# Review and Evaluation of Studies on the Use of E15 in Light-Duty Vehicles

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# Executive Summary

The objective of this study is to review and evaluate research conducted to date applicable to the effects of E15 on Model Year 2001 and newer cars, and to draw objective conclusions based on the entire available dataset. The project team reviewed 43 studies relevant to E15 usage in 2001 and newer model year on-highway automobiles. These included 33 unique research studies, as well as 10 related reviews, studies of methodology, or duplicate presentations of the same research data. The study does not address engines that EPA has not approved for use with E15, such as pre-2001 cars, marine, snowmobile, motorcycle, and small non-road engines. In the main section we critically review these studies in terms of the methodology, controls, and test fluids employed, and draw overarching conclusions based on the totality of the data, where possible. The appendix includes short, factual reviews of each study in the areas of material compatibility, engine and fuel system durability, exhaust emissions, catalyst durability, effect on on-board diagnostics, and evaporative emissions. The main conclusions of this analysis are:

- Several of the studies tested relatively large numbers of engines or vehicles, including:
    - The Coordinating Research Council's (CRC) engine durability study (28 engines)
    - The University of Minnesota's in-use fleet study (80 vehicles)
    - The USDOE's catalyst durability study (82 vehicles).

  The data presented in these studies did not show any evidence of deterioration in engine durability or maintenance issues for E15 (or E20) in comparison to E0 and E10 (when tested).
- Because of the wide variety of control fluids and unique test protocols, especially for fuel system component, engine, and vehicle durability studies, it is difficult to combine the results into a single analysis. This document distinguishes between test fuels and test fluids. Test fluids, such as those suggested by SAE publication J1681, do not meet fuel quality standards and were not intended for comparison of the effects of different fuels because the effects of the aggressive test fluids relative to commercial fuels are unknown.
- Materials compatibility testing provides no evidence that 15 volume percent ethanol blends will cause increased rates of metal corrosion in comparison to 10 percent blends. In most cases increasing ethanol content from 10 to 15 volume percent had no significant effect on elastomer swell.
- For 2001 and newer cars emission studies also show that engine control units are able to adequately compensate for the higher oxygen and lower energy content of E15.
- The engine performance and durability expectations from the materials compatibility and emission test results are confirmed by studies of fuel system, engine, and whole vehicle durability.

E10 has been in primary use in the United States since the promulgation of the Clean Air Act Amendments of 1990. Over two-hundred million vehicles on the road today regularly use E10 without experiencing systemic fuel-related component or engine failures. The main conclusion from our analysis is that the data in the 33 unique research studies reviewed here do not show meaningful differences between E15 and E10 in any performance category.

## Fuel System and Engine Durability

Five studies, each of unique design, were reviewed in this area and are described briefly below.

- The CRC engine durability study concluded that two popular engines used in 2001-2009 model year vehicles experienced mechanical failure when operated on E15. This study employed a design and methodology that leave the results open to a different interpretation than that provided by the study authors because of several factors, including the following: The leakdown failure criterion is not supported in the scientific or applicable OEM literature; statistical analysis included assumed data for vehicles that had not been tested, and omitted data for a vehicle that was tested; E10 was not used as a control fuel. When these factors are taken into account, the conclusion that engines will experience mechanical engine failure when operating on E15 is not supported by the data.
- Two large scale (of about 80 vehicles each) tests were conducted on whole vehicles (as opposed to engines or fuel system components). A study by University of Minnesota used E20 as the test fuel and an E0 control followed an in-use fleet of cars for one year. In a second study by USDOE both E15 and E20 were used as the test fuels with E10 as control for five out of twenty-five 2001 and newer vehicle models. The study utilized mileage accumulation dynamometers to age the vehicles to full useful life. Neither study found increases in fuel-related maintenance in the vehicles tested. While E10 controls were used for only 25% of the cars tested in the DOE study (with E0 as control for 75%) in the USDOE study, because no fuel related issues were apparent with the E15 and E20 fuels, E10 control testing was not necessary.
- Component durability studies used aggressive test fluids with poorly understood connection to commercial fuels.
  - The Minnesota Center for Automotive Research study examined a selection of components intended to represent a wide range of vehicle and material types and found no additional failures of fuel system components with fuels containing ethanol concentration up to 20 volume percent.
  - A second component durability study conducted by CRC, intended to identify the most sensitive components, located a single pump that failed repeatedly on E15 but not on E10; yet in an earlier phase of this work the same pump model did not fail when tested on aggressive test fluids containing 10 and 20 vol% ethanol. A hypothesis exploring the discrepancy between these results was not discussed, nor was the make and model of the pump revealed, making these results inconclusive and further analysis by others impossible.

## Materials Compatibility

Much of the research reviewed in this area uses ASTM Reference Fuel C as the hydrocarbon control and SAE J1681 Aggressive Ethanol blended with Reference Fuel C at different levels as the test fluids. These formulations were not intended for comparison of the effects of different fuels because the effects of the aggressive test fluids relative to real world fuels are unknown. A material that fails might prove to have acceptable durability in normal use. No study has quantified an acceleration factor for the aggressive fluids, or in other words, shown a correlation between the effects of aggressive fluids and more typical commercial ethanol blended fuels.

Studies using ethanol concentrations ranging from zero to 100% ethanol suggest that corrosion rates and effects on elastomers often peak at ethanol concentrations somewhere between E10 and E35.

- No corrosion was observed for mild steel, 304 stainless steel, 1100 aluminum, or 201 nickel immersed in Aggressive E10 or Aggressive E17 (a surrogate for E15). A second study found corrosion rates in 16 different metals to be less than 0.0025 mm/yr in Aggressive E10 and Aggressive E20, considered insignificant over a 20 year timeframe. Terne plate, galvanized steel, phosphor bronze and cartridge brass exhibited slightly higher rates of corrosion in aggressive test fluids, but without significant differences between Aggressive E10 and either Aggressive E17 or Aggressive E20. When using non-aggressive ethanol blends, measured corrosion rates were several orders of magnitude less.
- Elastomers and plastics showed some measurable effects from exposure to gasoline hydrocarbons with increasing ethanol content. The largest changes in material properties typically occurred between 0 and 10 volume percent ethanol; however, differences between materials were far more significant than differences between fuels. Fluorelastomers (generally approved for FFVs) saw the best retention of baseline properties with all levels of ethanol.
    - A detailed study conducted by ORNL showed differences in swell between E10 and E17 (a surrogate for E15) to be less than 15% in all cases, and less than 5% if silicone rubber, styrene-butadiene rubber, and polyurethane are excluded.
    - In a second study of a large group of elastomers by MnCAR only epichlorohydrin ethylene oxide copolymer swelled to a significantly greater extent in Aggressive TF20 than in Aggressive TF10.
- The reported results suggest that elastomers and plastics rejected for material compatibility reasons for use with E15 would likely be considered unacceptable for use with E10.

## Regulated Emissions

The emissions section comprises studies conducted on tailpipe emissions, catalyst durability, OBDII failures for lean operation, and evaporative emissions. These studies (with the exception of the analysis of OBDII failures) used test methods that are defined in the regulations and the results have been carefully reviewed by the EPA to ensure that E15 would not adversely affect emissions. Analyses of inspection and maintenance results for millions of vehicles in four different air quality jurisdictions suggest that in practice there is no discernible relationship between the numbers of malfunction indicator light (MIL) illuminations due to lean diagnostic trouble codes (DTCs) and increasing ethanol content. Overall the tailpipe emissions and OBDII results show that 2001 and newer cars are able to compensate for the increased oxygen content and lower energy content of E15 blends, such that combustion and exhaust temperatures do not change significantly. The evidence suggests that increases in evaporative emissions between vehicles using E10 and E20 are small or non-existent. Even after the equivalent of one year of aging, measured evaporative emissions remained below regulated levels.

