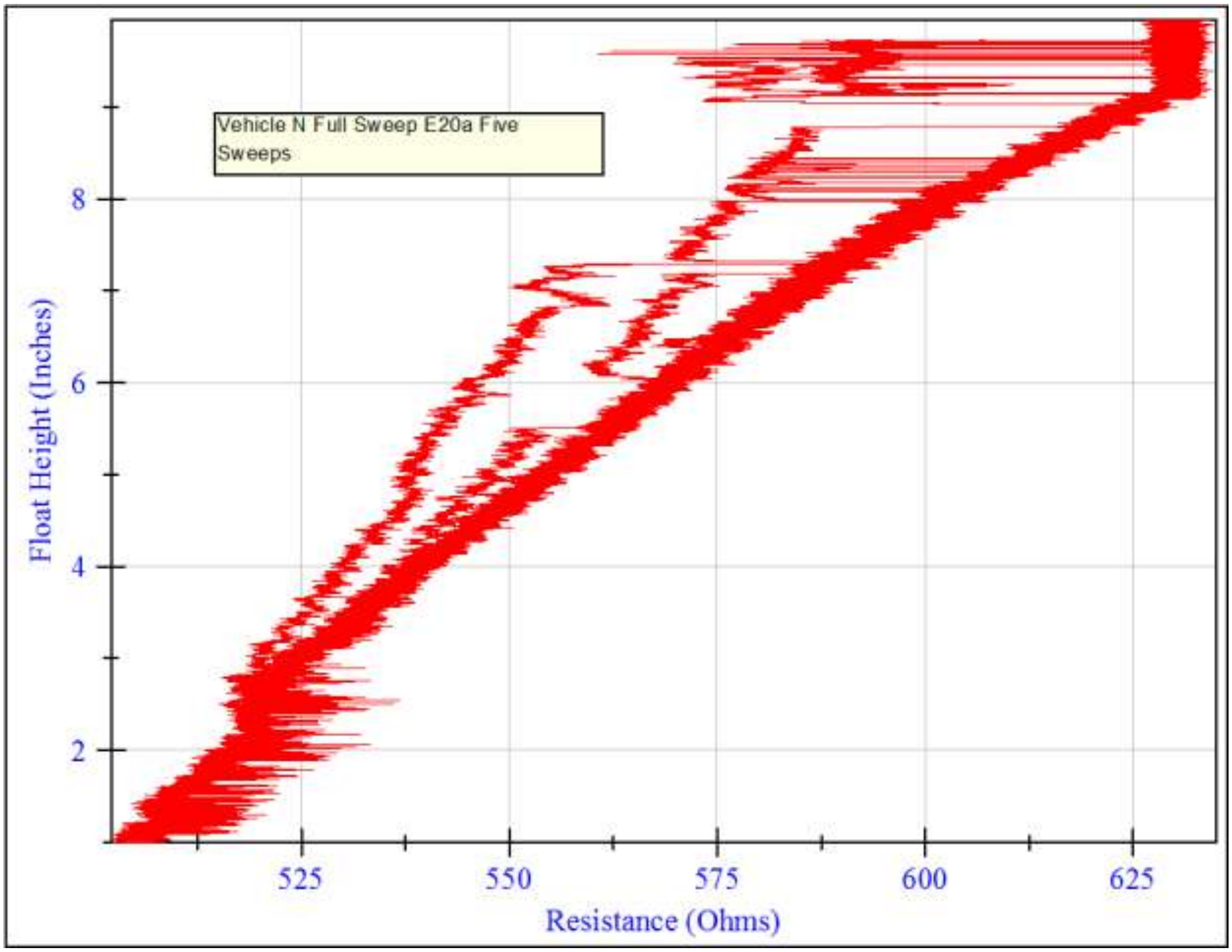

Figure V.16. Vehicle N Full Sweep E10 Endpoint (initial test series)

Repeat testing was done on Vehicle N. Four repeat samples were tested in $E20_A$, two in E10, and two in E0. One of the tests in $E20_A$ showed opens; all other tests were without any signal defects at the end of the test.

V.3.3.3. Vehicle M

Vehicle M was tested in the full sweep portion with $E20_A$ and E10 fuel and did not have any signal defects.

V.3.3.4. Vehicle C

Vehicle C was tested on $E20_A$ and E10 fuels in the full sweep portion of the test. On $E20_A$, the signal had opens and noise, and on E10 the signal had noise.

Figure V.17 shows the results of Vehicle C at the end of the full sweep tests.

