CRC Report No. 664

DURABILITY OF FUEL PUMPS AND FUEL LEVEL SENDERS IN NEAT AND AGGRESSIVE E15

CRC Contract No. AVFL-15a

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COORDINATING RESEARCH COUNCIL, INC.
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LIST OF ACRONYMS

ASTM..... ASTM International, formerly known as American Society for Testing and Materials
AVFL ..... CRC Advanced Vehicle / Fuel / Lubricants Committee
CRC..... Coordinating Research Council, Inc.
EPA ..... U. S. Environmental Protection Agency
in-lb ..... Inch-pounds
OBDII..... On-Board Diagnostics, two
OEM..... Original equipment manufacturer
RFS2..... EPA Renewable Fuel Standard 2
TSG ..... Testing Services Group
μm ..... Micrometer
MΩ ..... Mega Ohm

Preface

The Advanced Vehicle/Fuel/Lubricants Committee of the Coordinating Research Council, Inc. retained the services of The Testing Services Group, LLC (TSG, Lapeer, MI) to conduct a series of experiments that evaluated the compatibility and durability of fuel pumps and fuel level senders in mid-level ethanol blends under CRC Project No. AVFL-15a. This project was an extension of contract work conducted under CRC Project No. AVFL-15. The TSG contract for AVFL-15a was active from April 2011 to October 2012. Gage Products Co. of Ferndale, MI provided test fuels for the study. This report presents analyses of the AVFL-15a data collected by TSG. Documentation of testing protocols and results were provided by TSG staff, and the data analysis report presented here was prepared by the AVFL-15a Project Panel members listed in Appendix A1.

Executive Summary

This report describes an extension of an earlier scoping study that investigated how gasoline containing 20 percent ethanol by volume (E_{20}) might affect wetted automotive fuel system components such as pumps, dampers, level senders, and injectors. The scoping project (CRC Project No. AVFL-15) was used to identify areas where further testing should be performed. This study (CRC Project No. AVFL-15a) was designed to add depth to those initial findings, and explore potential impacts of gasoline containing 15 percent ethanol by volume (E_{15}). Both projects were conducted under the direction of the Advanced Vehicle/Fuel/Lubricants (AVFL) Committee of the Coordinating Research Council (CRC).

The primary test fuels for this study were E_{15} and an aggressive blend of E_{15} (E_{15a}). E_{15a} was formulated referencing the SAE specification J1681 to represent the worst case blends of gasoline and 15 volume percent ethanol that might be found in the field. E_{10} and E_0 test fuels were also incorporated into this study in a second phase as reference points to assess the relative performance of the E_{15} and E_{15a} test blends. Automobile manufacturers were contacted at the start of the scoping study in order to develop a candidate list of vehicles for testing. Based on manufacturer suggestions, 15 designs from different manufacturers spanning the 1996 to 2009 model years were selected. It is estimated that the design selections from the original scoping study represented at least 37 million vehicles with components and systems similar in construction and materials. Based on the scoping study, several fuel pumps and fuel level senders were selected for testing in the current work. The subset of parts used in the current work represents approximately 29 million 2001-2007 vehicles.

Table E.1 describes the test matrix and general content of the AVFL-15a Phase 1 study. Following completion of Phase 1, additional testing was conducted to provide context for the initial fuel pump results and to broaden the fuel types and fuel pump designs evaluated. The test matrix for Phase 2 is shown in Table E.2. Teardown analysis was done on the fuel pumps from both phases of the program.

The protocols for testing fuel pumps and senders - fuel pump endurance aging, soak durability, and tear down analyses; fuel level sender resistance and full sweep aging - followed the procedures used in the original scoping study. The testing procedures were based on existing SAE and USCAR protocols which are used in the automotive industry to predict new product life.

Table E.1. CRC Project No. AVFL-15a Phase 1 Test Matrix			
Test Protocol	**No. of Designs Tested**	**Test Articles per Design**	**Fuel Types**
Fuel Pump Testing			
Endurance Aging	2	6	E_{15} & E_{15a}
Soak Durability	2	6	E_{15} & E_{15a}
Fuel Level Senders			
Fuel Resistance	3	6	E_{15} & E_{15a}
Full Sweep	3	6	E_{15} & E_{15a}

Table E.2. CRC Project No. AVFL-15a Phase 2 Test Matrix			
Test Protocol	**No. of Designs Tested**	**Test Articles per Design**	**Fuel Types**
Fuel Pump Testing			
Endurance Aging	1	6	E_0
Soak Durability	3	6	E_0 E_{10} & E_{15a}

Two different test protocols were used to evaluate fuel pump performance. The soak durability testing evaluated the fuel pump's response to test fuels while in a static condition for 12 weeks interrupted only by eight, brief, flow tests. The endurance aging program investigated potential fuel pump failure mechanisms resulting from continuous operation. These pumps were aged for 3,000 hours of continuous operation at temperatures varying between 40° C and 60° C, interrupted only by three, brief, flow tests. 3,000 hours represents ~90,000 miles at a mean of 30 miles per engine hour; 30 miles per engine hour is an approximate conversion that comprehends engine time at idle, driving at lower city speeds and at higher highway speeds (see also reference **E1)**.

Fuel level senders were tested using two different protocols: a fuel resistance aging protocol and a full sweep aging protocol. The fuel resistance aging involved cycling the powered level senders in test fuel at one to two seconds per cycle for 250,000 cycles, followed by 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 test fuel at a rate of one cycle per second for five million cycles.

Results from this study showed that the pump soak test could discriminate the interaction of fuel pumps with test fuel. Some pump design - fuel combinations had no deviations in performance while other pump design-fuel combinations led to pump failures. One fuel pump model, currently in

use in the field, seized in almost every replicate of the pump soak test when either neat or aggressive E_{15} was used as test fuel, but pumps of this model did not fail on any replicate of the same test when either E_0 or E_{10} was used as test fuel. There are pump designs (currently in use in the field) that did not seize in the fuel pump soak test, but did exhibit statistically significant flow loss when tested with neat or aggressive E_{15}. While statistically significant, none of those pumps had sufficient flow loss that vehicle performance would degrade in ways customers would be likely to observe, nor was the flow shift statistically significantly different from the flow shift observed on E_0 fuel.

The pump endurance test could sort fuel pumps by their interaction with test fuel; some pump design-fuel combinations had no deviations in performance while other pump design-fuel combinations led to pump failure. One fuel pump model, currently in use in the field, seized in almost every replicate of the pump endurance test when either neat or aggressive E_{15} was used as test fuel, but did not fail on any replicate of the same test when E_0 was used as test fuel. Another design of pump, currently in use in the field, was not impacted by mid-blend ethanol in the endurance test. Exposure to E_{15} or aggressive E_{15} caused dimensional changes in all impellers. Depending on pump model, the standard deviation of thickness was approximately 2 to 27 times greater in E_{15} than in E_0 at the end of the soak test.

The tests showed issues with the performance of the fuel level senders when tested with the E_{15} and E_{15a} blends. Both the E_{15a} and E_{15} blends had three instances of significant signal defects. The significant signal defects experienced (consumer observable resistance spikes) could potentially cause interference with proper OBDII function. While not consistent and not found in all samples tested, the results indicate some effect of the E_{15} and E_{15a} blends on sender operation.

This study in conjunction with the prior scoping study has found that some fuel systems in modern vehicles survive testing in mid-blend ethanol fuels, while others will experience complete failures that would prevent operation. The fuel pumps and level senders that failed or exhibited other effects during testing on E_{15} and E_{15a} are used on a substantial number of the 29 million 2001 – 2007 model year vehicles represented by the components evaluated in this report.

I. Background

The possibility of increasing the ethanol concentration in motor gasoline has been suggested as a way to meet Renewable Fuel Standard 2 (RFS2) requirements. Various philosophical and technical grounds for support or opposition to this change have been offered, and an increasing amount of data is emerging on the impact of higher ethanol content in gasoline. While the studies published to date provide some perspective on the positive and negative impacts of E_{20} (where the subscript designates the percent by volume ethanol blended with unleaded gasoline) and E_{15}, there has been little independent reproduction of published results, and gaps in the published literature remain as well **[1-5].**

The durability of wetted fuel system parts was probed in the Coordinating Research Council (CRC) Report Number 662 **[1].** The screening study documented in that report covered a spectrum of fuel system components exposed to E_{20}; individual components were tested in addition to full fuel systems. That work concludes that E_{20} fuels do negatively impact a subset of fuel-wetted parts, while other fuel-wetted parts showed no effect in screening. However, all the conclusions in **[1]** are based on single or in some cases duplicate tests of a particular component/fuel interaction. A failure in a single test raises concern that vehicles in the field will at some point begin to experience similar failures. As a rule of thumb, original equipment manufacturers (OEMs) expect part failures to occur at less than one per thousand vehicles, so a part failure in a single test is highly worrisome. Nonetheless it is possible that such a failure is a random event that results from the chance influence of an uncontrolled variable in the experiment. Furthermore, a single point test cannot give a quantitative indication of the expected frequency of occurrence, only that the data suggests (but does not prove) that the observed event is fairly likely.

II. Technical Approach

In this report we investigate the interaction between E_{15} and components that exhibited some degree of sensitivity to E_{20} in reference 1. All tests were conducted at TSG, a well-known, independent test lab in the Detroit suburbs. Specifically, we seek to identify the effect of E_{15} fuel relative to the effect of gasoline with no ethanol (E_0), and to define the difference with greater confidence. While there had been discussion of a waiver for E_{20}, ultimately the US Environmental Protection Agency (EPA) set a maximum ethanol concentration of 15% in its waiver ruling **[6].** We chose to focus the present study on components identified in **[1]** as potentially sensitive to mid-blends; this strategy reduced the number of types and makes of components to test and thus allowed more replicates of each

component to be evaluated. In addition, some components that did not exhibit a response to fuel composition in **[1]** were also tested in replicate to more completely determine if they might be sensitive to mid-blend ethanol fuel but to a lesser extent.

In this program, six replicates of each component were tested in E_{15} and another six replicates were tested in E_{15a} (an aggressive version of E_{15}, defined below). Taking a 95% probability as acceptable, if none of the 12 parts fail in the testing, the true failure rate of that type of part could still be just over 4.2 per 1000. In truth, since the aggressive blend is designed to further enhance the failure rate, the actual failure rate due to E_{15} alone would be even lower, but as we cannot quantify that amount in this work, the safest statement would be that if the rate is lower than 4.3 per 1000 then there is at least a 95% probability no failures will be observed in twelve tests. If both 15% ethanol and the impurities in the E_{15a} blend are required together to cause a failure, but no failure is observed in those six tests, then the expected true failure rate would be less than 8.5 per 1000. Neither the 8.5 failures per 1000, nor the 4.2 failures per 1000 would be acceptable in the auto industry, but at least this level of replicate testing should give better confidence that wholesale failure will not go undetected.