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## List of Acronyms and Abbreviations

ABS – acrylonitrile butadiene styrene (plastic)
ACM – acrylic rubber elastomer
ASTM – American Society for Testing and Materials
BOB – blendstock for oxygenate blending
CO - epichlorohydrin homopolymer
CR – polychloroprene elastomer
CRC – Coordinating Research Council
DNPH- Dinitrophenylhydrazine
DOE – Department of Energy
DTC - diagnostic trouble code
DVPE – Dry Vapor Pressure Equivalent
ECO - epichlorohydrin ethylene oxide copolymer
ECU – engine control unit
EIS – electrochemical impedance spectroscopy
EPA – Environmental Protection Agency
FID- Flame ionization detector
FFV- Flex fuel vehicle
FKM – fluoroelastomer
FTP- Federal Test Procedure (aka FTP75) for emissions
FTP75 – Federal Test Procedure city driving cycle
GC- Gas Chromatography
GVW – Gross Vehicle Weight
HPLC- High Performance Liquid Chromatography
IM – inspection and maintenance
J1681 – SAE Standard for Gasoline, Alcohol, and Diesel Fuel Surrogates for Materials Testing
LA92 – Unified Driving Cycle
LEV- Low Emissions Vehicle
LTFT- Long Term Fuel Trim; learning ability of an engine controller to adjust fuel injection rates
MIL – malfunction indicator light
MY – model year
NBR – nitrile rubber elastomer
NLEV – National Low Emission Vehicle
NMHC- Non-methane hydrocarbons
NMOG- Non-methane organic gases
NONMHC- Non-oxygenated non-methane hydrocarbons
NREL – National Renewable Energy Laboratory
OBDII – second generation on-board diagnostics
OEM – original equipment manufacturer
ORNL – Oak Ridge National Laboratory
ORVR – On-board Refueling Vapor Recovery
OZO – nitrile/PVC blend elastomer
PA6 – polyamide 6 plastic
PA66 – polyamide 66 plastic
PBT – polybutylene terephthalate plastic
PET – polyethylene terephthalate plastic
PEI – poly etherimide 1010 plastic

PFI – port fuel injection
psi – pounds per square inch
PUR – polyurethane plastic
PVC – polyvinyl chloride plastic
PZEV- Partial Zero Emissions Vehicle
RFA – Renewable Fuels Association
RVP- Reid vapor pressure
SAE – Society for Automotive Engineers
SBR – styrene- butadiene rubber
SHED – Sealed Housing for Evaporative Determination
SRC- Standard Road Cycle
STFT – short term fuel trim
THC- Total hydrocarbons
WOT- Wide Open Throttle

# Introduction

Ethanol has a long history as a fuel component. For example, the original Ford Model T, produced in 1908, was a flexible fuel vehicle, with carburetors that could be adjusted to use alcohol, gasoline, or a mixture of the two.[1] More recently, the energy crises of the 1970s led to the passage of the Energy Tax Act of 1978. This act defined gasohol as a blend of gasoline with at least 10 volume percent non-fossil fuel based ethanol and exempted ethanol blends from part of the Federal highway tax. Because of its expected benefits to air quality, national energy security, and agriculture, 10% ethanol blends also received a waiver to requirements of the Clean Air Act in 1978. The phase out of tetraethyl lead in gasoline during the 1980s generated interest in the use of ethanol as a high-octane blendstock. However, methyl tert-butyl ether (MTBE) dominated this market until it was phased out beginning in March 2000.[2] Since that time, ethanol blending has grown to the point where over 95% of gasoline consumed in the United States contains 10% ethanol.[3]

In October 2010 U.S. Environmental Protection Agency (EPA) granted a partial waiver allowing E15 use in 2007 model year and newer light-duty automobiles,[4] and in January 2011, a second partial waiver allowing E15 use in 2001-2006 model year automobiles.[5] These waivers were based on data provided by the U.S. Department of Energy (DOE) and other data and information on the potential effect of E15 on vehicle emissions, emission control systems, and related health effects. EPA considered a range of factors for determining the model year breakpoint for approval of E15.[4] First, transitional national low emission vehicle (NLEV) standards became effective in all 50 states in 2001,[6] leading to the introduction of much more flexible and sophisticated emission control systems with greater authority to compensate for fuel composition. A second important factor was the implementation of the CAP2000 program which was optional for MY 2000 and required for MY 2001. CAP2000 requires actual in-use testing of cars over their full useful life to demonstrate emissions compliance.[7] It is also notable that this is the first Clean Air Act waiver granted for Tier 2 carss that are required to meet emission standards for an EPA defined 120,000 mile full useful life.

The objective of this review is to assess the research conducted to date applicable to the effects of E15 use in MY 2001+ cars, including aspects that were not a part of EPA's considerations for granting a waiver such as materials compatibility and fuel system durability. The study does not include discussion of engines that USEPA has not approved for use with E15, such as pre-2001 cars, marine, snowmobile, motorcycle, and small non-road engines. The project team reviewed 43 studies relevant to E15 usage in 2001 and newer model year on-highway automobiles. These included 33 unique research studies, as well as 10 related reviews, studies of methodology, or duplicate presentations of the same research data.

The focus of this report is to identify issues which limit the application of previous study results to the wide range of in-use fuels and cars. It is also notable that the studies considered were of insufficient sample size to provide quantitative predictions regarding possible failure rates in the overall vehicle fleet.

The appendix to this document presents summaries of the 43 studies assessed, which compare E15 (or in some cases E17, E20 or E25) with E10 and conventional gasoline (E0) from the following perspectives:

- Materials compatibility
- Engine and fuel system durability
- Exhaust emissions
- Catalyst durability
- Effect on on-board diagnostics
- Evaporative emissions

The main text reviews background information necessary to interpret the study results, summarize the results and provide a critical analysis of the studies. Studies were evaluated on the following criteria:

- Quality of the science
    - Is there sufficient information provided to allow other researchers to repeat the study?
    - Is detailed information on test subjects, fluids and conditions provided?
    - Are there adequate controls?
    - If standard methods or fluids are employed are they being used as designed or intended?
- Relative level of aggressiveness (severity) for various test conditions
    - Is the impact of control and test fluids relative to real world fuels understood?
    - Do the test conditions represent realistic conditions? If aging is accelerated, can an acceleration factor be determined?
    - Does the study consider the impact of additives normally present in fuels?
- Importance of the test results
    - Are the parameters evaluated important to the normal uses of the test subject?
    - Does the study explain how the results obtained relate to real world experience?

This document refers to test fuels and test fluids. A test fuel is a blend of an ASTM D4814 compliant gasoline or a hydrocarbon blendstock intended to meet this ASTM standard when blended with E10, with ASTM D4806 compliant ethanol. These blends are referred to using the Exx designation where xx is the volume percent ethanol. A test fluid, on the other hand, is a blend produced using non-compliant hydrocarbons such as Reference Fuel C and/or ethanol not meeting ASTM D4806 (such as the aggressive ethanol formulations described in SAE Recommended Practice J1861). In this report these fluids are referred to using the TFxx designation, where TF indicates test fluid and xx is the volume percent ethanol.

# Materials Compatibility

## Introduction and Background

This section discusses the testing of individual materials in continuous or intermittent contact with hydrocarbon only test fluids and fuels and hydrocarbon ethanol test fluid and fuel blends.

**Material Selection.** There is no database that lists all of the materials that OEMs and replacement part suppliers have used in vehicles that may come in contact with fuel. The Minnesota Center for Automotive Research[8,9,10]developed a list of materials to be tested based on literature reviews, manuals and recommendations from fuel system and engine manufacturers. After the list was assembled it was peer reviewed by engineers from several OEMs and Tier I and Tier II suppliers. Materials already approved for use in flex-fuel vehicles were removed from the list. An Oak Ridge National Laboratory study[11] included in this review was designed to test materials for fuel storage and transfer use, but since it included a number of the same materials used in vehicles it was considered applicable to this discussion. No other studies included here were as large or comprehensive as the ORNL study, but all included ethanol and gasoline test fluid or fuel blends and either specifically identified the materials as known to be used in vehicles, or suggest that the materials tested could potentially have been considered for automotive use.

While the studies reviewed quantitatively describe the performance of materials in different fluids, it is important to note that the specific criteria that an OEM would apply in selecting a material for a given application are unknown. The various materials compatibility studies simply compare materials based on standard metrics.

**Control fuel.** All of the experiments discussed in this section compare the effects of different ethanol containing fuels to a control fuel or test fluid. The control is used to represent the baseline condition that would exist if E15 were not present in the market. Its primary component is petroleum hydrocarbons. As greater than 95% of all gasoline sold in the United States is nominal E10,[12] it is reasonable to suggest that E10 be considered the appropriate control fuel. Nevertheless, some testing has been conducted with E0 as the control. However, the evidence presented here shows that when E0 is used as the control the largest impact with increasing ethanol concentration for elastomers and plastics seems to occur at very low ethanol concentrations. This suggests that the initial presence of ethanol is far more important than the change in concentration from E10 to E15. Consequently, E10 is the control fuel that best addressed whether E15 would contribute to reduced performance with 2001 and newer model year vehicles.

The base fuel is the hydrocarbon that constitutes the bulk of the test fluid. Normally, a specialized hydrocarbon blendstock known as a BOB, or blendstock for oxygenate blending is used for commercially available ethanol blended fuels. The BOB is formulated such that the blend of the BOB and ethanol will meet the requirements of the ASTM Standard Specification for Automotive Spark-Ignition Engine Fuel, D4814. BOBs are a variable mixture of hundreds of hydrocarbon compounds. For the studies reviewed in this report, the base fuel chosen was typically not a BOB, but more commonly emission certification fuels such as indolene or other standardized gasolines used in emission testing. From a materials compatibility perspective the emission testing fuels and typical BOBs have similar concentrations of paraffins, olefins, and aromatics and therefore should exhibit similar effects on materials.

The components of gasolines (paraffins, olefins, aromatics, and impurities) can affect vehicle fuel system materials in a variety of ways. Alkanes can be sorbed by polymeric materials, especially non-polar polymers, and cause swelling. Olefins have double bonds which are vulnerable to oxidation. Products of this degradation are gums, varnishes and peroxides. Aromatics such as toluene, xylene, or other compounds that contain a benzene ring typically comprise 20% to 30% of gasoline, but can be as high as 50%. Polymeric materials can undergo swelling and decomposition when exposed to high concentrations of aromatics.