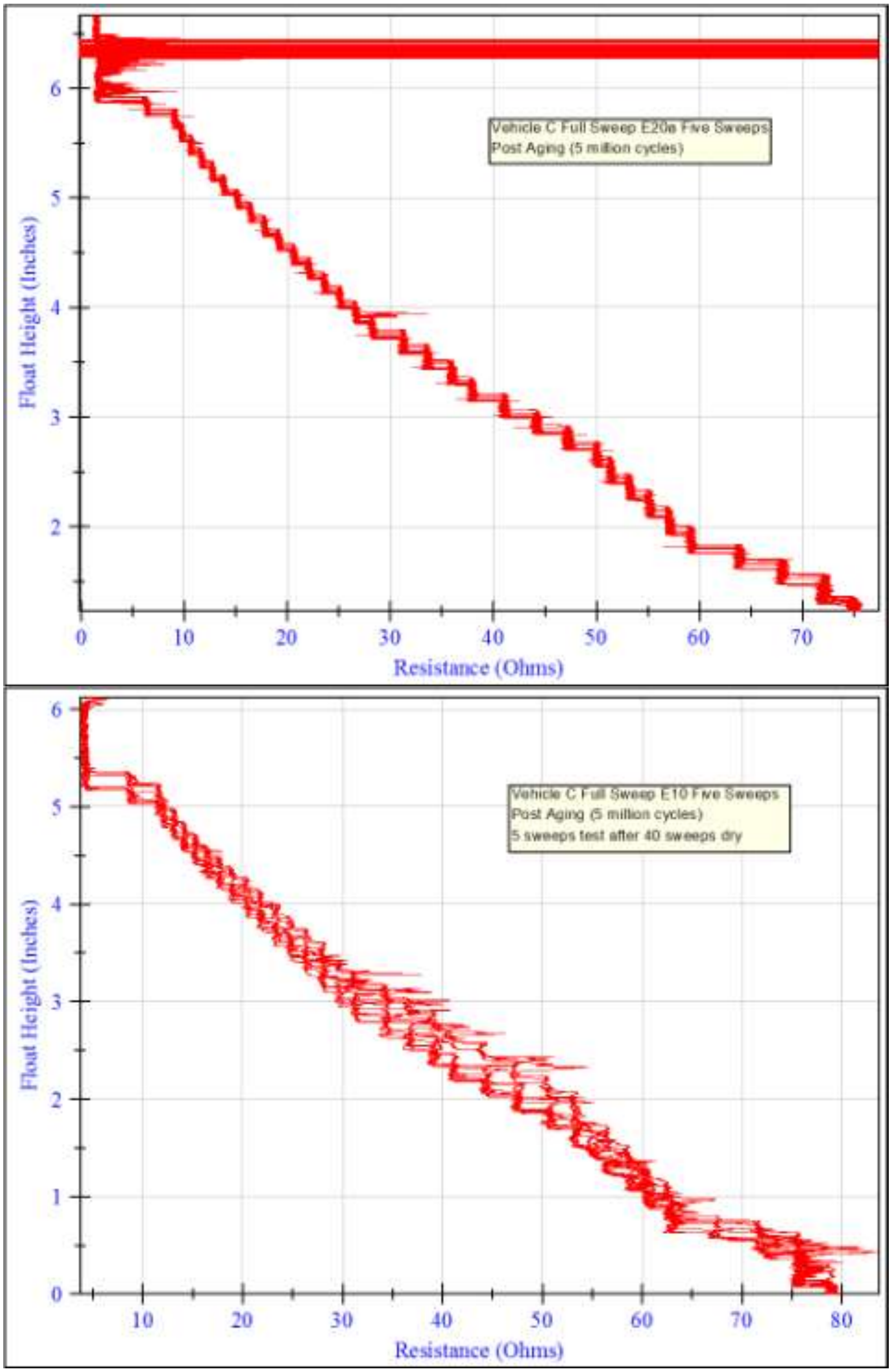

Figure V.17. Vehicle C Full Sweep $E20_A$ (top) and E10 Endpoint

Repeat testing was done on Vehicle C. Three of the four Vehicle C tests on $E20_A$ were noisy; the E10 and E0 test were without issues.

V.3.3.5. Vehicle L

The initial test of Vehicle L on $E20_A$ fuel had a failure in the resistor card. One portion of the circuit failed as an open, with a burned section visible, shown in Figure V.18.