On the other hand, if a response to the independent variable is observed in multiple replicate tests, it indicates that indeed the event is likely to occur in the field at a very significant rate. At a true failure rate of 93 per 1000, there is a one in ten chance of observing multiple failures in six trials, and obviously at higher true failure rates the odds of observing multiple failures increase. If every part in six replicate tests failed, then there is a 95% probability that the true failure rate is above 99%. Whatever the number of failures, if more than one failure is observed out of the six replicate tests, we can say that the particular test fuel causes failure rates in the tested component that would be highly unacceptable in the auto industry.

a. Tests

Based on the results in **[1]**, four different tests were chosen for more extensive study, the fuel pump soak test, the fuel pump endurance test, the fuel sender card full sweep, and the fuel sender card soak tests. Table 1 lists the full testing program undertaken in this project. Within each of these four tests, the candidate parts evaluated were limited to those that showed some indication of sensitivity in **[1]**. However, in some cases an additional part was tested to determine if it was sensitive to ethanol content. Because of this narrow focus, the results of these tests cannot be extrapolated to represent the entire light-duty vehicle on-road fleet. Rather this research is meant to determine with greater precision whether some high-sales-volume vehicle-models are at risk of part failure if E_{15} is used as fuel. To

facilitate comparison to the tests in **[1]**, the same part naming convention is used. For example, fuel pump 'M' in this research designates the same year and model of pump reported in **[1]** as pump 'M'. In all tests new, unused parts were used.

b. Vehicle Models

The parts are all derived from well-known vehicles with significant light-duty vehicle on-road fleet penetration of more than 29 million vehicles; this compares to 37 million vehicles represented in the initial program **[1].** Some of the parts are shared with other vehicle models. The following models are represented in one or more tests reported here. Alphabetically they are: 2007 Nissan Altima, 2001 Chevrolet Cavalier, 2004 Ford Focus, 2003 Nissan Maxima, and the 2004 Ford Ranger.

Table 1. Test program.

Test	**Models tested**	**# of tests using E_0**	**# of tests using E_{10}**	**# of tests using E_{15}**	**# of tests using E_{15a}**
Fuel pump soak test	L M N	6 6 6	0 0 6	0 6 6	6 6 6
Fuel pump endurance test	A L	6 0	0 0	6 6	6 6
Sender resistance test	C L N	0 0 0	0 0 0	6 6 6	6 6 6
Sender full-sweep test	C L N	0 0 0	0 0 0	6 6 6	6 6 6

c. Fuels

Four fuels were used in component testing: E_{15} – an ethanol mid-blend with unleaded gasoline, E_{15a} - an aggressive ethanol mid-blend derived from the E_{15}, E_{10} – a standard ethanol blend with unleaded gasoline, and E_0 - an unleaded gasoline. All fuels were produced by Gage Products in single batches and shipped in drums to an indoor storage facility at Bay Logistics. Fuel drums were collected and brought to TSG in advance of testing and stored there in a shed until used. The E_{10} fuel was generated by blending two parts E_{15} with one part E_0. The blended E_{10} was then stored in sealed drums until needed.

The aggressive ethanol was produced using the same protocols and specifications as reference 1 (AVFL-15), i.e. ASTM 4806 and SAE J1681. It is a worst-case test fuel based on impurities observed in field samples of ethanol blends. Aggressive fuel increases the chances of finding impacts

with a small sample size while using recognized, appropriate fuel chemistry. This approach is similar to that taken in some of the studies cited in the Growth Energy E15 waiver request, and in reference 1. The resulting aggressive ethanol contained approximately 10 ppm_{mass} chloride ions, 4 ppm_{mass} sulfate ions, and 1% water. Table 2 summarizes the blend definition of aggressive ethanol. For a more in-depth discussion, see **[1]**, SAE J1681 and ASTM D4806-08a. Fuel acceptance data for the test fuels follow in Tables 3-6 (blender certificates of analysis are included in Appendix A12). The program was run in two phases; fuel was bought for each segment separately.

Table 2. Aggressive ethanol definition.

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

Table 3. Acceptance data E_{15} test fuel.

Property	Test method	UOM	Specification	Value
Specific Gravity @ 60°F	ASTM D4052	Report	Report	0.7662
RVP @ 100°F	ASTM D5191	PSI	Report	8.37
Ethanol	ASTM D6730	Vol.%	14.70 - 15.30	14.83
Distillation, IBP	ASTM D86	Deg F	Report	103.6
Distillation, 5%	ASTM D86	Deg F	Report	123.4
Distillation, 10%	ASTM D86	Deg F	Report	132.1
Distillation, 20%	ASTM D86	Deg F	Report	144.0
Distillation, 30%	ASTM D86	Deg F	Report	153.1
Distillation, 40%	ASTM D86	Deg F	Report	159.6
Distillation, 50%	ASTM D86	Deg F	Report	169.0
Distillation, 60%	ASTM D86	Deg F	Report	233.1
Distillation, 70%	ASTM D86	Deg F	Report	251.6
Distillation, 80%	ASTM D86	Deg F	Report	275.2
Distillation, 90%	ASTM D86	Deg F	Report	322.0
Distillation, 95%	ASTM D86	Deg F	Report	353.5
Distillation, DP	ASTM D86	Deg F	Report	403.9
Recovery	ASTM D86	Vol.%	Report	97.7
Residue	ASTM D86	Vol.%	Report	1.0
Loss	ASTM D86	Vol.%	Report	1.3

Table 4. Acceptance data E_{15a} test fuel.

Property	Test method	UOM	Specification	Value
Water Content	ASTM E1084	Vol. %	1, max.	0.145
Peroxide Content	ASTM D3703	PPM	Report	2.68
Acid Number	ASTM D974	mg KOH/g	Report	0.0017
RVP @ 100°F	ASTM D5191	PSI	Report	8.41
Total Sulfur	ASTM D5463	PPM	Report	14.41
Ethanol	ASTM D6730	Vol. %	14.70-15.30	14.70
Inorganic Chloride Content	Ion Chromatography	PPM	Report	1.63
Nitrate Content	IC	PPM	Report	2.34
Total Sulfate Content	Ion Chromatography	PPM	Report	0.51
Specific Gravity @ 60°F	ASTM D4052	Report	Report	0.7658
Aromatics	ASTM D6730	Vol. %	Report	34.6
Olefins	ASTM D6730	Vol. %	Report	4.3
Saturates	ASTM D6730	Vol. %	Report	46.4
Benzene	ASTM D6730	Vol. %	Report	0.31
Toluene	ASTM D6730	Vol. %	Report	14.9
Distillation, IBP	ASTM D86	Deg F	Report	102.2
Distillation, 5%	ASTM D86	Deg F	Report	122.0
Distillation, 10%	ASTM D86	Deg F	Report	136.0
Distillation, 20%	ASTM D86	Deg F	Report	143.2
Distillation, 30%	ASTM D86	Deg F	Report	152.8
Distillation, 40%	ASTM D86	Deg F	Report	159.4
Distillation, 50%	ASTM D86	Deg F	Report	166.1
Distillation, 60%	ASTM D86	Deg F	Report	232.2
Distillation, 70%	ASTM D86	Deg F	Report	251.4
Distillation, 80%	ASTM D86	Deg F	Report	275.9
Distillation, 90%	ASTM D86	Deg F	Report	319.8
Distillation, 95%	ASTM D86	Deg F	Report	352.9
Distillation, DP	ASTM D86	Deg F	Report	399.6
Recovery	ASTM D86	Vol.%	Report	97.7
Residue	ASTM D86	Vol.%	Report	1.0
Loss	ASTM D86	Vol.%	Report	1.3

Table 5. Acceptance data E_0 used for flow test fuel.

Property	Test method	UOM	Specification	Value
Research Octane Number	ASTM D2699	RON	Report	91.5
Motor Octane Number	ASTM D2700	MON	Report	82.1
Specific Gravity @ 60°F	ASTM D4052	Report	Report	0.7627
RVP @ 100°F	ASTM D5191	PSI	Report	7.43
Total Sulfur	ASTM D5453	PPM	80, max.	16.4
Oxidation Stability	ASTM D525	min.	240, min.	>960
Aromatics	ASTM D6730	Vol. %	Report	41.2
Olefins	ASTM D6730	Vol. %	Report	5.2
Saturates	ASTM D6730	Vol. %	Report	52.7
Benzene	ASTM D6730	Vol. %	Report	0.3
Toluene	ASTM D6730	Vol. %	Report	18.8
Distillation, IBP	ASTM D86	Deg F	Report	98.8
Distillation, 5%	ASTM D86	Deg F	Report	126.0
Distillation, 10%	ASTM D86	Deg F	Report	139.8
Distillation, 20%	ASTM D86	Deg F	Report	163.6
Distillation, 30%	ASTM D86	Deg F	Report	187.2
Distillation, 40%	ASTM D86	Deg F	Report	209.3
Distillation, 50%	ASTM D86	Deg F	Report	228.2
Distillation, 60%	ASTM D86	Deg F	Report	244.0
Distillation, 70%	ASTM D86	Deg F	Report	261.7
Distillation, 80%	ASTM D86	Deg F	Report	286.3
Distillation, 90%	ASTM D86	Deg F	Report	329.9
Distillation, 95%	ASTM D86	Deg F	Report	360.7
Distillation, DP	ASTM D86	Deg F	Report	405.1
Recovery	ASTM D86	Vol.%	Report	97.5
Residue	ASTM D86	Vol.%	Report	1.2
Loss	ASTM D86	Vol.%	Report	1.3
Nitrogen	ASTM D4629	PPM	Report	14
Mercaptans	ASTM D3227	PPM	Report	3
Silver Corrosion	ASTM D130	Corrosion	1, max.	0
Copper corrosion	ASTM D130	Copper corr.	1, max.	1A
Existent gum (washed)	ASTM D381	mg/100 ml	5, max.	<0.5

Table 6. Acceptance data E_0 used as soak test fuel.