Lead, sulfur, and gum content in gasoline are limited by ASTM D4814. The ethanol standard ASTM D4806 limits water, acid, chloride, sulfate, sulfur, and copper. Water and ionic compounds can accelerate the corrosion of metals. Sulfur in the form of disulfide and related oxidation products can affect metals, some elastomers, and plastics.

More than two decades ago, the automotive industry attempted to standardize the selection of test fluids for the testing of materials for use in motor vehicles. The result was SAE J1681, a recommended practice for gasoline/methanol mixtures for materials testing.[13] The primary intention was to limit the variability found in commercial test formulations but also to meet the following requirements:

a. Representative of marketplace fuels
b. Create a severe, reproducible level of a particular effect
c. Safe and easy to handle in a laboratory setting
d. Safe and easy to use at temperatures between -40 °C and +60 °C
e. Globally available to scientists and engineers
f. Available with no potentially active impurities or contaminants

The test fluid components in J1681 typically emphasize repeatability over representativeness. For example, for ethanol, it recommends the use of synthetic ethanol, because this will minimize the potential for microcomponents that may vary depending on the feedstock. They propose the use of a consistent denaturant (heptane isomer) and addition of reagent water at 1 wt%.

As a result of requirement (b) above, the standard specifically states (emphasis added):

*Formulations in this document are intended to exaggerate the effects of typical severe fuel on materials.*

Thus, the test fluids in J1681 are intended to include a worst case selection of challenging constituents, with the intent that every potential problematic interaction with materials can be readily identified. For example Reference Fuel C, a 50/50 mixture of toluene and isooctane, is proposed as the base hydrocarbon because ASTM Test Method D471 states that it produces “the highest swelling which is typical of highly aromatic premium grades of automotive gasoline". Thus Reference Fuel C may create a potentially exaggerated view of hydrocarbon impact on these materials.

While the use of harsh test fluids like Reference Fuel C may be a good choice to ensure that materials are more than adequate for normal fuel exposure, the fluids discussed in J1681 were not intended for comparison of materials effects of different fuels. Many of the fluids listed in J1681 have components that overemphasize certain effects (for example, the addition of chloride to Reference Fuel C to test for corrosion). Comparison tests using these aggressive test fluids are difficult to interpret without information on the degree to which additives affect degradation of materials in comparison to more representative fuels.

Interestingly, J1681 proposes that materials be qualified for "world-wide basic, gasoline, and diesel fuel system applications" using the following fluids:

- C $(M15)_A$ = ASTM Reference Fuel C with 15v/v% aggressive methanol[*]
- C(ME15) = ASTM Reference Fuel C with 15v/v% methyl tertiary-butyl ether
- CP = ASTM Reference Fuel C with 6.43 g of 70% of tertiary butyl hydroperoxide (an auto-oxidized fuel)/liter
- Cw = (for metals testing only) contact with three phases, vapor phase, ASTM Reference Fuel C and separate aqueous phase containing 100 ppm chloride ion per liter of water

If automakers used J1681 in determining appropriate materials used in their fuel systems and engines, these materials have already been tested using 15% aggressive methanol in Reference Fuel C. Methanol is generally considered to be far more incompatible with materials than ethanol,[14] so that logically materials approved using J1681 would be unlikely to fail in a similar concentration ethanol blend. At no point does J1681 recommend the use of Reference Fuel C alone for materials testing. It is proposed only as a substrate for the testing of potentially harsh added constituents that can, on occasion, be found in gasoline. Reference Fuel C alone is neither a worst case as envisioned under J1681, nor representative of typical marketplace fuels. Despite this, Reference Fuel C, with no additions has been selected as the control fluid for materials testing in more than half of the studies considered here, many of which imply that J1681 is the basis for their choice of test fluids. A better choice for a repeatable control that is representative of marketplace fuels would be a reference gasoline. J1681 suggests that reference gasolines be used in place of Reference Fuel C when "test fluids more representative of commercial fuels are required".[13]

**Test Fuel.** Test fuel, in this context, means the fluid intended to represent E15 in material compatibility testing. Since E15 is the fuel of concern, ideally we would use only E15 testing for this analysis, but materials compatibility testing with E15 has been rare. However, in 2005 the State of Minnesota legislated the use of 20 percent volume ethanol blended into gasoline if approval by the EPA could be obtained. In order to obtain approval, Minnesota undertook a large materials compatibility testing program on E20. That data are also reported here, although care should be used as there may not be a linear correlation between E10, E15 and E20. However, if differences in material effects are not

[*] A discussion of aggressive alcohols follows in this section.

detectable between E10 and E20, or if E20 seems less problematic than E10, it seems reasonable to conclude that E15 will be equally compatible with the materials tested at both E10 and E20. Conversely, if E20 were dramatically worse than E10, it suggests that at some concentration between E10 and E20 materials compatibility begins to become a concern.

Generally, the test fuel used the same hydrocarbon base as the control fuel, which is the most appropriate approach to isolate the effect of changing ethanol concentration.

More contentious has been the use of "aggressive" ethanol. As discussed above, J1681 recommends testing with "worst case" fluids, and in the case of ethanol proposes addition of water, sodium chloride, sulfuric acid and glacial (anhydrous) acetic acid to ethanol to make Aggressive Ethanol. Water and sodium chloride are ubiquitous compounds that can be found in the fuel transport and distribution system, and can increase corrosion rates. One paper claims chloride is potentially more prevalent in alcohol containing fuels, although without supporting data or citation.[14] Acetic acid and sulfuric acid can be present in ethanol in trace quantities from certain ethanol production processes. Acetic acid has been found to act as a buffer, tending to control the pH of the alcohol when strong acids such as sulfuric acid are present.[15] We could not identify a published justification for the amount of these compounds added to Aggressive Ethanol and no justification is given in the SAE paper describing the standard's development.[15] The J1681 composition for Aggressive Ethanol is listed in Table 1. Both RFA and CRC published a chemical analysis of a typical ethanol to which the aggressive components were then added. Table 2 shows a comparison of these typical ethanol samples, Aggressive Ethanol, and the ASTM standard applicable to fuel grade ethanol.

Table 1. Recipe for 1 Liter of Aggressive Ethanol from SAE J1681 and Modified Aggressive Ethanol (discussed later).

| **Component** | **Recipe for Aggressive Ethanol from SAE J1681** | **Recipe for Modified Aggressive Ethanol from CRC Report No. 662** |
|---|---|---|
| Ethanol, synthetic | 816.0 g/L* | As necessary to make up 1 liter |
| Deionized water | 8.103 g/L | As necessary to make a concentration of 1vol% |
| Sodium chloride | 0.004 g/L | 0 |
| Sulfuric acid | 0.021 g/L | 0.003 g/L |
| Glacial acetic acid | 0.061 g/L | 0.061 g/L |
| Hydrochloric acid | Not included | 0.008 g/L |
| Nitric Acid | Not included | 0.015 g/L |

*Note that while this recipe is taken verbatim from the SAE J1681 recommended practice, the density of 99.9% ethanol is 791 g/L at 20°C.

Table 2. Measured properties of two samples of Fuel Grade Ethanol, Aggressive Ethanol, and Modified Aggressive Ethanol (discussed later).

| Property | Fuel Grade Ethanol Sample 1[16] | Fuel Grade Ethanol Sample 2[17] | Aggressive Ethanol* | Modified Aggressive Ethanol† | ASTM D4806-13a Limit |
|---|---|---|---|---|---|
| Moisture (vol%) | 0.69% | 0.79% | 1.45% | 0.79% | 1.0% |
| Chloride (mg/L) | <0.4 | <0.1 | 3.1 | 4.9 | 8 |
| Acidity (% mass) | 0.002% | Not reported | 0.014% | Not reported | 0.007% |
| pHe | 7.5 | 7.46 | 2.6 | 2.3 | 6.5 to 9.0 |
| Sulfur (ppm) | 0.6 | 2 | 10.6 | Not reported | 30. |
| Existent Sulfate (mg/L)¥ | 0.5 | <0.1 | 31.5 | 3.8 | 4 |
| Conductance (µs/cm) | <2 | Not reported | 14.5 | Not reported | Not in D4806 |
| Gums Unwashed (mg/100 ml) | 4.8 | Not reported | 9.9 | Not reported | Not in D4806 |

*made from Fuel Grade Ethanol Sample 1

†made from Fuel Grade Ethanol Sample 2

¥At the time of these studies this was referred to as total sulfate

Aggressive ethanol exceeds allowable limits for fuel grade ethanol by large amounts in numerous ways. The added fluids will affect material compatibility (in fact that is the stated intention). However, no published studies have demonstrated that the reactivity of the aggressive alcohol is in some way proportional to that of the base alcohol. Although the J1681 formula may have been in some way representative of a "worst-case" ethanol available on the market at some historical point two decades ago when the initial recipe for Aggressive Ethanol was developed, it is far from representative of ethanol currently on the market.[18] Aggressive Ethanol was not intended for comparison or ranking of different fuels. Most importantly, ASTM D4806 has set the allowable pHe between 6.5 and 9.0. To ensure that ethanol remains in that range for at least sixteen weeks after manufacture, it is standard to add corrosion inhibitor/pHe buffer additives.[19] No corrosion inhibitors/pHe buffers have been included in Aggressive Ethanol or Modified Aggressive Ethanol.