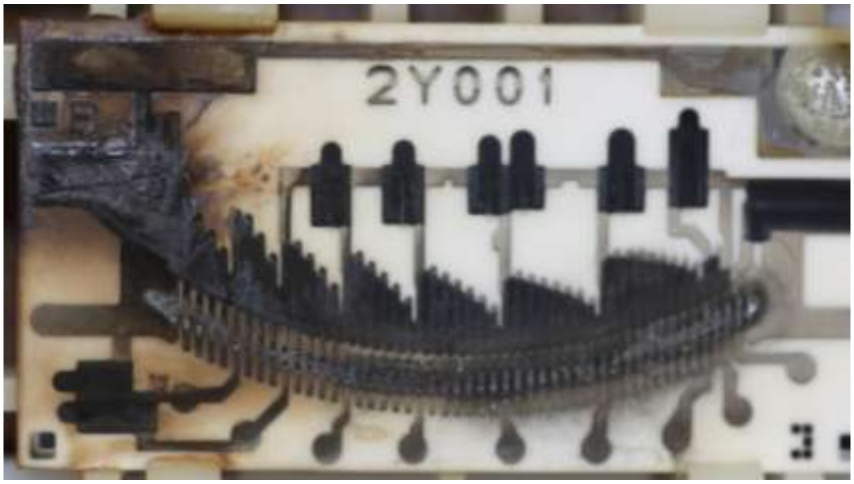

Figure V.18. Vehicle L Full Sweep $E20_A$ card

A new resistor card completed the $E20_A$ test with no signal defects. The test in E10 also was completed with no defects.

Repeat full sweep testing was done on Vehicle L. Two tests were done in $E20_A$, without any signal defects at the end of the test (one did have a slight increase in signal noise). One test was done in both E10 and E0 with no signal defects at the end of the test.

V.3.3.6. Vehicle K

Vehicle K was tested in both $E20_A$ and E10. The test in $E20_A$ had a slight section with noise, as shown in Figure V.19. The signal from the test in E10 was defect-free.

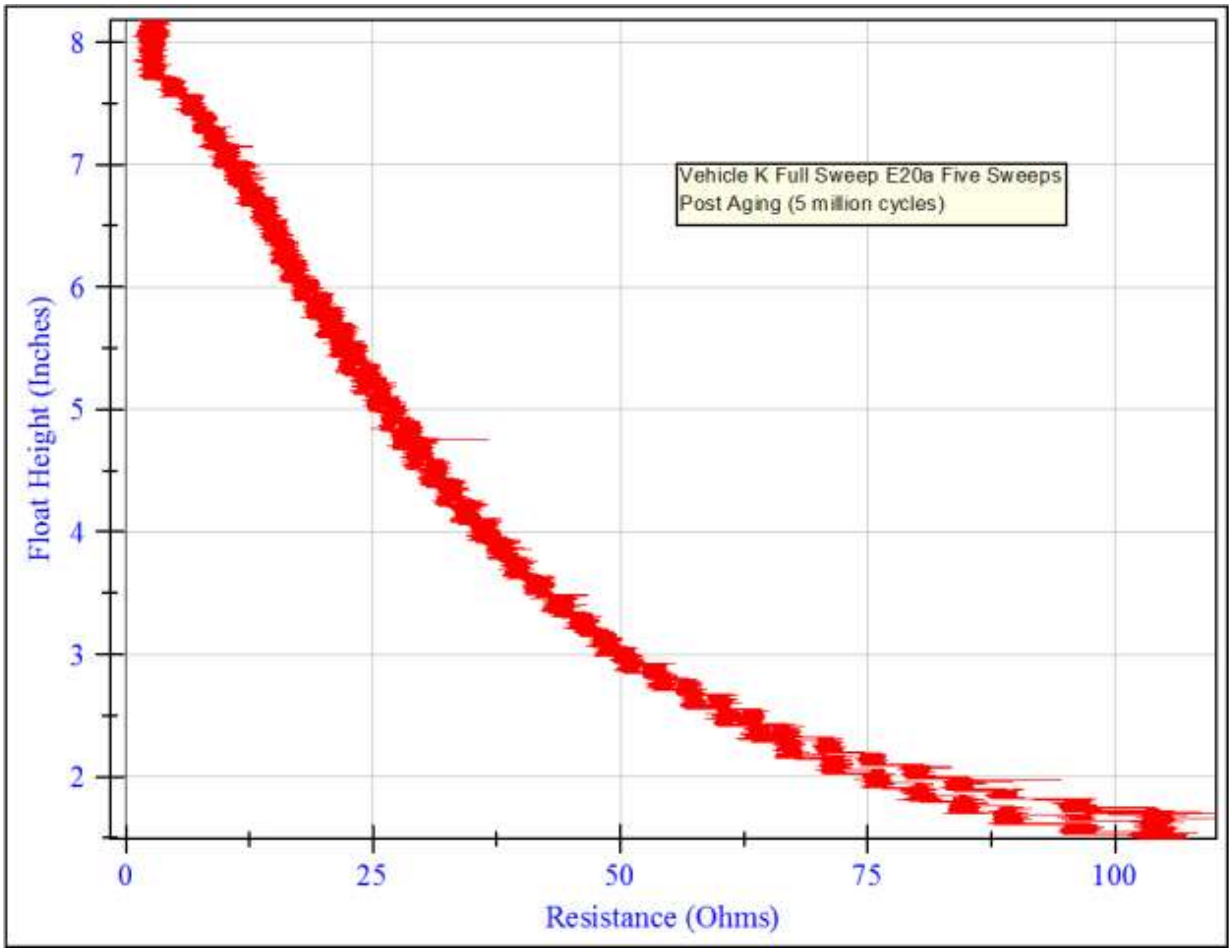

Figure V.19. Vehicle K Full Sweep $E20_A$

V.3.3.7. Vehicle F

When tested with $E20_A$ in the full sweep, Vehicle F had no defects at the midpoint of the test, but a mechanical failure prevented completion of the test. Vehicle F was not tested on E10.