Property	Test method	UOM	Specification	Value
Research Octane Number	ASTM D2699	RON	Report	93.8
Motor Octane Number	ASTM D2700	MON	Report	84.0
Specific Gravity @ 60°F	ASTM D4052		Report	0.7603
RVP @ 100°F	ASTM D5191	PSI	Report	10.53
Total Sulfur	ASTM D5453	PPM	80, max.	10.13
Oxidation Stability	ASTM D525	min.	240, min.	1440
Aromatics	ASTM D6730	Vol. %	Report	41.4
Olefins	ASTM D6730	Vol. %	Report	5.0
Saturates	ASTM D6730	Vol. %	Report	52.8
Benzene	ASTM D6730	Vol. %	Report	0.326
Toluene	ASTM D6730	Vol. %	Report	12.80
Distillation, IBP	ASTM D86	Deg F	Report	85.8
Distillation, 5%	ASTM D86	Deg F	Report	111.5
Distillation, 10%	ASTM D86	Deg F	Report	127.4
Distillation, 20%	ASTM D86	Deg F	Report	158.2
Distillation, 30%	ASTM D86	Deg F	Report	190.4
Distillation, 40%	ASTM D86	Deg F	Report	219.3
Distillation, 50%	ASTM D86	Deg F	Report	242.3
Distillation, 60%	ASTM D86	Deg F	Report	262.5
Distillation, 70%	ASTM D86	Deg F	Report	283.5
Distillation, 80%	ASTM D86	Deg F	Report	308.1
Distillation, 90%	ASTM D86	Deg F	Report	329.3
Distillation, 95%	ASTM D86	Deg F	Report	343.6
Distillation, DP	ASTM D86	Deg F	Report	392.2
Recovery	ASTM D86	Vol.%	Report	97.1
Residue	ASTM D86	Vol.%	Report	1.0
Loss	ASTM D86	Vol.%	Report	1.9
Nitrogen	ASTM D4629	PPM	Report	8.4
Mercaptans	ASTM D3227	PPM	Report	3.0
Silver Corrosion	ASTM D130	Corrosion	1, max.	0
Copper corrosion	ASTM D130	Copper corr.	1, max.	1A
Existent gum (washed)	ASTM D381	mg/100 ml	5, max.	<0.5

III. Results and Discussion

a. Fuel Pump Soak Tests

Fuel pump soak tests were conducted according to the procedure developed in the AVFL-15 program **[1].** Briefly, the pump was flowed using unleaded gasoline (E0) to establish the baseline. It was then filled with test fuel and placed in a sealed container at a fixed 60º C temperature. At weekly intervals, the pump was removed and the test fuel in the container renewed. At this same time the fuel

flow rate was determined. The pump was then reloaded with test fuel and returned for further soaking. After eight weeks, the pump then underwent an uninterrupted four week soak (with a change of fuel at the midpoint) to complete the 12 week test. Details of the process are contained in Appendix A2 and in Appendix C of **[1]**.

Two pump designs from the AVFL-15 program were selected for further testing to better assess the significance of the results observed in that screening study. The two pumps ("M" and "N") were selected prior to completion of testing in the AVFL-15 program. Both pump designs are found on vehicles that were made by major OEMs and sold widely in the United States. Because the test procedure had already been validated in the AVFL-15 program, testing began on the E_{15} and aggressive E_{15a} fuels. Only if these fuels produced significant results would the reference test in E_0 or E_{10} be conducted to determine if the result was fuel related. One pump design ("N") did indeed show failures and was subsequently tested in both E_0 and E_{10}. The other pump design had no failures but manifested a change in flow and was subsequently tested in E_0 to determine if the result was both fuel-related and statistically different from fuel without ethanol.

At the time of the E_0 or E_{10} verification tests for pumps "N" and "M", it was decided to test a third pump design to broaden the program. This pump design was coded as "L" in the AVFL-15 program; it was tested on E_{15}, E_{15a} and E_0 simultaneously in the interest of timing.

Six pumps were tested for each combination of fuel and hardware. Each pump was soaked in its own sealed container. At the end of testing, the pumps were torn down (disassembled), and torque was measured on those for which the pump shaft failed to rotate. The basic parts of a fuel pump are shown for reference in Figure 1. The complete soak test results are provided in Appendix A3.

The most basic measurement of soak test performance is survival of the pump. Pump designs "M" and "L" all survived in both E_{15a} and E_{15}, while Design "N" generally failed by Week 5 in either fuel type (see Figure 2). The shafts on the failed pumps no longer rotated, and resistance measurements showed them to be in an open circuit condition (above scale on the MΩ range). In contrast, pumps of Designs "L", "M" and "N" that were tested in E_0 experienced no failures, and the pumps of Design "N" that were tested in E_{10} also all survived the soak test. These results appear to contrast with those of **[1]** and **[4]**. However different fuels were used, and in **[4]** a shorter test was used with different models. In this work, it is clear that some models of pump are more sensitive than others, and so it is not unusual that the shorter test in **[4]** found no failures. It is also clear that not all test articles of sensitive models fail, which may explain why the single Design "N" pump tested in **[1]** did not fail.

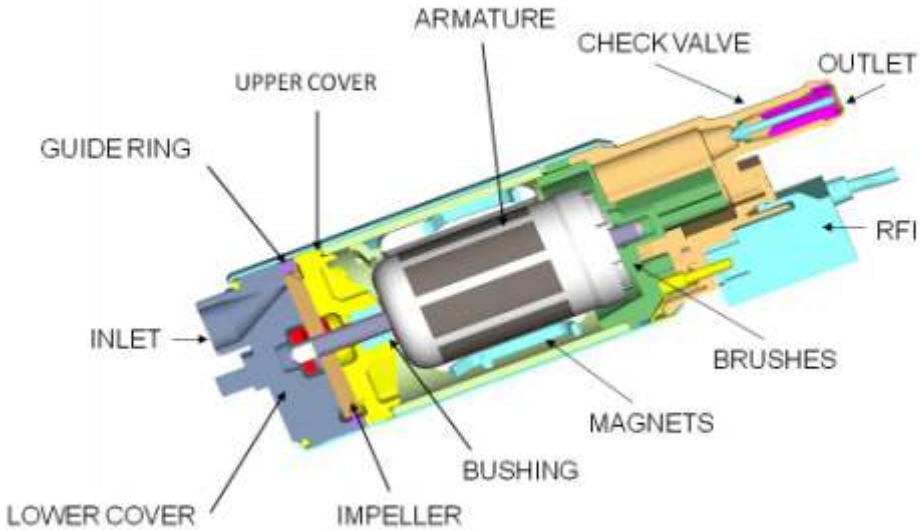


Figure 1. Cutaway diagram of a fuel pump: *The fuel pump internal parts are shown in this figure. The commutator permits power to reach the windings and spin the pump shaft. The impeller, mounted on the shaft, moves fuel into the fuel line.*

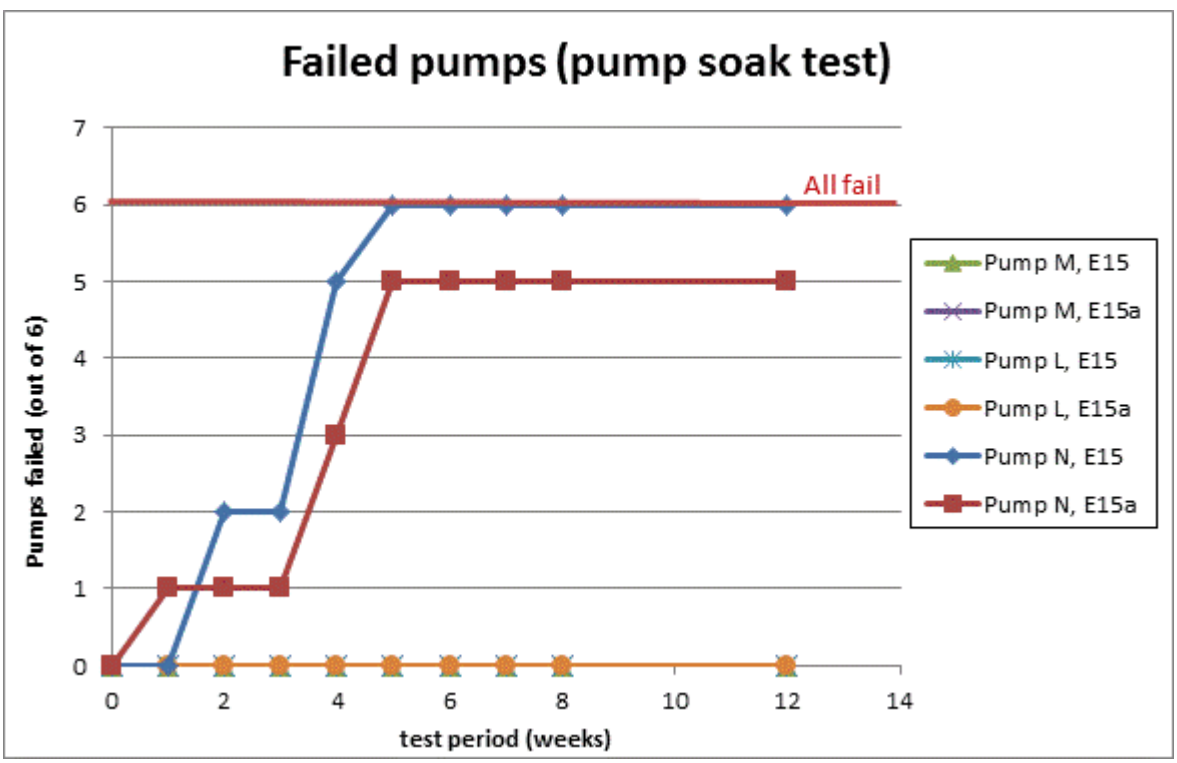


Figure 2. Survival of pumps in E_{15a} and E_{15}. *Pump designs "L" and "M" all survived the full 12 weeks of soak testing. Pump Design "N" experienced failures starting in week 1, with all but one pump failing by Week 5.*

For those pumps that survive, the next measure of performance is maintaining adequate flow rate over the duration of the test. The flow rate for all pumps was impacted by E_{15a} and, in some cases, appears to have been impacted by E_{15} as well, though to a lesser extent.

Figures 3-5 show the change in average flow rate for each design of pump over the test duration. With one exception, the data shown in each of these graphs represent averages over six pumps. In the case of the Design "N" pumps (Figure 4), the E_{15} and E_{15a} data at each time point represent the average of a progressively smaller cohort of survivors, reflecting the increase in pump failures from week to week (shown previously in Figure 2). For every fuel tested, some degradation appears to occur by the end of the test. However, the rate of degradation is statistically different from zero in only some of the tests. In establishing statistical significance, we use a fairly conservative 95% confidence criterion due to the number of test items. Degradation of flow in pumps tested with E_{15} or E_{15a} is not statistically significantly different from that observed with pumps soaked in E_0 fuel.