**Test Methods.** Ideally, one would replicate typical vehicle lifetime exposure to different fuels to determine the impact of fuel changes. But in order for testing to be of use for cars already on the road, long-term effects must be extrapolated from short term tests. Researchers have developed several approaches to estimate the materials impact of new fuels for the life of the vehicle based on shorter term testing. The most straightforward is careful measurement of small effects, such as corrosion rates, which are proportional to time of contact. These measured values can readily be extrapolated to longer times. In other cases certain materials effects are relatively immediate, such as the swelling or loss of flexibility of elastomers in certain liquids. This is more useful in ruling out the use of specific material-fuel combinations than in assuring that any specific combination will work for long periods of time. Another approach is increasing the contact time, by soaking materials around-the-clock, while in normal use these materials might only be in intermittent contact. This is only applicable for materials in certain types of applications, and it may be misleading, because in some cases the combination of air and liquid contact may be worse than continuous submersion.

Most tests were conducted on coupons submerged or partially submerged in a control and in a test fuel. When the test fuel has the same or less impact on the tested materials than a fuel representative of marketplace fuels, it can be concluded that the material is acceptable for use with the test fluid. However, in the vast majority of cases the results are far more ambiguous. Sometimes, the results are not consistent, or there is no measurable difference between the impacts of the fuels. This could be because the test conditions are not acceptably harsh or long, because measuring equipment is not adequately sensitive, or it could be because there is no significant difference between the impacts of the fuels. Other programs have indicated that the tested fuel makes a small negative impact on some materials, but it is not clear how small is too small to be significant in practical use. Other tests have shown mixed results when the impacts of the control and test fuel are compared, with increased impact on some properties, and a less severe impact on other properties. Without access to information on materials usage in the vehicle fuel systems and engines (typically proprietary), it is not possible to determine which is more significant.

## Discussion

**Metals.** Metals corrode by chemical or electrochemical interaction with fuels. With the higher conductivity found in alcohol fuels corrosion can be enhanced at high voltage interfaces, sometimes found in the fuel pump module. Acceptable levels of corrosion would depend on the usage but the Oak Ridge National Laboratory considered corrosion levels of below 0.030 mm/yr (approximately 1 mil per year, or 0.001 inch/year) to be a low rate of corrosion and the Minnesota Center for Automotive Research set up their experiments such that they were accurate to levels at approximately one-tenth that, 0.0025 mm/year (0.1 mil/year), based on the assumption that corrosion rates below that level would not be significant even over a potential 20-year lifespan of an automobile.

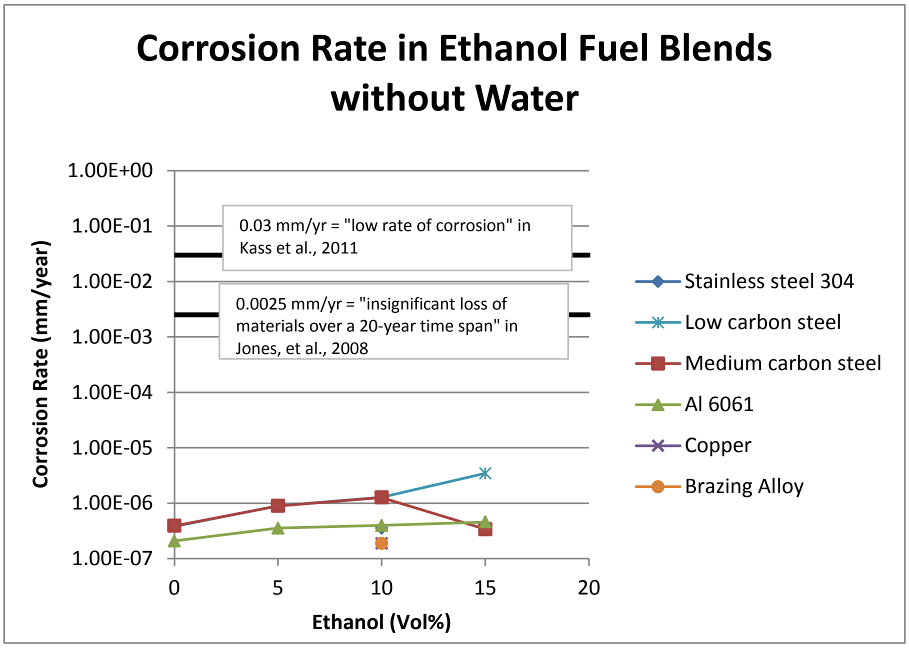
Several studies on the corrosion of metal in gasoline-ethanol blends have been conducted. Some materials are susceptible to corrosive attack by ethanol. General Motors identified copper, zinc plating and aluminum as particularly susceptible to attack by alcohol gasoline blends, and generally uses stainless steel for most fuel-contacting components.[14]

The Oak Ridge National Laboratory conducted a material compatibility study[20] using Reference Fuel C as the base test fluid, Aggressive TF10, Aggressive TF17 and Aggressive TF25 fuels. Corrosion rates of 1020 mild steel, 1100 aluminum, 201 nickel, 304 stainless were too low to be measured; while cartridge brass, phosphor bronze, zinc-plated galvanized steel, lead-plated (terne) steel were slightly susceptible but all at levels below 0.010 mm/year in Aggressive TF17. Overall, they concluded that metal corrosion was below levels of concern, with the highest corrosion level (0.030 mm/year) measured on cartridge brass immersed in Aggressive TF10. Generally, they did not find any consistent trends between ethanol content and corrosion rate. Galvanic coupling was tested for several pairs of metals, but resulted in no excessive corrosion levels.

A similar study on 19 different metals, using Reference Fuel C, Aggressive TF10 and Aggressive TF20 was conducted by the Minnesota Center for Automobile Research with similar results.[10] According to the text, seventeen of the 19 metals showed no significant corrosion rate in any of the three fluids. However, according to the Appendix (but not the text), a corrosion rate of 0.0036 mm/yr was found for terne plate in liquid E20, while corrosion in E10 and E0 was below this research's *de minimis* level (of 0.0025 mm/yr). Magnesium AZ91D exhibited a mass loss higher in Reference Fuel C than in the Aggressive TF10 or Aggressive TF20. Zamak 5 showed unacceptable levels of corrosion, excessive mass loss and pitting in both Aggressive TF10 and Aggressive TF20 but not Reference Fuel C. While the results of Zamak 5 and (possibly) terne metal are a concern, Zamak 5 was only used in some early OEM carburetors and aftermarket carburetors. Since carburetors have not been not used in U.S. automobiles since the mid-1990's, compatibility is not expected to be a problem in modern vehicles. Terne plate (a lead-tin alloy coated steel sheet) was commonly used for vehicle fuel tanks, but was largely phased out in the 1990s in response to regulations directed at reducing the environmental impact of the manufacturing process.[21]

In the only modern study that did not use Aggressive Ethanol, corrosion rates of various automotive components made from different metals were measured using electrochemical impedance spectroscopy (EIS), and non-aggressive fuels: E0, E5, E10, and E15.[22] As shown in Figure 1, all corrosion rates measured were extremely small, less than $10^{-3}$ mils/year (i.e. less than 0.000030 mm/year). Medium and low-carbon steel were the most susceptible to corrosion at all levels of ethanol. (Note that, in these figures, there was only a single data point (E10) for brazing alloy and stainless steel.) Contamination of ethanol blends with water reduced solution resistance in all cases, but did not increase the corrosion rate of Al 6061 and copper. For Al 6061, it was proposed that oxygen in the water may contribute to the formation of a thin layer of $Al_2O_3$ on its surface that protects the aluminum from corrosion. No explanation was provided for copper.

**Elastomers.** Elastomers can be used as seals, adhesives and molded flexible parts. The physical properties important in these roles include volume swell, hardness, elongation, permeation, and tensile strength. Changes in weight with exposure are also an indication of fluid permeation into the elastomer. However, volume swell is generally considered the most significant material property.[23] Gasoline and ethanol can dissolve or chemically react with the compounds in elastomeric materials changing the physical properties. Additionally, in many cases in which elastomers are exposed to fluids, they may also undergo dry periods, and the properties of the dry elastomers after wetting may differ from both the wetted and the pre-wetted condition. Thus, most material compatibility testing includes some or all of these physical parameters measured before and after fluid exposure. An important feature of elastomer testing is that for each elastomer type, there is a wide range of properties, depending on the degree of crosslinking, copolymers, plasticizers and other additives, and their concentration. Therefore, quantitative results from two different studies may not agree because elastomers tested were not actually the same material.