V.3.3.8. Vehicle G

Vehicle G was tested in the full sweep with $E20_A$ fuel and did not have any signal defects. It was not tested with E10 fuel.

VI. Fuel Damper Tests

A Vehicle O fuel damper was selected for testing. Two copies of this damper were tested. The test required a baseline of the new fuel damper (pretest) to determine the frequency response to a pressure spike. The dampers were then aged for 120 hours at 120°C while filled with $E20_A$, and then an evaluation of the response to the same pressure spike was measured. The pressure spike was created by flowing E0 gasoline at a high rate through a long tube simulating a fuel line and engine fuel rail assembly. The closure of a fast-acting valve was then closed, which created a pressure wave that moved past the damper before coming to a dynamic pressure transducer. At each test point, the test was performed with and without the damper installed in order to determine a baseline dynamic response for the system. Two dampers were tested before and after aging. The data was reviewed by the experts at the manufacturer who determined there was no significant difference between the aged and new dampers after aging. An example of the test results is shown in Figure VI.1, and the remaining graphs can be found in Appendix E.

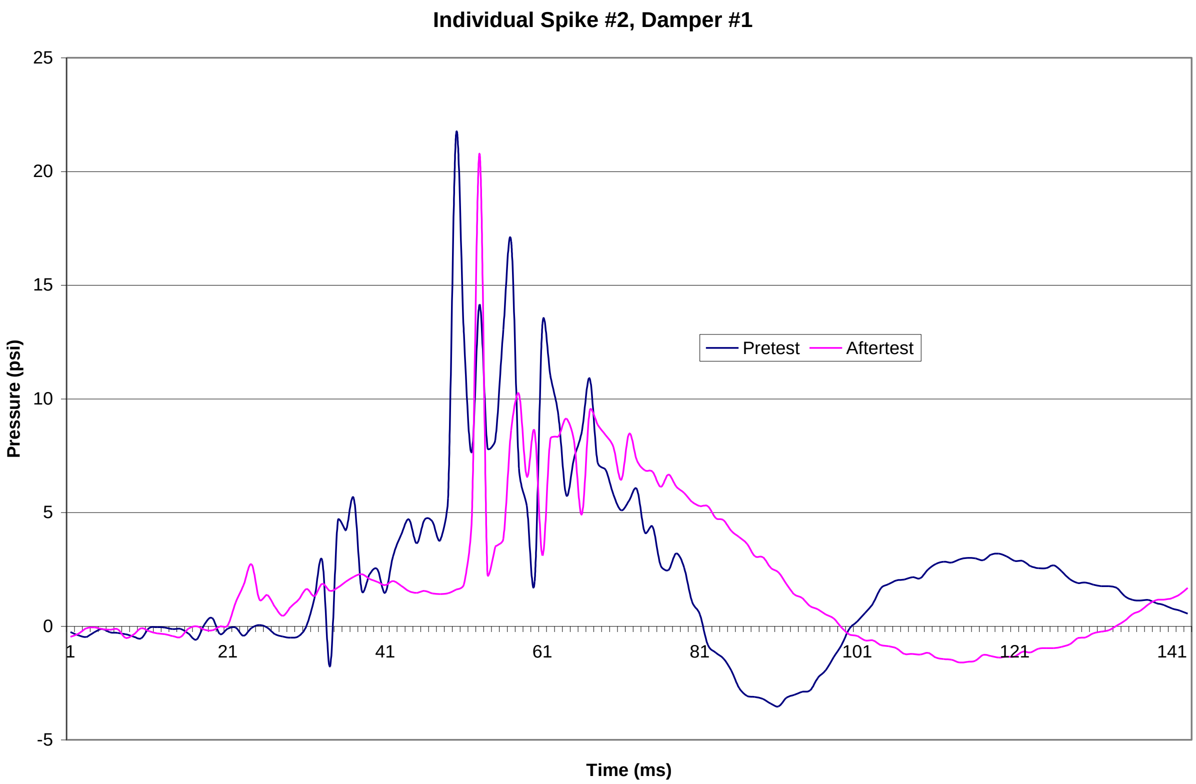

Figure VI.1. Vehicle O Fuel Damper

VII. Fuel Injector Tests

Fuel injector sets from three different vehicles, all with four-cylinder engines, were chosen to undergo fuel injector aging and testing on the $E20_A$ fuel. A fuel injector test stand, which met the requirements for flow testing as specified by SAE J1832, was utilized to test and age the fuel injectors. This stand incorporated the OEM fuel filter and rail. Two flow tests were performed at each test point. The dynamic flow test measured the amount of fuel sprayed by the injector with a period of 10 milliseconds and a pulse rate of 2.5 milliseconds for a set number of pulses. The static flow test measured the amount of fuel sprayed by the injector while being energized continuously for a set number of seconds. An example of the test apparatus and a schematic of the fuel flow from the testing and aging stand are shown in Figures VII.1 and VII.2, respectively.