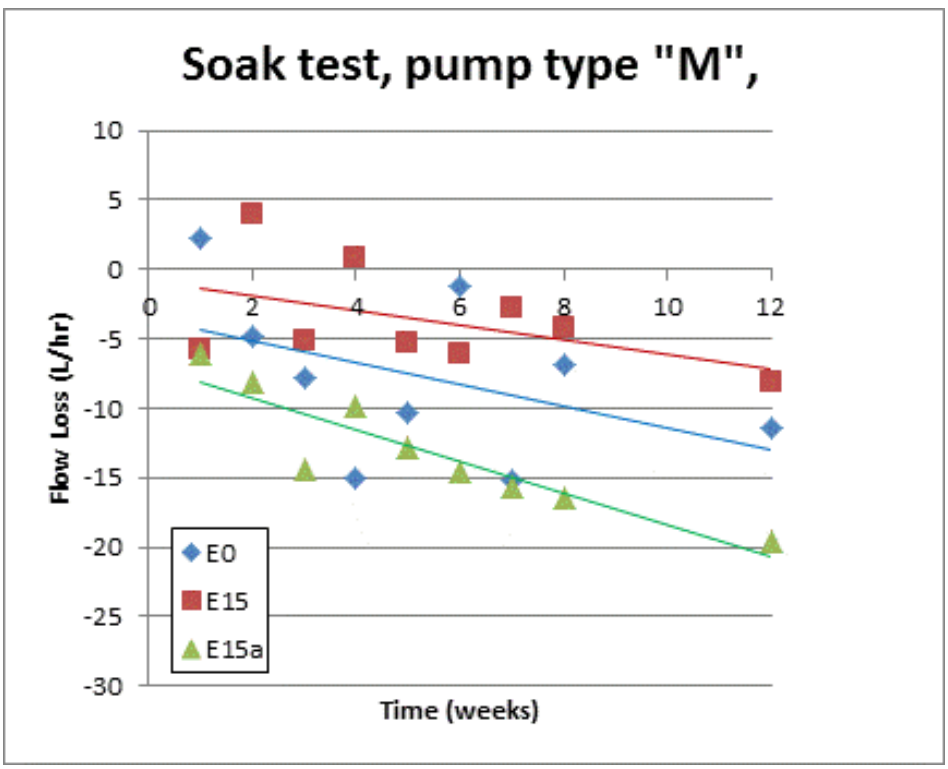


Figure 3. Average flow loss for pump Design "M". *Regardless of fuel, steady degradation in flow was observed over time, with E_{15a} causing the greatest loss.*

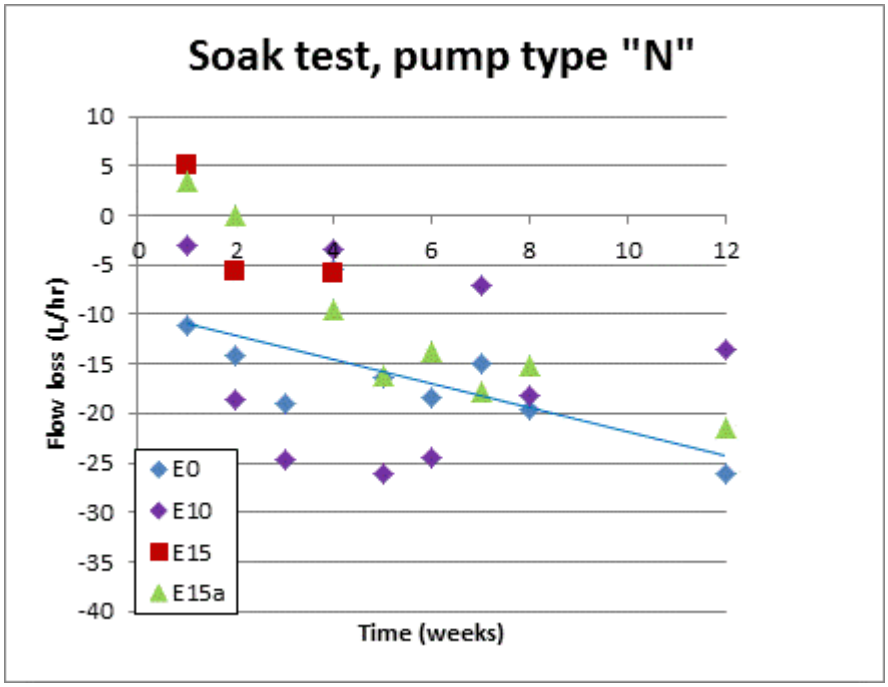


Figure 4. Average flow loss for pump Design "N". *This pump design exhibited a decline in flow for all fuels. Tests with E_0 show a relatively linear response after Week 1. Tests with E_{10} show continued degradation in flow but noisy data, tests with E_{15} exhibit decreased flow through Week 6 where all pumps failed, and tests with E_{15a} also show decreasing flow, though past Week 5, only a single pump is represented by the points.*

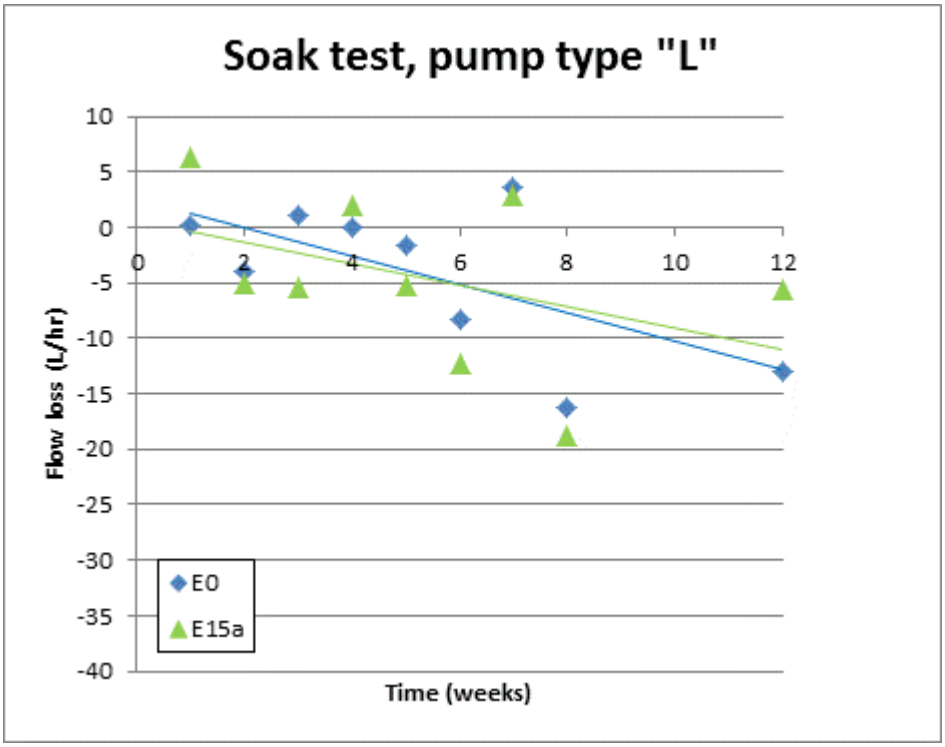
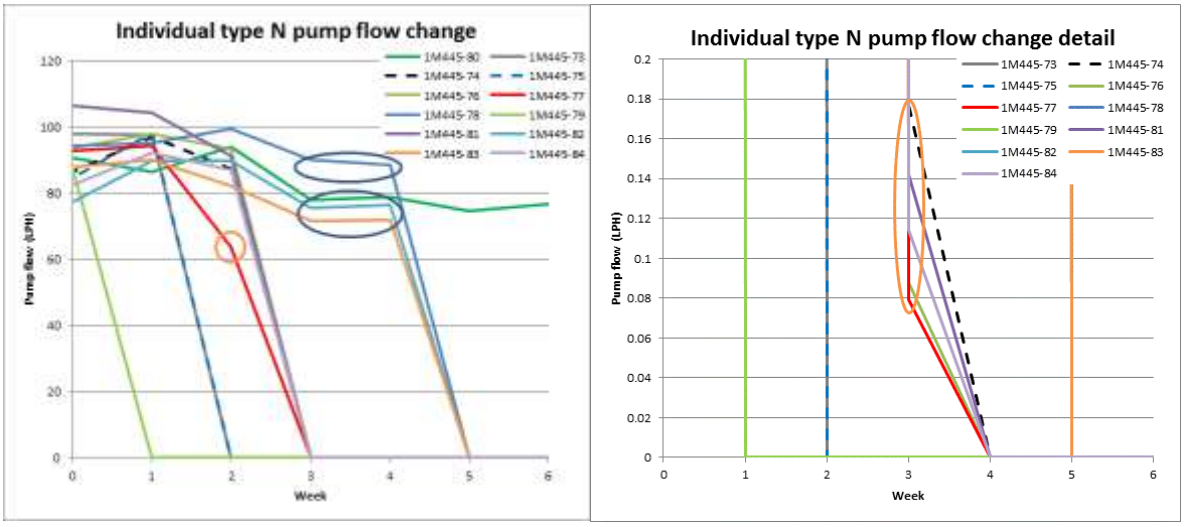


Figure 5. Average flow loss for pump Design "L". *Flow loss is about the same for each fuel, though the E_{15a} data has higher variance.*

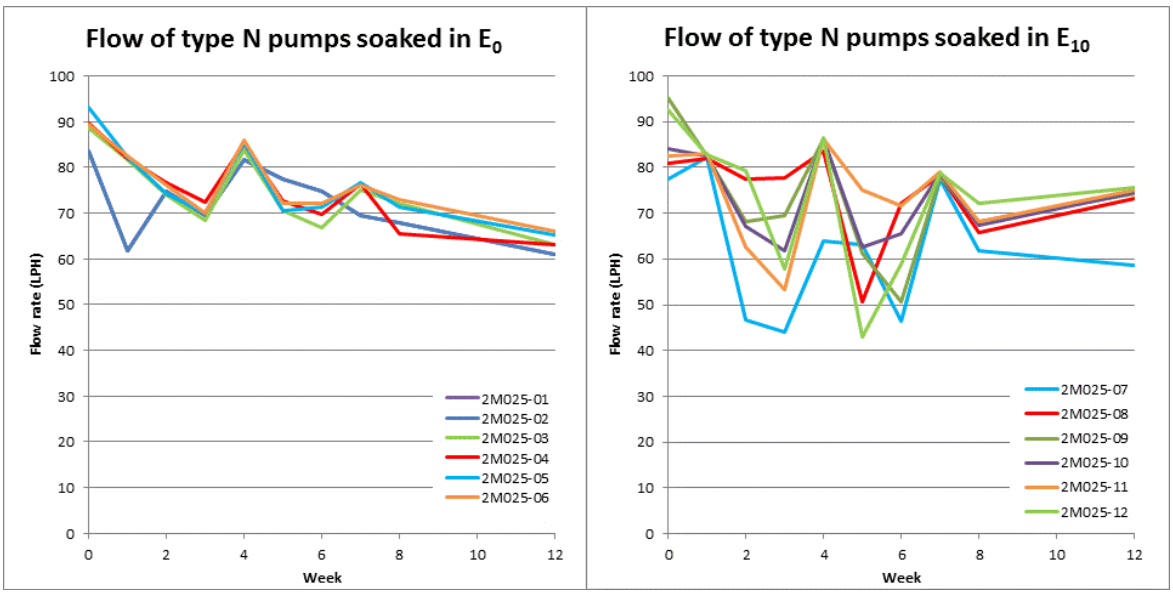
The flow degradation rate is statistically significant at 1.28 L/ (hr·week) (99% level) for Design "L" pumps in the E_0 tests. The E_{15a} tests appear to have similar response: a degradation rate of 0.97 is observed, but due to high variance, this is statistically significant only at the 90% level, which is below our conservative threshold value. Design "M" pumps exhibit a statistically significant (99% level) flow loss of 1.15L/ (hr·week) with E_{15a} fuel. In the E_{15} tests, the flow degradation rate of 0.54L/ (hr·week) is lower, but still significant (95% level). The flow degradation rate for the E_0 tests with pump Design "M" appears similar, but was not statistically different from zero at the 95% level due to variability in the data.