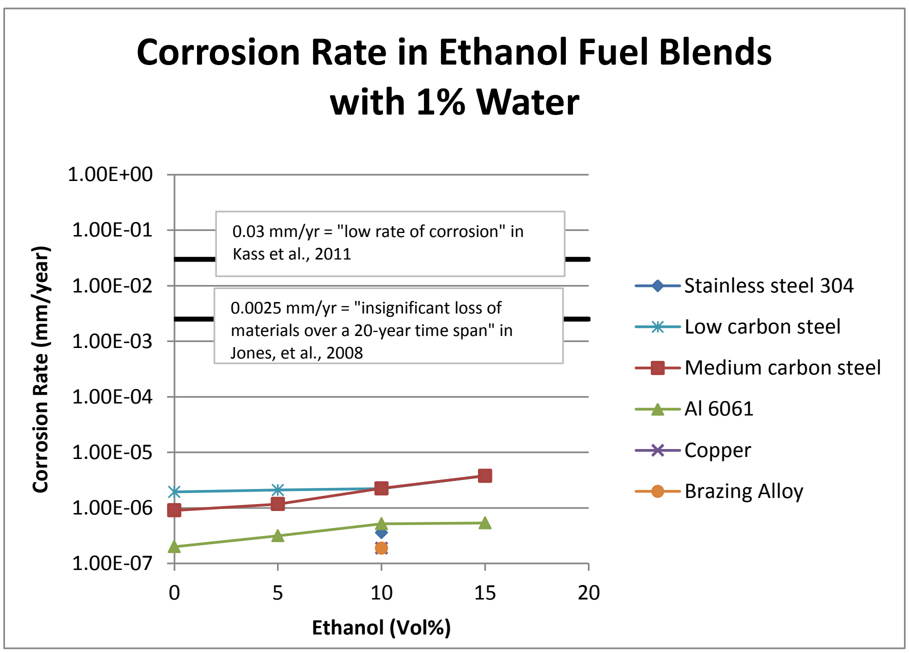




Figure 1. Corrosion rates for various metals as a function of fuel ethanol content, with and without water.[22] Note logarithmic scale for corrosion rate.

Numerous elastomers are already in use in flexible-fuel vehicles, and thus have presumably been tested and approved for use with any ethanol blend between E10 and E85 including E15. These include acrylic ethylene [Vamac®], chlorinated polyethylene, chlorsulfonated polyethylene [Hypalon®], hydrogenated nitrile rubber , fluoroelastomer with terpolymers of VF2/HFP/TFE and 68% fluorine [Viton B®], flouroelastomer with terpolymers of VF2/HFP/TFE and 70% fluorine [Viton GFLT] and Santoprene, according to Mead and coworkers, although no reference was cited. Yuen and coworkers at GM,[14] identify the following polymers as resistant to alcohol-containing fuels in automotive applications: Viton FKM AHV from DuPont, fluorosilicone rubber, and nitrile rubber. Note that a number of the elastomers listed above considered to be relatively impervious to ethanol containing fuels were tested in the studies below and found to swell 68% or more in exposure to E10 suggesting either that high levels of swell can be accommodated in some automotive uses of these elastomers, or that these lists should be considered as somewhat tolerant.

Abu-Isa[24] in an early study on elastomer compatibility with ethanol and methanol blends did not provide results for all of the tests run. However, he does state that for fluorocarbon, fluorosilicone, epichlorohydrin homopolymer, polyester urethane, Hypalon, and nitrile, the most severe effects occur at concentrations of ethanol between 10% and 25%, as opposed to either E0 or E100. Fluorocarbon elastomer and fluorosilicone showed greater swell with E15 than with E10 (7% versus 2% and 20% versus 6%, respectively). Swell was greater with E10 for ecpichlorohydrin homopolymer and Hypalon® (50% and 81%, respectively) than for E15 (specific values not provided). Volume change for polyurethane peaked at E20 with 56% swell, while only showing 51% swell at E10, and for nitrile rubber at E25 with 99% swell, while only showing 68% swell at E10, suggesting a trend of increasing effect between these two concentrations such that these two elastomers might be less compatible with E15 than with E10.

Newer studies have not directly compared the effect of E15 with E10 on elastomers. However, there have been a number of studies employing Aggressive Ethanol blends at various other concentrations. ORNL researchers used E17 as a conservative estimate of actual ethanol content in E15 fuels considering the variable nature of commercially available fuels.[20] However, it is not clear that increasing ethanol content always exaggerates ethanol's impact as they found that the greatest amount of swell could occur with either Aggressive TF10 or Aggressive TF17. They also tested Aggressive TF25 and Reference Fuel C (used as the base hydrocarbon for all four fluids). Other studies done in the 1980s and 1990s, found consistent results that the most pronounced effect on materials occurred in the concentration range of 10% to 35%.[23,25,26]

ORNL's study focused on elastomers used in fuel infrastructure use. Figure 2 is taken from this report and shows dry volume change as a function of wet volume swell. The results generally grouped by material being tested; materials showed similar levels of volume swell and dry volume change in all fluids tested. The differences between Reference Fuel C and Aggressive TF10 were generally larger than the differences between Aggressive TF10 and Aggressive TF17. Differences in swell between Aggressive TF10 and Aggressive TF17 were less than 15% in all cases, and less than 5% if silicone rubber, styrene-butadiene rubber, and polyurethane are excluded. Fluorelastomers (generally approved for FFVs) saw the best retention of baseline properties with all levels of ethanol in the ORNL study. Polyurethane exhibited much greater swell in ethanol fuels than in Reference Fuel C. Various nitrile rubbers (NBR) also showed increased swell in the presence of ethanol. Neoprene, SBR and silicone are not considered satisfactory for standard gasoline use (according to the Parker O-Ring Handbook), thus, although they were tested here they are not likely to be used in automotive fuel systems or engines.

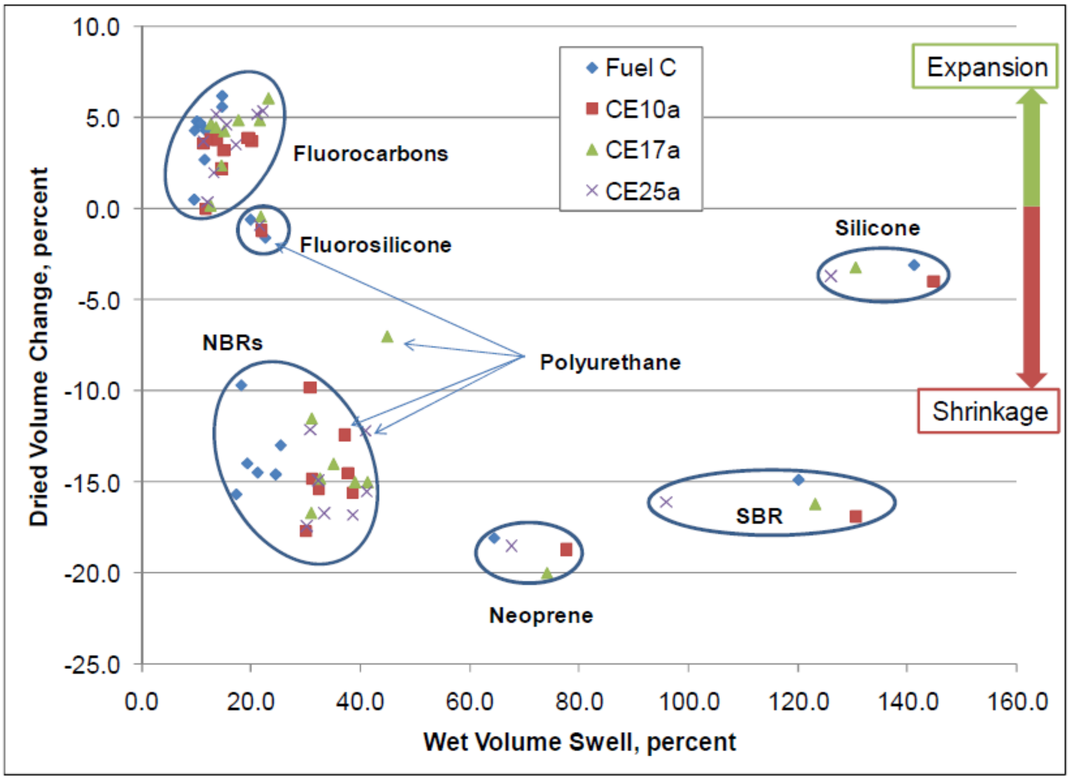



Figure 2. Dry volume change as a function of volume swell for various elastomers exposed to aggressive test fluids.[11]

In the large study conducted by the Minnesota Center for Automotive Research, samples of eight elastomers were soaked for 500 hours at 55 °C in Reference Fuel C, Aggressive TF10 and Aggressive TF20 both made with Reference Fuel C as the base fluid.[9] The following properties were measured before and after soaking: appearance, volume swell, weight, tensile strength, elongation and hardness. All tests were done with 5 different samples for each fuel/material combination. The elastomers tested included a number tested previously in addition to a few more: acrylic rubber, epichlorohydrin homopolymer, epichlorohydrin ethylene oxide copolymer, polychoroprene, nitrile rubber with medium and high CAN content, nitrile/PVC blend, and fluoroelastomer Viton A.