After baseline dynamic and static flow tests were performed on each injector using E0 test fuel, photographs of each injector's spray pattern were taken. Once the photography was complete, the fuel was changed to $E20_A$, and the injectors were operated through the durability test described in SAE J1823. This consisted of pressurizing the rail to the vehicle-specific fuel pressure and cycling the injectors on and off with a pulse width of 2.5 milliseconds and a period of 5.0 milliseconds for a total of 100 million cycles. After the 100 million cycles were completed, the fuel was changed back to E0, and the static and dynamic tests were performed again. Photographs were taken as well. The fuel was changed back to $E20_A$, and the injectors began another 100 million cycles. The aging and testing continued until 600 million cycles had been accumulated on each injector set. The complete test procedure is provided in Appendix F. The spray volume was collected and weighed. Therefore, flow rate was recorded as grams per second (g/s).

The three fuel injectors chosen to be tested were all 12-hole injectors. Vehicle B, Vehicle E, and Vehicle I.

Figure VII.1. Fuel Injector Testing and Aging Stand

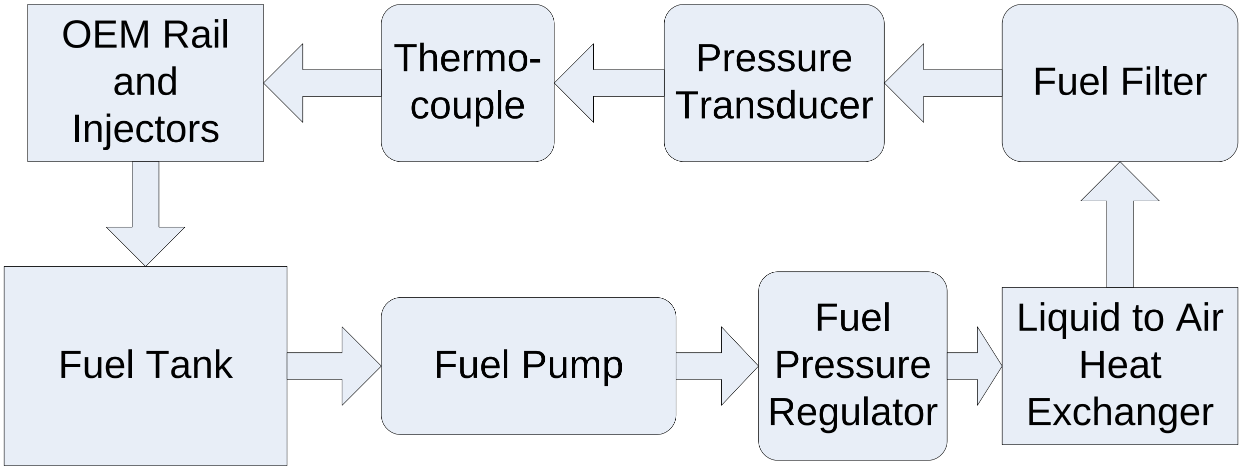

Figure VII.2. Block Diagram of Fuel Flow from Testing and Aging Stand

Sample pictures taken from the injector tests are shown below. There did not appear to be any changes in spray pattern that developed in any of the injectors tested. Vehicle B and Vehicle I fuel injectors showed a flow loss of no more than 2.6% over the course of the program (static and dynamic tests). This loss in flow was not deemed significant by the respective manufacturers' representatives. Three of the four Vehicle E injectors showed more significant fluctuations in dynamic flow, and one injector had a flow reduction of more than 6% after 600 million cycles. However, Vehicle E manufacturer's representatives concluded that this was not a significant reduction in flow, and no further testing was performed.