To understand the meaning of these flow shifts, it is critical to place them in proper context. During the break-in phase of a brand new fuel pump, in many cases it will exhibit a flow decline of up to 30%. **[1].** The pumps in this program were subjected to testing after experiencing only a short break-in period. Therefore, degradation in flow rate is expected as a natural part of the pump's early response to operation. In the AVFL-15 program, a 30% flow loss was used as the threshold for determining that the degradation was detrimental from an engineering perspective. None of the pumps that completed soak testing in the current study had an average flow loss greater than 30%.

It should be noted that this analysis measures only change in physical flow; it does not account for energy content or vapor formation. It is well understood that E_{15} fuel has both a lower volumetric energy content, and, at low temperatures, a lower vapor pressure than a typical, hydrocarbon-only gasoline. These factors can increase the impact of reduced flow on vehicle performance. Pump failures, on the other hand, are not a matter of degree, but are clearly unacceptable to consumers.
Mid-blend fuels caused failures in Design "N" pumps while E_0 and E_{10} did not. Looking at the data for individual pumps (Figures 6a and b), it is clear that some pumps soaked in mid-blend fuel suffered large week to week changes in flow rate prior to failure (from over 10% to more than 99%). It is possible that this behavior reflects increased rotation resistance due to fuel exposure. Figures 7a and 7b show that while there were no failures in E_{10}, nonetheless the variation is much higher than in E_0. This could be due to increased rotational resistance that is subsequently relieved by wear. There is no reason to believe the behavior in the E_{10} tests is an artifact; similar variation is not seen in E_0 tests performed simultaneously. However, there was no direct measurement of the resistance to rotation in the test protocol until teardown, so the torque required to turn the pump is unknown at these reduced flow points.



Figures 6a and 6b. Changes in Design "N" pump flow in E_{15}. *Figure 6a (left) shows that at least four Design "N" pumps had flow shifts of over 10% in the week or weeks prior to failure in the soak test. Figure 6b (right) is the same data presented to show only the very low flow regime. It can be seen that five of the 12 pumps tested had extreme low flow one week prior to complete cessation of flow.*



Figures 7a and 7b. Changes in Design "N" pump flow in E_0 and E_{10}. *Figure 7a (left) shows that in E_0 Design "N" pumps exhibit limited variability over a general flow decrease in the soak test. Figure 7b (right) shows significant flow losses followed by recovery for several pumps soaked in E_{10}. In some cases, this happened multiple times.*

This flow loss pattern in E_{15} is consistent with mid-blends causing swelling sufficient to cause the pump to stop rotating, at which point the windings would overheat. It is possible but unproven that the variability in E_{10} flow is due to rotational restriction that does not reach the point of seizing the pump. This condition might be alleviated by wear of the swollen part yielding good flow again.

To better understand the observed failures in the planned tests, three smaller scale tests were performed with additional fuels on pumps of Design "N"; the data are provided in Table 7. In each of these additional tests, the pumps were soaked in test fuel for four weeks with no interruption. In the first tests, four pumps were soaked in E_{15} and four more were soaked in E_{15a} fuel, but, prior to flow testing, the freedom of rotation of the fuel pump impeller was tested manually. The first pumps to be flow tested rapidly overheated, confounding the source of the high torque measured; accordingly the rest of the pumps were not flow tested so the torque represents only the resistance to rotation due to the exposure to test fuel. In the second set of tests, six pumps were soaked in E_{15a}, and the impeller rotation torque was measured with a torque screwdriver adapted to fit the pump shaft. In a third set of tests, eight pumps of Design "N" were soaked in the same E_{20} used in the AVFL-15 program.

In each case, most or all of the pumps failed. In the tests where torque measurements were made prior to flow testing, the torque rose from values too low to be measured prior to test (<0.44 inch-pounds), to an average of 2.4 in-lb in E_{15} tests and >12 in-lb in E_{15a} tests. This is a minimum five-fold increase in resistance to impeller rotation, and the increase probably is much greater since the initial value is too small to be accurately measured. When tested for flow, these pumps immediately seized and began to overheat. The resistance to rotation occurred *prior* to pump activation; it is critical to understand the heat evolved by the stalled pump did not cause the loss of free rotation, since the technician made the torque measurements and only then proceeded to flow testing. In E_{20}, the pumps were also all bound and not able to flow fuel. Clearly higher ethanol blends can cause changes in the Design "N" pumps that lead to either hindered or no rotation of the impeller.

b. Pump Teardown Tests

A final set of data comes from the teardowns. The teardown procedure measures the impeller thickness as an indicator of swell or shrinkage. The diameter is subject to wear which could impact measuring any trends, but there should be less wear in the thickness dimension, making it a better measure of dimensional change. The data are included in Appendix A4. The average and standard deviation of impeller thickness measurements were obtained, and the standard deviation was then divided by the standard deviation of the E_0 tests to provide a measure of the relative variability attributable to the presence of ethanol in the test fuel.

Table 7. Results of short term soak tests for Pump "N".

Test #	Fuel	Rotation torque (inch-pounds)	Pre-soak torque (inch-pounds)	Flow rate (LPH)	Soak time (weeks)
1M445-86	E_{15}	Seized	N/A	0	4
1M445-87	E_{15}	Seized	N/A	not flow tested	4
1M445-88	E_{15}	Seized	N/A	not flow tested	4
1M445-89	E_{15}	Seized	N/A	not flow tested	4
1M445-91	E_{15a}	Seized	N/A	0	4
1M445-92	E_{15a}	Seized	N/A	not flow tested	4
1M445-93	E_{15a}	Seized	N/A	not flow tested	4
1M445-94	E_{15a}	Seized	N/A	not flow tested	4
1M445-75	E_{15}	2.6	<0.44	not flow tested	4
1M445-76	E_{15}	1.7	<0.44	not flow tested	4
1M445-77	E_{15}	2.9	<0.44	not flow tested	4
1M445-79	E_{15a}	>12	<0.44	not flow tested	4
1M445-81	E_{15a}	>12	<0.44	not flow tested	4
1M445-84	E_{15a}	>12	<0.44	not flow tested	4
1M445-101	E_{20a}	Seized	N/A	not flow tested	4
1M445-102	E_{20a}	Seized	N/A	not flow tested	4
1M445-103	E_{20a}	Seized	N/A	not flow tested	4
1M445-104	E_{20a}	¼ inch movement	N/A	not flow tested	4
1M445-105	E_{20a}	Seized	N/A	not flow tested	4
1M445-106	E_{20a}	Seized	N/A	not flow tested	4
1M445-107	E_{20a}	Seized	N/A	not flow tested	4
1M445-108	E_{20a}	Seized	N/A	not flow tested	4

Complete data set, no data in appendix

Table 8 and Figure 8 show that impeller thickness variation is low in E_0, but significant variation occurs in gasoline containing ethanol and especially E_{15}. There is no clear impact of aggressive ethanol vs. non-aggressive ethanol on dimensional stability. In Figure 8 it is clear that very little dimensional variability occurs in any pump design when tested in E_0. This observation holds for

both the soak and the endurance tests. Table 8 numerically displays the Figure 8 data: column 7 provides the ratio of standard deviation for E_{10} or E_{15} to standard deviation for E_0. In every case, the variability in the mid-blend ethanol tests is at least 1.9 times as high as is observed in the E_0 tests. As shown in Figure 8, the single E_{10} test set lies just above the range of results for E_0, and at the bottom end of the range of results for E_{15}. Overall there is a trend of increasing variation in impeller thickness with increasing ethanol concentration in gasoline.

The greater variation in dimensions offers a possible explanation of the failures in pump Design "N" and in pump Design "A" under the endurance protocol, as we will soon see. There is no reason to believe the variation in impeller diameter would be any less than the thickness; indeed a greater absolute change is likely since the impeller is much wider than its thickness. Assuming a similar degree of variation, some, but not all impellers would increase in diameter and contact the housing. If the degree of swell was sufficient, the resulting friction would prevent rotation and the pump would rapidly overheat, as was observed. The clearance in these pumps is under 30 μm. The standard deviation of impeller thickness in Design "N" pumps tested using mid-blends was 17.7μm (0.64%) and in Design "A" pumps was 58μm (2.1%), while for the pumps tested in E_0, it was 5 to 7μm. Clearly,

Table 8. Standard deviation and average of impeller thickness.