All of the elastomers swelled in size and weight to some extent after soaking with all fuels. Polychloroprene swelled more in Reference Fuel C than in ethanol blends. All the others swelled and increased in weight more in ethanol fuels than in Reference Fuel C, but only epichlorohydrin ethylene oxide copolymer swelled a noticeable extent larger in Aggressive TF20 than in Aggressive TF10, and only acrylic rubber increased in weight a noticeable amount more in Aggressive TF20 than in Aggressive TF10. After dryout period, seven of the eight elastomers shrank down below their pre-immersion size. Only the fluoroelastomer remained larger in size and weight. All of the elastomers in all three fuels became softer, and tensile strength was reduced and elongation was reduced after soaking. One elastomer, acrylic rubber became softer in Reference Fuel C than in either of the ethanol fuels. When comparing effects of Aggressive TF10 and Aggressive TF20 there was no significant difference in the effect of the two fluids on hardness and tensile strength. Only one of the elastomers epichlorohydrin ethylene oxide copolymer was affected more by Aggressive TF20 than Aggressive TF10, but the difference was small and considered unimportant. After dryout, acrylic rubber specimens exhibited higher loss in tensile strength and elongation than in E10 or Reference Fuel C. This loss in tensile strength and elongation was much less than the loss immediately after soaking so it was not considered significant.

Although, no statistical analysis was performed, the graphic presentation conclusions suggest that in the cases where Aggressive TF20 caused a change greater than that of Aggressive TF10 and Reference Fuel C, the magnitude of the difference was not significant. As with the ORNL study, the difference between materials was more important than the differences between the fuels.

In a separate study[27] of various fluoroelastomers, coupons were soaked for 168 hours, and tested before and after for changes in volume, hardness, tensile strength and elongation. Generally, fluoropolymers with the lowest concentration of fluorine showed greater changes in tensile strength, elongation, swell and hardness with all fuels. Changes were more pronounced with E25 than with any of the other concentration ethanol blends. The weakest effects were for 100% ethanol or hydrocarbon gasoline.

**Plastics.** In the past two decades plastics have replaced metals in some fuel system functions, in order to reduce weight and reduce emissions (by replacing terne-coated tanks which included lead), while maintaining structural integrity. Generally, modern fuel tanks hold up well to alternative alcohol fuels, according to GM,[14] however some older polymer tanks were treated with sulfonation or fluorination and have not been validated for use with alcohol fuels. Polybutylene terephalate or polyurethane foams, both occasionally used in fuel level floats, have been found to be sensitive to higher alcohol contents.[14]

Numerous plastics are already in use in flexible-fuel vehicles, and thus are approved for use with any ethanol blend between E10 and E85 including E15. These include ethyl vinyl alcohol, polyamide 12 conductive version, polyamide 46, polyphtalamide, high density polyethylene (HDPE), low density polyethylene, polypropylene (PP), polyphenylene sulfide, polyoxymethylene, Zytel®, and polyterafluoroethylene (PTFE) according to Mead and coworkers, although no reference was cited.

The Minnesota Center for Automotive Research tested samples of eight different plastics in Reference Fuel C, and two ethanol blends in Reference Fuel C, Aggressive TF10 and Aggressive TF20.[9] Before and after soaking, the samples were tested for volume, weight appearance, impact resistance, tensile strength, ultimate elongation. The list of plastics tested: acrylonitrile butadiene styrene (ABS), polyamide 6 (PA6)[Nylon 6], polyamide 66 (PA 66)[Nylon 66], polybutylene terephthalate (PBT), polyethylene terephthalate (PET), polyetherimide 1010 moldable (PEI), polyurethane 55D-90Adurameter hardness (PUR), and polyvinyl chloride flexible version (PVC) was created from literature reviews, manuals, and recommendations from fuel system and engine manufacturers, according to authors. Although, in their conclusions they determine that they cannot identify any automotive fuel system use of ABS, PUR or PVC. Several of the tested plastics were worse in the ethanol blends than in Reference Fuel C, but no significant difference was observed between the Aggressive TF10 and the Aggressive TF20 . The authors conclude PA6, PA66, PET and PEI were compatible with all three fuels and ABS is totally incompatible with all three. PVC has lesser problems with all three fuels, but it is worse in the ethanol containing fuels. PUR is not compatible with ethanol fuels. It was concluded PBT is not compatible with ethanol containing fuels.

The Oak Ridge National Laboratory also tested various plastics in Reference Fuel C based E0 and Aggressive TF25, as well as several higher levels of ethanol concentration.[28] Because no testing was conducted on E10 or Aggressive TF10, it is difficult to determine which effects were due merely to the presence of any level of ethanol, and which represented changes that would be significant when comparing ethanol concentrations in the levels between E10 and E15.

Plastics tested included the thermoplastic materials polyphenylene sulfide (PPS), polytetrafluoroethylene (PTFE), polyvinylidene fluoride (PVDF), polyester (3 types), nylon (4 types), acetal (2 types), polypropylene (PP), polythiourea (PTU), high-density polyethylene (HDPE), and fluorinated high-density polyethylene (F-HDPE). The thermosets included two isophthalic polyesters, one terephthalic polyester, one vinyl ester, and two epoxies. Note that Mead and coworkers identified a number of these as in use in flex-fuel vehicles, including polyphenylene sulfide (PPS), polyterafluoroethylene (PTFE), polypropylene (PP) and high density polyethylene (HDPE). The materials were tested for changes in volume, mass and hardness after soaking. The best performing materials in all fuels were PPS, polyethylene terephthalate (PET) and PTFE. Polypropylene and HDPE were unique in that the highest volume increase was found with exposure to Reference Fuel C, and diminished with increasing ethanol concentration. The volume change of PP, HDPE, PETG, and the thermosets showed a positive correlation with ethanol concentration. In contrast, the other plastic materials showed little to no change in volume swell for the Aggressive TF25 and higher ethanol content test fuels. In general, volume swell was correlated with softening. Significant softening was found in PP, PETG, nylon 11, and the thermosets.

## Analysis

Eight laboratory studies plus several literature reviews were reviewed on the response of metals, elastomers, and plastics to contact with various ethanol hydrocarbon blends. Elastomers and plastics were evaluated on numerous properties which varied between the different studies, although volume swell and mass increase were consistently considered. Both of these parameters are significant for many uses of materials, imply the likelihood of other effects, and are straightforward to test. Metals were evaluated for corrosion rate using well documented methods that could be repeated by other researchers.

These results, by themselves, are not adequate to disqualify materials, without understanding the specific requirements for which the material will be used. Rather, these results should be used as a general guide to identify materials which are affected by small changes in ethanol concentration, so that their use in vehicles can be further examined to determine whether or not the changes are significant enough to affect long term durability. There is little publicly available evidence to determine what would be acceptable results for the various materials tested. To the extent we have been able to draw conclusions on the acceptability of various materials it is based on comparisons with materials believed to be acceptable for flexible fuel use, or by comparison with results of materials in E0 or E10.

The effect of higher ethanol concentration fuels relative to control fuels on specific materials was generally consistent across the studies, suggesting that the general conclusions of this review on the effects of E15 versus E10 are relatively robust. Results of performance measurements on specific materials were frequently below measurable rates (metals corrosion) or could not be compared between tests as test materials, fuels, time of exposure, and exposure conditions varied widely.

Much of the testing reviewed here uses J1681 Aggressive Ethanol in the test fluids and Reference Fuel C as the base fuel. These are fluids which were developed to represent certain worst-case conditions and were not intended to be used for comparisons as the relationship between the effects of these fluids and typical fuels is unknown. However, if effects with Aggressive TF10 and Aggressive TF20 are below levels of concern, it suggests that the less reactive commercially available E15 will not present an issue in-use. Moreover, if Aggressive TF10 and Aggressive TF20 (or Aggressive TF17) show little difference in effects, it is reasonable to theorize that Aggressive TF15 and Aggressive TF10, and by extension non-aggressive E10 and non-aggressive E15, will also show little difference in materials effects.

All the reported results on plastics and most of those on metals and elastomers were conducted with Aggressive Ethanol and Reference Fuel C blends. The only metals study using non-aggressive blends showed extremely low levels of corrosion (less than $10^{-5}$ mm/year). The two other metals studies used much higher minimum detection levels and so direct comparisons between standard and aggressive fuels were not possible.

## Findings

There has been little testing of material compatibility that directly compares E15 to E10, however, many automotive materials have already been approved for use in flex-fuel vehicles where they are exposed to ethanol concentrations at all levels from E0 to E85.

Early testing, using ethanol concentrations ranging from zero to 100% ethanol, suggests that corrosion rates and effects on elastomers often peak at ethanol concentrations somewhere between E10 and E35. Corrosion inhibitors are added throughout the fuel distribution system, but none of the studies reviewed incorporated the types of corrosion inhibitors commonly found in the fuel supply. Thus, in some cases it is unclear how a study relates to the typical real world experience of ethanol blended fuels that do contain these additives.