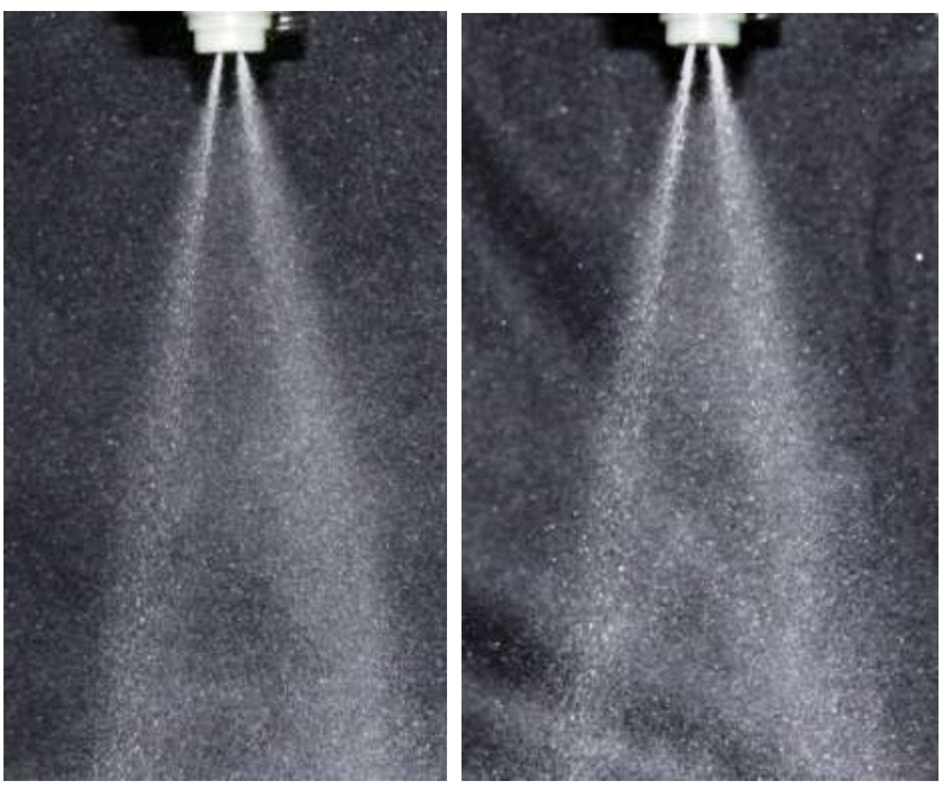

Figure VII.3. Vehicle E Spray Pattern Before and After Aging

Flow results from Vehicle E's injector set are shown in Table VII.1, and the test results for the other two injector sets are provided in Tables F.1 and F.2 in Appendix F.

Table VII.1. Vehicle E Fuel Injector Test Results

Vehicle E	Injector	Static Flow Rate (g/s)	% Change	Dynamic Flow Rate (g/s)	% Change
0 cycles	1	4.08	0.00%	0.658	0.00%
100 MM cycles	1	4.06	-0.68%	0.669	1.70%
200 MM cycles	1	4.06	-0.50%	0.662	0.56%
300 MM cycles	1	4.05	-0.91%	0.659	0.07%
400 MM cycles	1	4.03	-1.26%	0.657	-0.14%
500 MM cycles	1	4.04	-1.06%	0.653	-0.80%
600 MM cycles	1	4.04	-1.10%	0.663	0.73%
0 cycles	2	4.06	0.00%	0.658	0.00%
100 MM cycles	2	4.07	0.20%	0.647	-1.60%
200 MM cycles	2	4.04	-0.52%	0.640	-2.71%
300 MM cycles	2	4.05	-0.19%	0.639	-2.88%
400 MM cycles	2	4.07	0.28%	0.626	-4.76%
500 MM cycles	2	4.08	0.35%	0.636	-3.35%
600 MM cycles	2	4.07	0.25%	0.648	-1.53%
0 cycles	3	4.09	0.00%	0.660	0.00%
100 MM cycles	3	4.08	-0.39%	0.652	-1.15%
200 MM cycles	3	4.06	-0.89%	0.651	-1.24%
300 MM cycles	3	4.06	-0.86%	0.632	-4.17%
400 MM cycles	3	4.08	-0.35%	0.631	-4.39%
500 MM cycles	3	4.07	-0.47%	0.625	-5.30%
600 MM cycles	3	4.07	-0.56%	0.619	-6.10%
0 cycles	4	4.04	0.00%	0.649	0.00%
100 MM cycles	4	4.00	-0.99%	0.644	-0.78%
200 MM cycles	4	3.98	-1.49%	0.631	-2.77%
300 MM cycles	4	3.99	-1.29%	0.626	-3.56%
400 MM cycles	4	4.00	-0.93%	0.626	-3.57%
500 MM cycles	4	4.00	-1.00%	0.630	-2.88%
600 MM cycles	4	4.01	-0.77%	0.642	-1.11%

VIII. Conclusions

As a scoping study, the findings of this program should be used to determine where additional testing might be valuable. This study is not to be considered as a comprehensive or exhaustive determination of compatibility. Numerous components were tested and additional testing on several of these components might yield an understanding of ethanol content effects on fuel wetted parts. This scoping study tested complete fuel system rigs, fuel pumps, fuel level senders, fuel dampers, and fuel injectors.