Vehicle	test	Volume % ethanol	aggressive	Average (mm)	SD (mm)	Normalized variability (SD/average)	Ratio SD to E_0 test SD
A	endurance	0	--	2.817	0.0069	0.0024	--
A	endurance	15	N	2.809	0.0678	0.0241	9.85
A	endurance	15	Y	2.785	0.0483	0.0173	7.08
L	endurance	15	N	3.809	0.0174	0.0046	--
L	endurance	15	Y	3.839	0.0520	0.0135	--
N	soak	0	--	2.752	0.0066	0.0024	--
N	soak	10	N	2.770	0.0127	0.0046	1.90
N	soak	15	N	2.786	0.0188	0.0068	2.84
N	soak	15	Y	2.747	0.0166	0.0060	2.50
M	soak	0	--	4.538	0.0037	0.0008	--
M	soak	15	N	4.558	0.1022	0.0224	27.8
M	soak	15	Y	4.570	0.008	0.0018	2.17
L	soak	0	--	3.824	0.0091	0.0024	--
L	soak	15	N	3.834	0.0333	0.0087	3.63

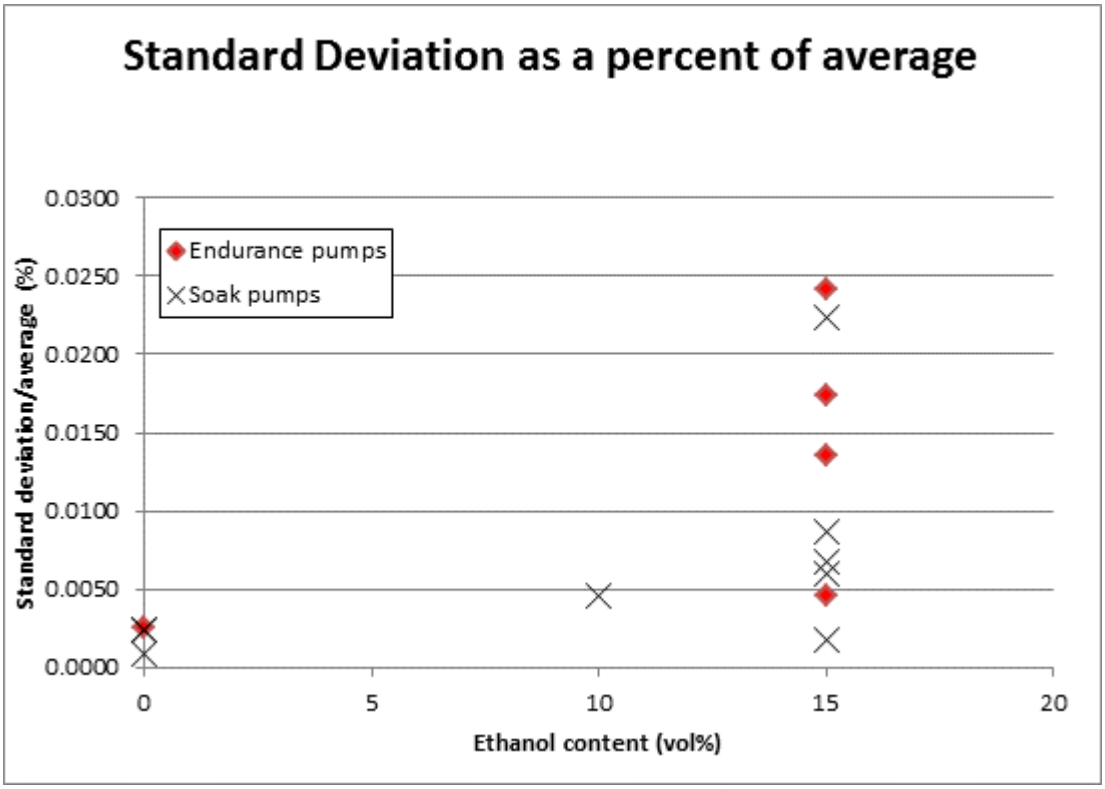


Figure 8. Standard deviation in impeller thickness as a percentage of average thickness. *Variation of pumps tested in E_0 is small, less than 0.25% of average thickness for all pumps. In contrast, for E_{10} and E_{15}, variation is generally much greater, indicating significant dimensional change.*

even if the diameter of the impeller expanded only as much as its thickness, many of the impellers would expand to fill the housing, while if they expanded by 0.6 to 2 percent of the diameter most or all would fail. This is consistent with the failure rate of these pumps and the observation that design "N" pumps that had not yet been flow tested had high resistance to rotation after soaking in E_{15}.

Figure 9 shows one of the Design "N" impellers from soak testing. It has clearly lost some of its vanes as a result of the jamming that also stopped flow. This confirms that the impellers could swell to a size that caused the pump to jam, and, in this case, actually broke off portions of the impeller.

While the variation in impeller thickness increases in E_{15} blends, the cause of this variation is not clear. Several causes are possible, but these experiments are not designed to evaluate them. Pinning down the precise physical mechanism requires additional information; a partial list of such information includes: the nature, thickness and variation in impeller surface finish, impeller chemistry including homogeneity and any anisotropy, ethanol diffusion coefficient in the polymer and co-diffusion of hydrocarbons in the presence of ethanol, and any polymer-level structural changes due to ethanol fuel.

Figure 9. Pump design N impeller from teardown. *This impeller shows obvious loss of vanes as a result of the jamming that caused flow to halt.*

c. Fuel Pump Endurance Tests

Based on performance evaluated partway through the AVFL-15 program, two designs of pump were selected for more extensive endurance testing. These were pumps "L" and "A" in **[1]**. The test was conducted in the same manner as in the AVFL-15 program, but with more replicates (i.e., six copies per pump design). Briefly, the fuel pump was placed in a sealed container with the test fuel to be used and operated according to a cycle of flow rates. The fuel was filtered and returned to the container at a fixed temperature. After 800, 2000, 2700 and 3000 hours, the pumps were tested for flow using unleaded fuel and then returned to test. Test fuel was changed periodically. Full details are available in Appendix A5 and in **[1]**.

Endurance aging tests were completed using E_{15} and E_{15a}, for both pump designs, and also using E_0 with the Design "A" pumps. Figure 10 shows the survival rate for each pump design and fuel. In both mid-blend fuels, more than 80% of the Design "A" pumps failed prior to 3000 hours of operation. Those pumps that survived experienced reduced flow rate, on average, as seen in Figure 11.

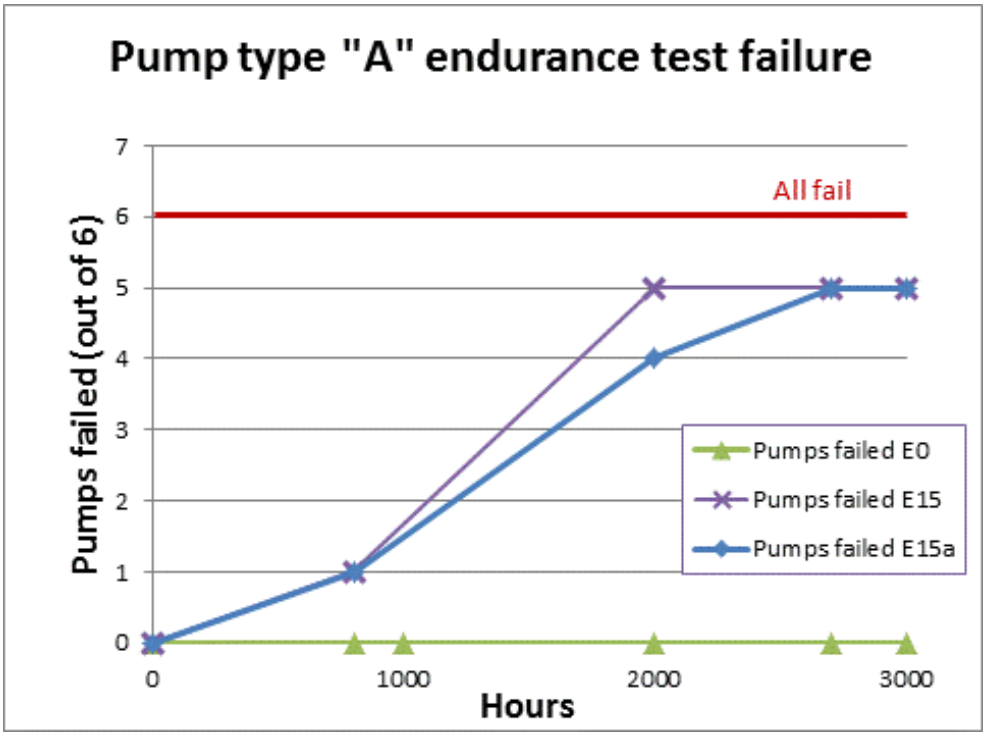


Figure 10. Survival of pumps in the endurance test. *Design "A" pumps generally failed prior to reaching completion at 3000 hours in E_{15} and E_{15a} but they survived testing in E_0.*

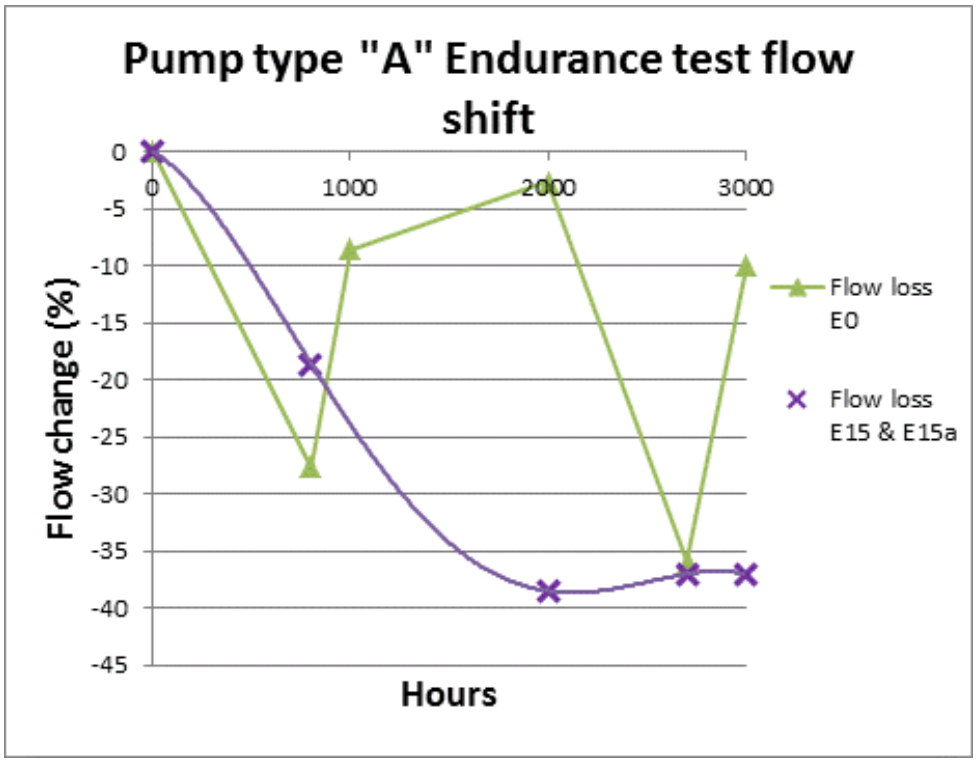


Figure 11. Flow rate for operational pumps in the endurance test. *Design "A" pumps experienced declining flow rates when tested on E_{15} and E_{15a}. Flow stabilized at a time after 700 hours, and remained stable at ~40% flow loss until 3000 hours. Tests in E_0 had substantial variability but on average experienced lower flow loss.*

Because there is continuing attrition up to 2700 hours, the number of pumps in each average changes from point to point in Figure 11. The average flow loss of the two surviving pumps exceeds the 30% threshold where customers might notice degraded performance (possible impacts are longer cold starts, poor acceleration, or even stalling). The fuel pumps that failed endurance testing on E_{15} and E_{15a} are used on a substantial number of the 29 million vehicles represented by the components evaluated in this report.