Testing of metals has found that corrosion rates with all fuels and almost all metals were below measurable rates (0.030 mm/year or lower) for all those tested with Aggressive TF20 or Aggressive TF17 with Reference Fuel C as the base fuel, with the exception of Zamak 5, no longer in common automotive use and Magnesium AZ91D which was more corroded by Reference Fuel C than either of the ethanol blends tested. A test on four other metals using non- Aggressive E15, E10, E5 and E0, showed steadily increasing corrosion rates for higher ethanol content fuels, but the overall corrosion rates, were below $10^{-5}$ mm/year. Water has a pronounced effect on conductivity of hydrocarbon-ethanol blends, but its inclusion at concentrations of up to 1% in E15 and Aggressive TF20 blends, did not raise corrosion levels to above 0.030 mm/year. Thus, the materials compatibility testing provides no evidence that 15 volume percent blends will cause increased rates of corrosion in comparison to 10 percent blends.

Unlike metals, elastomers and plastics showed some measurable effects from exposure to gasoline hydrocarbons with increasing ethanol content. The largest changes in material properties typically occurred between 0 and 10 volume percent. Differences between E10 and E15 were not statistically significant in most cases. Differences between materials were far more significant than differences between fuels. The reported results suggest that elastomers and plastics rejected for material compatibility reasons for use with E15 would also be considered unacceptable for use with E10.

It is important to note that the criteria that an OEM would apply in selecting a material for a given application are unknown. The various materials compatibility studies compare materials based on standard metrics. It is not possible to say if a material meets or fails the unknown performance requirements for a specific usage.

# Engine and Fuel System Durability

## Introduction and Background

Studies reviewed involved soaking or operating fuel system components, engines, or whole vehicles on E15 or E20, typically with a control group operating on E0 or on E10 (or corresponding test fluid). It is important to note that in comparison to material compatibility testing fuel system and engine durability testing adds another level of complexity because of the following factors:

- The large number of different makes and models of vehicles each of which may react differently to different fuels, even when limited to MY 2001+, making it difficult to use individual tests to provide fleet-wide estimates of the impact of changing fuels. The most comprehensive test reported here included only 27 different make/model/model year combinations.
- Only a very low failure rate is acceptable. A recent CRC document states that OEMs typically consider parts failure rates of less than one in one thousand acceptable.[29] Testing of a thousand or more repeats of each different component would be necessary to ensure this level of dependability in a statistically defensible manner. Many of the tests here included no replications; the most was 6 of the same component in the same fuel.
- The high cost of testing components, engines, and entire vehicles is a severe practical limitation. Engines and vehicles may cost $15,000 or more per test and even small components can represent significant expense. Then it is necessary to add in the cost of developing and building systems to operate the components or vehicles for an extended time period to represent a lifetime of vehicle operation.

In addition, the issues associated with choosing appropriate test and control fluids and scaling up short term testing results to long term predictions are applicable.

## Discussion

**Fuel System Component Durability.** The CRC published two reports on fuel system component testing intended to identify the most sensitive components and vehicles. The first, CRC Report No. 662,[17] reported on pilot testing using Modified Aggressive TF20 on a selection of fuel pumps, fuel dampers, level senders, fuel injectors and entire fuel system rigs in an attempt to identify sensitive parts for further testing. Testing was done on new components sold as service parts for MY 1996 to 2009 vehicles and purchased from local OEM dealerships. Design changes may have occurred since the original designs, and thus the tested parts may not be exactly the same as those originally installed in the vehicles.

The complete fuel system rigs were tested on all fuels, but for the other components only some of those tested on Modified Aggressive E20 were tested on either E10 or E0. Generally, the only components which were tested on E10 were those which did poorly on Modified Aggressive TF20. These strategies, while understandable from a cost perspective, can mask the possibility that failures are due to random component defects or excessively harsh test fluids or test conditions rather than fuel effects. Additionally, when comparing the results of Modified Aggressive TF20 with E10, it is necessary to consider whether the differences were due to changes in ethanol content or due to the additional acids in Modified Aggressive TF20. Some qualitative differences attributed to differences in fuels were found on visual inspection of fuel system rigs after testing, but nothing significant enough to lead to the loss of pressure over the test period.

Fuel pumps were tested in a soak test and an endurance test, which included operation of the pump. All ten soak durability tested fuel pump models were tested on the Modified Aggressive TF20, three were tested on Modified Aggressive TF10 and one on E0. None of the tested pumps failed, defined as a decline in flow rate of more than 30%. The endurance aging study was conducted on eight pumps. Three of the pump models tested in E10 showed a lesser decline in flow rate than the Modified Aggressive TF20 pump, one showed a greater decline in flow rate. Only one pump model (Pump A) exceeded the acceptable 30% flow rate loss, and it did this in both Modified Aggressive TF20 and regular E10, but not when tested in E0.

Eight different fuel level sender models were tested in two different aging protocols with Modified Aggressive E20. A selection of these models were retested in E10 and E0 on one or both tests, but there was no explanation as to why the specific models were selected for testing in E10 or E0, although generally those that had no problems operating in Modified Aggressive E20 were not (with one exception) retested in E10 or E0, and those which failed on both Modified Aggressive TF20 and E10 were not tested on E0. Thus, only three models were tested in E0, and these were tested on only one of the aging protocols, but all passed. Some testing was done in replicate, although there is no consistent or stated strategy. The results are presented as a qualitative description, and so in some cases it is not clear which senders exhibited unacceptable levels. Only two out of the eight senders exhibited no problems at all in Modified Aggressive TF20 in either test, but given the uneven testing strategy it is not possible to compare these results summarily to those in E10 and E0.

Two fuel dampers, both of the same make and model were tested in all three fuels. No difference associated with test fuels was found. Four injectors of each of three models of fuel injector were tested on Modified Aggressive E20 for 600 million cycles. The report concludes that "neither showed any significant difference between pre- and post-aging dynamic response".

Based on these results the CRC identified fuel pumps and fuel senders as potentially more sensitive than other parts to ethanol content in fuel and so conducted additional testing on those components which was reported in CRC Report No. 664.[29] CRC Report No. 664 does not identify the source of the specific parts only that they were from one of the following five popular vehicles: 2007 Nissan Altima, 2001 Chevrolet Cavalier, 2004 Ford Focus, 2003 Nissan Maxima and 2004 Ford Ranger.

The same laboratory test protocols were followed in this round of testing with fewer models and more replicates. One fuel pump model Vehicle N (of the three tested) failed with Modified Aggressive TF20, Modified Aggressive TF15, and E15 but not with E0 or E10 on soak durability. Interestingly, the same part did not fail in CRC 662 when tested on Modified Aggressive TF20 or TF10, although it was one of the more sensitive pumps of the ten tested in terms of loss of flow rate. During teardown they found vanes of the impeller had been damaged and measuring impeller thickness they found greater variation in width with impellers tested on E15 and Modified Aggressive TF15, than those tested on E0. Six fuel pumps each from two vehicles were also tested for 3000 hour endurance tests in E15 and Modified Aggressive TF15 (did not include Pump from Vehicle N which failed in soak test). Results showed six out of six pumps tested failed in E15, and six out of six in Modified Aggressive TF15. No failures were found in E0. However, since no testing was conducted in E10 or Modified Aggressive TF10, we cannot draw any conclusions regarding the difference in impact between E10 and E15. Vehicle N fuel pumps were retested with E15, Modified Aggressive TF15 and Modified Aggressive TF20 after the results from the other experiments were available. No control E0 or E10 was used for this last round of testing. While failures were observed for Vehicle N fuel pumps in work reported in CRC Report No. 664, the fact that the same pump model operated without failure on E15 in work reported in CRC Report No. 662 renders these results inconclusive.

Three fuel level senders, six replicates each, were tested in E15 and Modified Aggressive TF15. While not consistent and not found in all samples tested, there were some effects on the sender operation. However, since control tests on E10 and E0 were not conducted there is no evidence that these fuel level senders were adversely affected by the higher ethanol content in E15.

However, it should be noted that Pump N was selected as the result of a program to find the most ethanol sensitive pump available. It is not representative of most pumps on the road. No analysis of the ethanol used in this program was included and it presumably did not include corrosion inhibitors, normally considered standard for commercially available ethanol. The certificate of analysis for some of the fuels used in the testing had expired. In light of these irregularities, and considering the results described above on material compatibility testing that showed that differences in effects between E15 and E10 were consistently small and in many cases impossible to detect, results which show six out of six pumps completely failing with E15 and Modified Aggressive TF15 while zero out of six pumps fail under the same conditions with E10 are surprising and potentially worthy of retesting. Unfortunately, the CRC (because of confidentiality agreements with the OEMs) is unable to identify the make or model, or even the materials of either this failed pump or the acceptable components and thus, the benefits of the information in these reports to the general scientific and engineering community are limited.

Similar test procedures were used by the Minnesota Center for Automotive Research[30,31] on fuel pumps and fuel level senders using Reference Fuel C, Aggressive TF10 and Aggressive TF20 (both with Reference Fuel C as base fuel). However, rather than choosing components considered more likely to fail these researchers targeted a “broad sample of high volume vehicles on the road” , by choosing pumps and fuel unit senders from a variety of manufacturers, model years and designs. In the initial soak test individual samples of eight different model fuel pumps and three different model sending units were tested in each fuel. All of the fuel pumps met the performance requirements (J1537) for startup before and after soak. All modern vehicle fuel pumps showed an increase or decrease of less than 20%, which is within the range that is considered normal. Other than that, no trends in flow rate change by fuel were found. Visual inspection found no change in sending units and resistance and voltage drop of the units was unchanged before and after soak.