Fuel System Rigs

Twelve fuel system rigs were built, two from each of six vehicle models: Vehicle A, Vehicle G, Vehicle M, Vehicle C, Vehicle K, and Vehicle F. One rig of each model pair was aged on E10, while the other was aged on $E20_A$. On Vehicle A, the only notable difference between the two rigs was that the $E20_A$ rig's fuel filler neck was stiffer and the inner wall material was discolored compared to the E10 Vehicle A Rig. The Vehicle G $E20_A$ rig had a very soft and pliable fuel pump seal compared to the Vehicle G E10 rig. The Vehicle M $E20_A$ rig's fuel filler hose inner wall material seemed to be affected by the test fuel. The material was shiny, somewhat sticky, and could be removed with one's finger, while the Vehicle M E10 rig's fuel filler neck inner wall was shiny but not sticky and could not be removed with one's finger. There were no notable differences with Vehicle C. The Vehicle K $E20_A$ rig's FLVV seal was swollen but did not leak. The Vehicle F $E20_A$ rig's fuel delivery module seal had signs of cracking around the edges, and there appeared to be some loss of physical properties compared to the Vehicle F E10 rig. Clearly more extensive testing on fuel rigs would be required to determine if any failures will occur in fuel pump seals, filler hoses, or other fuel system components.

Fuel Pumps

After an initial pilot program designed to identify pumps that may be affected by $E20_A$, fuel pumps were further tested through two different test procedures: soak durability testing and endurance aging testing. The soak durability testing evaluated the fuel pumps' response to longer term exposure to the $E20_A$ while the pump was in a static condition. Each pump was soaked for 8 to 12 weeks at 60°C with fuel pump flow performance evaluated weekly for the first eight weeks and then at the end of twelve weeks. Table VIII.1 summarizes the results.

Table VIII.1. Fuel Pump Soak Durability Summary of Results

	Test Fuel		
Vehicle	**E20$_A$**	**E10**	**E0**
Vehicle K	- 2.8% (1 pump)	N/A	N/A
Vehicle C	+ 7.5% (1 pump)	N/A	N/A
Vehicle F	- 3.2% (1 pump)	N/A	N/A
Vehicle M	- 15% (5 pumps)	- 14% (4 pumps)	- 18% (3 pumps)
Vehicle G	- 3% (1 pump)	- 0.5% (1 pump)	N/A
Vehicle H	+ 2.9% (1 pump)	N/A	N/A
Vehicle A	- 11.5% (1 pump)	N/A	N/A
Vehicle D	+ 1.2% (1 pump)	N/A	N/A
Vehicle L	+ 0.5% (1 pump)	N/A	N/A
Vehicle N	- 12% (1 pump)	- 18% (1 pump)	N/A

No negative impact of ethanol on pump performance could be determined from the soak durability test data. None of the pumps tested exhibited a flow decline in excess of the failure metric, a loss in flow capacity on the order of 30%.

The endurance aging protocol evaluated potential fuel pump failure mechanisms resulting from continuous operation. The pumps were aged to 3,000 hours of continuous operation at temperatures varying between 40°C and 60°C. The results are summarized in Table VIII.2.

Table VIII.2. Fuel Pump Endurance Aging Summary of Results

Vehicle	Test Fuel E20$_A$	E10	E0
Vehicle C	- 2.2% (1 pump)	N/A	N/A
Vehicle K	- 5.4% (1 pump)	+ 0.3 % (1 pump)	N/A
Vehicle F	- 1.6% (1 pump)	N/A	N/A
Vehicle M	- 3.2% (1 pump)	N/A	N/A
Vehicle G	- 15.1% [a] (2 pumps)	- 3.9% [b] (1 pump)	- 2.8% (1 pump)
Vehicle A	- 58.8% [c] (2 pumps)	- 43.3% (2 pump)	- 21.9% (1 pump)
Vehicle L	- 12.8% (1 pump)	Incomplete [d] (1 pump)	N/A
Vehicle N	- 12.7% (1 pump)	N/A	N/A

[a] Phase 1 E20$_A$ pump failed due to procedural error. Post-test analysis showed melted impeller and charring suggesting pump had run dry. Failure not considered fuel related.

[b] Phase 2 E10 pump failed due to excessive debris in test fuel. Post-test analysis showed melting in brush/commutator section - most likely due to clogged inlet screen. Failure not considered fuel related.

[c] Although three pumps were tested in E20$_A$ fuel, one pump failed during test due to high resistance at the brush-commutator interface caused by formation of brush deposits – either chloride or sulfate – consistent with addition of ethanol to gasoline. This observation is based on post-mortem analysis in the vehicle manufacturer's fuel pump lab.

[d] Phase 2 E10 pump failed due to handling error. Plastic piece from fuel pump module flange entered fuel line during flow testing.