In contrast, no pumps failed testing with E_0 fuel, and the flow rate degraded to a lesser extent. The flow data exhibit substantial variability, but final flow degradation was well below the threshold of 30% loss. The large differences in pump survival between E_0 versus E_{15} and E_{15a} clearly indicate that there is a mid-level ethanol blend impact on this pump design for this test.

Pumps of the "L" design were not affected by mid-blend ethanol fuels. Two pumps of Design "L" had failed by the first test point: one in the E_{15} test group and one in the E_{15a} test group. However, these failures were from non-fuel-related causes (electrical malfunction early in the test period). Accordingly, those pumps were replaced with pumps of the same design which were also tested over the entire endurance cycle to give a full set of 12 pump tests (six each in E_{15} and E_{15a}). The mid-blend ethanol fuels did not cause failure in any of the "L" design pumps. The flow rates in these pumps did not decrease meaningfully over time, so no E_0 tests were required. The data are provided in Appendix A6. There is no clear impact of E15 and E_{15a} on this pump design. Pump "L" is the only pump design tested with both the Soak and the Endurance protocols, and the results are self-consistent.

These results can be seen as in contrast to **[3],** though they are supported by **[1]**. The testing in **[3]** was conducted somewhat differently and used a different set of parts for endurance testing. As with the soak test, it is clear that some parts are more sensitive than others, so it is not inconsistent that no failures in E_{20} tests were seen in **[3],** while repeatable failures were observed in this testing. The results in **[1]**, with "L" design pumps passing with little impact and one of the "A" design pumps failing, align with the results in the current work. In the current work, the Design "A" pumps had higher commutator wear in E_{15} testing (relative to the wear observed in parts tested in E_0 or E_{10}). The commutator allows electrical power to reach the rotating windings of the motor and excess wear will impact motor performance. Wear was as great as 0.005mm for test article 1M445-69; similar trends were reported in [**1**]. In the same test article that had high wear, resistances between some commutator segments were three times higher than observed in E_0 tests. High brush-commutator resistance was observed in **[1]** in the Design "A" pumps.

d. Fuel Sender Tests

This study also evaluated fuel sending units from three vehicle models (see Table 1). Two vehicle models were the same as those discussed in the prior section (fuel pump soak and endurance testing). Two different tests were conducted on the fuel senders, similar to those performed in the AVFL-15 program. Six senders, of each of the three vehicles, were tested for fuel resistance by cycling for 250,000 cycles (with the sender card powered in a similar fashion to its production application), followed by a one-week unpowered soak. This was repeated three times for a total exposure of one month soak and one million cycles of motion.

Six senders, of each of the three vehicles, were also tested for 5 million cycles using a "full sweep protocol". The senders were powered during the test using the production level sender circuit. The test procedures for both the fuel resistance and full sweep protocols are included in Appendix A8.

The fuel level sender generates a voltage 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 so that the vehicle operator is aware of the fuel remaining. The secondary purpose of the fuel level sender is to provide the fuel level information to the diagnostic system on OBDII vehicles. Many OBDII functions use the fuel level either as part of the enable criteria (which defines the vehicle conditions, such as fuel level, that allow the OBDII diagnostic to run), 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 fuel level over the entire range of the fuel volume. The lever arm is connected to a wiper assembly with a set of contacts. The contacts are typically one of several different designs. Common designs for the contacts are button or ribbon. 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 is chosen to be resistant to corrosion, wear, and attack by fuel impurities (such as free sulfur).

A ribbon design system is shown in Figure 12, and a button contact is shown in Figure 13. A typical circuit board is shown in Figure 14.

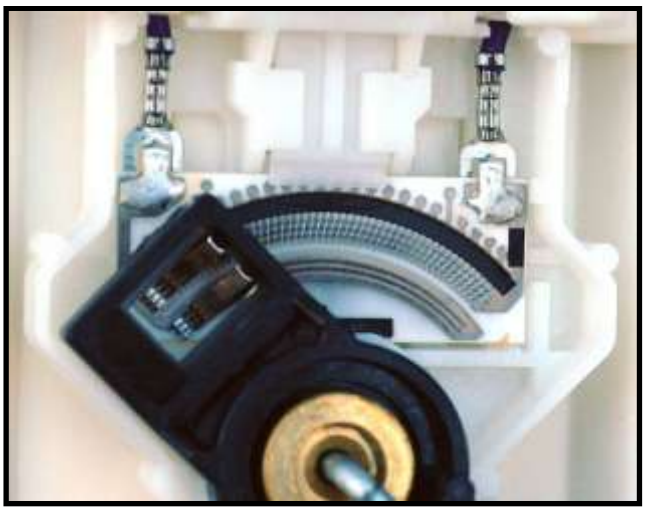


Figure 12. Ribbon design sender.

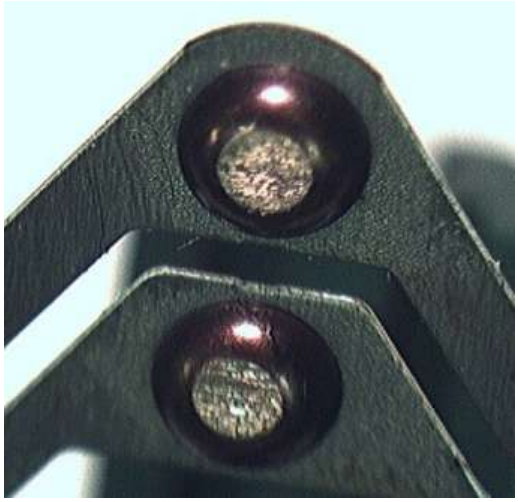


Figure 13. A button contact Sender.

Figure 14. A sender circuit board.

The level indication and OBDII systems must have a “clean” signal without spikes or open circuits in the resistance level. 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 the limiting factor for signal noise is the OBDII system requirements.

Many vehicle manufacturers use a visual indication of the signal output to determine the pass/fail criterion after a fuel level sensor test. An example of a "clean", acceptable signal and a signal defect ("dirty", unacceptable signal) are shown in Figures 15 and 16.

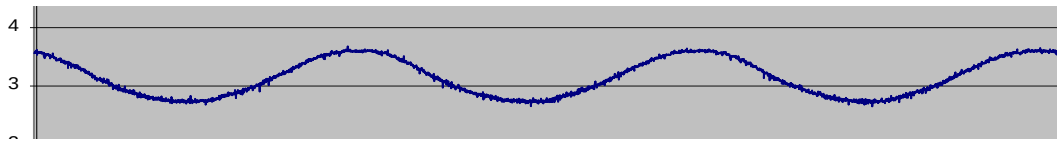


Figure 15. An acceptable sender signal.

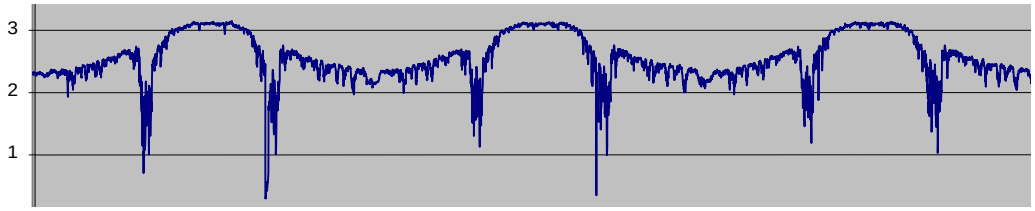
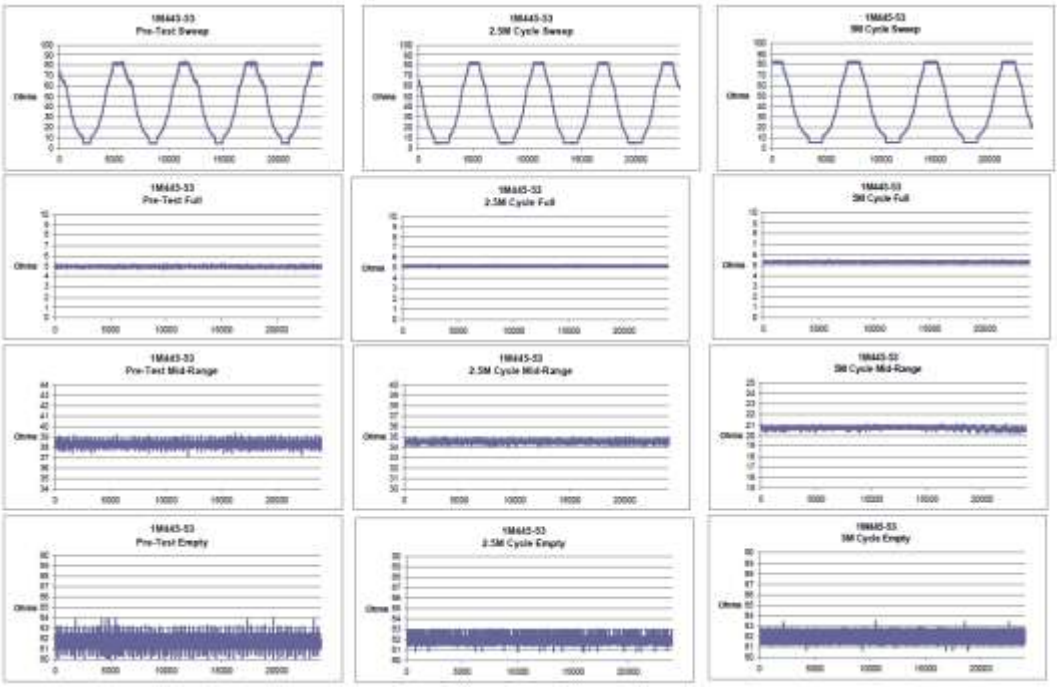


Figure 16. An unacceptable "dirty" sender signal.