The overall average trend from this limited data set showed increased flow loss with E20$_A$ test fuel compared to both E10 and E0 test fuels. No conclusions can be drawn, due to the limited data set and numerous non-fuel related failures. However, the observed trends suggest that additional testing with a statistically robust dataset might be instructive.

Fuel Level Senders

Fuel level senders were tested through two different aging protocols, a fuel resistance protocol and a full sweep aging protocol. The fuel resistance aging involved moving the powered level senders in and out of test fuel at one to two seconds per cycle for 250,000 cycles, then soaking unpowered for one week. This process was repeated until one million cycles and four weeks of soak had been accumulated. Eight different models of level senders were tested before and after aging to determine if their output signal had changed. The full sweep aging protocol involved cycling the powered level senders in and out of fuel at a rate of one to two seconds per cycle for five million cycles. The same eight models tested in the fuel resistance protocol were also tested in the full sweep protocol. Their results are summarized in Table VIII.3.

Table VIII.3. Level Sender Summary of Results

Summary of Results

Vehicle	Test Mode	Results $E20_A$	E10	E0	Comments
Vehicle A	Fuel Resistance Full Sweep	Noise Noise, opens	OK Noise	Not Tested	Bad resistance data in E20a fuel
Vehicle N	Fuel Resistance Full Sweep	Signal Shift Repeats OK Signal Shift, Noise, Opens,	Minor Noise Repeats OK Noise, Opens, Repeats OK	OK	
Vehicle M	Fuel Resistance Full Sweep	OK OK	Not Tested OK	Not Tested	
Vehicle C	Fuel Resistance Full Sweep	Opens, Noise on repeats Noise, Opens	OK, OK on repeats Noise	OK	
Vehicle L	Fuel Resistance Full Sweep	OK Failed Repeats OK	Not Tested OK Repeats OK	Not Tested OK	Failure due to burned resistor
Vehicle K	Fuel Resistance Full Sweep	Failed Open Minor Noise	Failed Open OK	Not Tested	Failures due to burned/shorted section of card
Vehicle F	Fuel Resistance Full Sweep	Open at top end OK at midpoint	OK Not Tested	Not Tested	Full Sweep EOT data missing due to broken arm
Vehicle G	Fuel Resistance Full Sweep	OK OK	Not Tested	Not Tested	

After the initial round of testing, eight Vehicle N level senders were purchased and tested in the fuel resistance program utilizing $E20_A$, E10, and E0 test fuels. As can be seen in the summary in Table VIII.1, none of these repeats showed any signal degradation across any of the fuels. An additional eight Vehicle N level senders were tested through the full sweep protocol, again utilizing all three test fuels. One of the level senders aged on $E20_A$ showed open circuits at the end of aging while the remainder of those aged on $E20_A$, E10, and E0 did not exhibit any open circuits. Repeat testing was also performed utilizing eight Vehicle C level senders. Three of the four Vehicle C tests on $E20_A$ were noisy while the E10 and E0 tests were without issues. Four Vehicle L level senders also underwent repeat testing with one of the two tests on $E20_A$ showing a slight increase in signal noise with no signal defects on the E0 or E10 tests. Although this testing was not exhaustive, the level senders were clearly affected by $E20_A$ and more testing could quantify the frequency of the effects observed.

Fuel Dampers

Since this was a scoping study, only two fuel dampers of the same part number were tested; they were from Vehicle O. The dampers were tested for dynamic response and then they were both soaked for 120 hours at 120°F while filled with $E20_A$. After the soak period, they were tested again for dynamic response. The results were reviewed by experts at the manufacturer who determined that no significant difference existed between the initial dynamic response and the aged response. Additional testing performed on fuel dampers from different vehicle makes and models could have different results.

Fuel Injectors

The three fuel injectors chosen to be tested were all 12-hole injectors: Vehicle B, Vehicle E, and Vehicle I. Four injectors of each model were tested simultaneously. This testing, which utilized the OEM fuel rail, involved cycling the injectors on and off with a pulse width of 2.5 milliseconds for a period of 5.0 milliseconds for a total of 600 million cycles while the rail and injectors were pressurized with $E20_A$. Static and dynamic flow tests were performed prior to aging and at every 100 million cycles. All of the injectors showed some reduction in flow, but none of the manufacturer representatives deemed the flow reductions significant. While these three injector models did not show any $E20_A$ compatibility issues, many other models of injectors are presently in use where susceptibility is unknown.

Since this was a scoping study, the findings should only be used to identify areas for additional testing. This study was never considered to be comprehensive or an exhaustive determination of fuel system component compatibility. Lack of failure cannot be interpreted as predicting no impact in any vehicle in the field, only that the frequency of occurrence is not expected to be very high. Likewise a failure in these tests does not imply that a similar failure in customer vehicles is certain, but it does indicate there is risk that such a failure could occur. Further testing would be prudent to better understand the effects of >E10 upon wetted fuel system components.