Other methods to determine the suitability of a level sensor signal are quantitative. Depending on the filtering of the receiving electronics, a certain number of defects from the ideal signal are allowed. For reference, an example of a quantitative pass-fail criterion is included in Appendix D to **[1]**. 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.

Figure 17 is an example of a fuel level sender sweep test with no defects and is indicative of the method used to report the results. The upper row shows the resistance of the sender circuit as it is swept from empty to full for at least four cycles. The second, third, and fourth rows are steady state tests with the level sender held fixed at full, mid-level, and empty, respectively. The first column indicates results for the initial condition, prior to fuel exposure. The second column shows the results after 2.5 million cycles and the third column shows results after 5 million cycles at the end of test. Data points were taken every 0.25 milliseconds.



Fuel Level Sender Sweep Sender "C" (E_{15} Test Fuel)

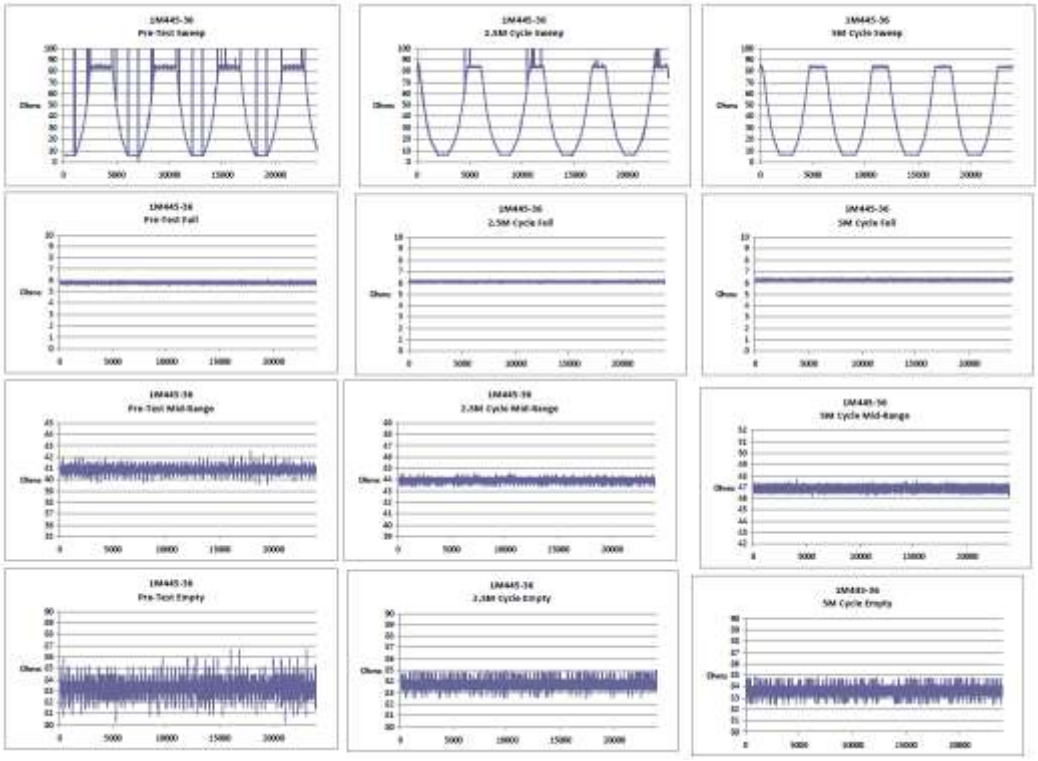
Figure 17. Representative data from sender testing. *Four rows of data show a sweep and three important steady states (full, intermediate, and empty).*

The sweep curves are smooth, with no indication of spikes in the segment of the curves which are used to indicate the fuel level. The steady state plots only show a "dither" of a few ohms over the test period and are not indicative of any circuit problems.

An example of a fuel level sender sweep test which shows some signal defects (i.e., unacceptably large deviations or spikes in the sender signal) is shown in Figure 18. High resistance spikes are evident in the pre-test sweep, and are also present in the test at 2.5 million cycles, but at a reduced level. At the end of the test, the signal is clear of any defects. None of the steady state measurements in the test program showed any areas of concern.

The performance of each sender was evaluated using the following criteria:

- Noise at empty (high resistance), which drove the output to higher resistance beyond the normal range, (i.e., to "less than empty" or "more than empty") was not considered a problem in the discussion of the test results, despite the signal not being considered "clean".
- Resistance noise ("spikes") in the normal readout range of the sender was investigated as a concern that could possibly interfere with OBDII system performance.
- Resistance noise ("spikes") at full (low resistance) which could result in lower fuel indication was also of concern.



Fuel Level Sender Sweep Sender "L" (E_{15a} Test Fuel)

Figure 18. Partly defective response from a sender. *Note the spikes in the sweep data in the top row*.

The results of the fuel level sender tests (Table 9) are briefly summarized in the following. Some tests are noted below Table 9 which show either defects that would not impact customers or OBD systems, or which resolved prior to the end of testing.

Sender "L": This sender had no signal defects on any of the tests (both fuel resistance and sender sweep) with E_{15} fuel. In the E_{15a} tests, two samples of the six had mid-fuel level spikes at the end of the fuel resistance tests, and one sample had fuel level spikes at the high level segment of the range after the fuel level sender sweep test. These might be observable by consumers (erratic or incorrect fill level) and might interfere with OBDII operation.

Sender "C": Two of the six samples of the Design "C" sender, when tested on the fuel resistance protocol, showed spikes in the mid-fuel level range on E_{15} fuel. These might be observable by consumers and might interfere with OBDII operation. There were no signal defects found in the fuel level sender sweep portion of the test with E_{15} fuel. No issues were found with the E_{15a} fuel with either protocol.

Sender "N": One of the six "N" senders tested on E_{15} fuel had mid-fuel level range signal spikes when tested on the fuel resistance protocol. These might be observable by consumers and might interfere with OBDII operation. No issues were found on any of the senders in the fuel level sender sweep test protocol with E_{15} fuel. In the fuel resistance test with E_{15a} fuel, no issues were found. Two of the six samples, when tested with E_{15a} fuel in the fuel level sender sweep test, had slight signal noise at full. It is not expected that this level of noise is an issue with vehicle operation.

The plots for each of the samples with signal defects are shown in Appendix A9. Sample photos are also included in Appendix A10.

Table 9. Summary of sender results.

Fuel Level Sender
Summary of Results

Vehicle	Test Mode	End of Test Results E15	End of Test Results E15a
Sender "L"	Fuel Resistance	No Issues	Mid range spikes 2 samples (20,24)
	Full Sweep	No Issues	High range spikes 1 sample (31)
Sender "C"	Fuel Resistance	Mid range spikes 2 samples (38,39)	No Issues
	Full Sweep	No Issues	No Issues
Sender "N"	Fuel Resistance	Mid range spikes 1 sample (89)	No Issues
	Full Sweep	No Issues	Slight noise at full 2 samples (103,108)

Notes: Sender "L", 2 samples (34, 36) with spikes at empty (drives gauge more to empty) at the intermediate 2.5 million cycle point with E15a
Sender "C", 1 sample (50) with spikes at full (drives gauge to empty) at the intermediate 2.5 million cycle point on E15

IV. Conclusions

1) The pump soak test could discriminate the interaction of fuel pumps with test fuel; some pump design-fuel combinations had no deviations in performance, while other pump design-fuel combinations led to pump failure.
2) One fuel pump model, currently in use in the field, seized in almost every replicate of the pump soak test when either neat or aggressive E_{15} was used as test fuel, but pumps of this model did not fail on any replicate of the same test when either E_0 or E_{10} was used as test fuel.
3) There are pumps currently in use in the field that did not seize in the fuel pump soak test, but did exhibit statistically significant flow loss when tested with neat or aggressive E_{15}. However, none of those pumps had flow loss that would unambiguously impact vehicle performance, nor was the flow shift statistically significantly different from the flow shift observed on E_0 fuel.
4) The pump endurance test could sort fuel pumps by their interaction with test fuel; some pump design-fuel combinations had no deviations in performance while other pump design-fuel combinations led to pump failure.
5) One fuel pump model, currently in use in the field, seized in almost every replicate of the pump endurance test when either neat or aggressive E_{15} was used as test fuel, but did not fail on any replicate of the same test when E_0 was used as test fuel.
6) Another design of pump, currently in use in the field, was not impacted by mid-blend ethanol in the endurance test.
7) Exposure to E_{15} or aggressive E_{15} caused dimensional changes in impellers. Depending on pump model, the standard deviation of thickness was 2 to 27 times greater in E_{15} than in E_0 at the end of the soak test.
8) The tests showed issues with the performance of the fuel level senders when tested with the E_{15} and E_{15a} blends.
9) Both the E_{15a} and E_{15} blends had three instances of significant signal defects.
10) The significant signal defects experienced (consumer observable resistance spikes) could potentially cause interference with proper OBDII function
11) While not consistent and not found in all samples tested, the results indicate some effect of the E_{15} and E_{15a} blends on sender operation.

The fuel pumps and level senders that failed or exhibited other effects during testing on E_{15} and E_{15a} are used on a substantial number of the 29 million 2001 – 2007 model year vehicles represented by the components evaluated in this report.

V. References

[E1] See also http://nhts.ornl.gov/index.shtml

[1] Durability of Automotive Fuel System Components Exposed to E20. CRC Report No. 662, December, 2011.

[2] Intermediate-Level Ethanol Blends Engine Durability Study. CRC Report No. CM-136-09-1B, April 2012.

[3] An Examination of Fuel Pumps and Sending Units During a 4000 Hour Endurance Test in E20. Gary Mead, Bruce Jones, Paul Steevens, Nathan Hanson and Joe Harrenstein, March 2009. http://cset.mnsu.edu/aet/facilities/e20_fuel_pump_endurance_study_3-25-09_final.pdf

[4] The Effects of E20 on Automotive Fuel Pumps and Sending Units. Gary Mead, Paul Steevens, Bruce Jones, Nathan Hanson, Thomas Devens, Colin Rohde, Adam Larson. February 2008. http://cset.mnsu.edu/aet/facilities/msu_e20_fuel_pump_soak_study_2-21-08_final.pdf

[5] Evaluation of Inspection and Maintenance OBD II Data to Identify Vehicles That May Be Sensitive to E10+ Blends. Dennis McClement, Thomas C. Austin. CRC Report No. E-90-2a. January, 2011.

[6] Partial Grant of Clean Air Act Waiver Application Submitted by Growth Energy to Increase the Allowable Ethanol Content of Gasoline to 15 Percent; Decision of the Administrator. Federal Register Volume 76, Number 17. p 4662-4683.