Following the soak study, an endurance study, in which the same pumps and senders were operated continuously, was carried out. Performance data was collected before the study started and then every 500 hours. At the end of the study the pumps were disassembled and inspected. Four of the pumps failed before the test was completed, two in Aggressive TF10, two in E0. Commutator wear was consistently higher in gasoline than in ethanol fuels, and the less ethanol the more wear. All of the sending units failed over the course of the 4000 hour study. No significant differences between the time of failure and the fuels tested were found.

**Engine Durability.** The CRC conducted an engine durability study of intermediate-level ethanol blends effects on several models of current, on-road non-Flexible Fuel Vehicles (non-FFVs).[32] The objective of the study was to assess engine component wear caused by ethanol containing fuels over the course of a 500 hour test cycle simulating 100,000 miles of operation. Engines were tested with E20 and if a failure was observed then tested on E15. Vehicles which failed on both E20 and E15 were tested on E0.

There are several characteristics of standard engines which might be sensitive to higher ethanol content in fuel.[33] Some valve seat materials are claimed to be sensitive to ethanol and can experience increased wear. An increase in valve seat wear can lead to a variety of problems including valve leakage, valve burning, compression loss, misfire, power loss, and catalyst damage. Also, it is possible that increased solvency of lubricants in ethanol containing fuels, could result in an increase in bore and ring wear, leading to increased blow-by, oil consumption and compression and power loss. Finally, if ethanol caused an increase in engine exhaust temperature this could be damaging to catalysts. In order to determine how significant these effects could be for modern non-flexible fuel vehicles, the CRC conducted a durability test program on eight different vehicle models.[32]

As failures among typical vehicles are expected to be rare, the CRC testing was intended to maximize the number of failures in order to make it possible to differentiate between fuels. Several technologies have been developed to improve valve and valve seat performance in modern engines. In order to include the vehicles most likely to have valve problems, the CRC specifically chose vehicles that did not utilize these technologies and were more likely to experience valve problems. They specifically chose engines with the following characteristics:

- Mechanical valvetrains; these designs have the smallest ability to accommodate valve and valve seat wear
- Hydraulic lash adjuster valve trains; these designs also can tolerate only small changes in valve and valve seat wear if they are designed to only allow a small amount of travel.
- Valve trains using less than top grade valve materials

The list of vehicles is included in Table 3 below.[32] This list included several engines already known to have durability issues, including one that was subject to a recall involving valve problems when running on E0 and E10.[34] The vehicles selected were all recruited from the used car market.

Table 3. Vehicle / Engine data for the CRC engine durability study.

| Vehicle | Emissions | Valve Train Design | Mileage for E20 vehicles* | OEM specified acceptable leakdown rate [35,36,37,38,39,40,41,42] |
|---|---|---|---|---|
| 2001 Honda CR-V, 2.0L I4 | Tier 1 NLEV | Rocker arm, threaded adjuster | 71,412/110,681 | No leakdown specification provided |
| 2002 Volkswagen Jetta, 2.0L I4 | Tier 1 NLEV | Direct acting, hydraulic | 77,891/106,761 | No leakdown specification provided |
| 2004 Scion xA, 1.5L I4 | Tier 2 Bin 9 | Direct acting, mechanical | 61,351/56,671 | No leakdown specification provided |
| 2005 Chevrolet Colorado, 3.5L I5 | Tier 2 Bin 9 | Roller finger follower, hydraulic | 48,109/33,972 | "Cylinder leakage that exceeds 25% is considered excessive and may require component service." |
| 2007 Ford Edge, 3.5L V6 | Tier 2 Bin 5 | Direct acting, mechanical | 17,906/14,450 | "Leakage exceeding 20% is excessive." |
| 2007 Dodge Ram, 5.7L V8 | Tier 2 Bin 5 | Pushrod, hydraulic | 28,597/26,078 | "All gauge pressure indications should be equal, with no more than 25% leakage." |
| 2009 Dodge Caliber, 2.4L I4 | Tier 2 Bin 4 | Direct acting, mechanical | 11,941/12,494 | "All gauge pressure indications should be equal, with no more than 25% leakage." |
| 2009 Chevrolet Aveo, 1.6L I4 | Tier 2 Bin 5/4 | Direct acting, mechanical (but service literature references 2nd running change design to hydraulic lash adjuster; type is not documented by CRC) | 8,327/3,758 | No leakdown specification is provided, and leakdown is not even referenced as a diagnostic tool / method. |

*CRC did not report initial mileage for vehicles tested on E15 or E0.

The test cycle selected for this study was a modified engine durability cycle from an unspecified OEM. The durability test cycle schematic published in CRC's report does not contain enough detail to allow it to be independently reproduced, likely to protect OEM intellectual property.[32] In particular, loads (even in terms of manifold vacuum) and details describing the 1-2-3 wide open throttle (WOT) accelerations are absent.

The cycle was modified to limit maximum engine speed to less than 3500 rpm. The speed limitation was intended to "significantly reduce the test severity making it more likely that the test engines will complete the test without failures unrelated to the test objective" (i.e. the intention is to show fuel related failures) but it also had the effect of increasing the likelihood of valve damage, because low speed operation may decrease valve rotation rates and valve rotation is used to clean deposits off the seat, continuously spread the lubricant around the seating and distribute wear and pitting uniformly around the seat. Some scientists have suggested low speed operation decreases oil pullover[43] potentially also increasing wear.

The final CRC report[32] did not state how the (simulated) vehicle data was specified for the engine dynamometer durability test cycle, notably what vehicle and trailer weights were used. So it is not clear if CRC used weights proposed in their Request for Proposals of "vehicles at 80% of GVW or 80% GVW plus 80% of allowable trailer weight for those that allow trailers".[33] The final CRC report only states: "Relating test cycle duration to vehicle mileage involves vehicle weight and tow capacity, transmission and final drive gear ratios, and engine power and torque curves. Nonetheless, the test cycle used should correlate with ~100,000 miles of vehicle usage."[32] The durability cycle was run with engines removed from vehicles and tested on engine dynamometers with umbilical systems to utilize the OEM Engine Control Module, which was retained in the vehicle.

The engines were tested for the following before and after the 500 hour durability cycle for the following parameters

E = emissions during FTP75 (mostly vehicle, but a few test were conducted on the engine dynamometer)

D= presence of diagnostic trouble codes,

V= valve clearance measurement out of OEM specification,

C = compression measurement, compared to OEM specification,

L= leakage measurement on at least one cylinder above 10%

Results are shown in Table 4. Vehicle 8 failed on all fuels and these results were not included in subsequent statistical analysis based on the idea that the test cycle was too severe for this particular engine model because it was sensitive to the low engines speeds with respect to valve rotation. Vehicles 2 and 3 both exhibit failures on E15 for leakdown and Vehicle 2 also fails for emissions.

Table 4. Summary of Engine Durability Test Results

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

*Waived = Vehicle did not pass specified criteria, but after OEM teardown decision was made not to retest vehicle on E15 or E0

** According to the study text, Vehicle 1, Sample A "The Engine dynamometer based EOT emission test was waived after technical challenges prevented comparison of the SOT [start of test] and EOT [emission data]."

EPA permits emissions to degrade over the life of the vehicle and emissions are not expected from a regulatory standpoint to meet standards beyond what is considered full useful life of the vehicle, which is typically on 120,000 miles for Tier 2 vehicles and 100,000 for Tier 1 vehicles. The vehicles in this study ranged from 2001 to 2009 model year and were selected to have accumulated no more than 12,000 miles per year. Thus, the older vehicles in this study may have greatly exceeded equivalent full useful life during the course of the 500 hour durability test cycle, given that it was intended to simulate approximately 100,000 miles of use; and thus should not be expected to meet emission requirements. Even the 2009 model year vehicles, assuming they were tested during 2011, could have exceeded full useful life mileage.

The selection of leakdown loss of 10% or less as passing is very significant in the analysis of the data. All of the vehicles which failed for leakdown, with the exception of Vehicle 8, had leakdown values of 22% or less on the worst performing cylinder. As seen in Table 3, Honda[35] and Scion[37] do not specify leakdown in their service literature. VW also states no OEM leakdown specification, instead stating, "leakdown limit specifications are usually supplied by the equipment manufacturer,"[36] referring to the leakdown testing equipment. Ford specifies leakage exceeding 20% to be excessive and that leakdown be used as part of a comprehensive analysis including other measurements.[39] Chrysler specifies no more than 25% leakage.[40,41] General Motors specifies 25% leakage to be excessive for the Chevrolet Colorado in its manual,[38] but specifies no limit and does not reference the use of leakdown testing diagnostics for the Chevrolet Aveo.[42] To further complicate the issue, diagnostic instructions related to an intake valve seat recall on the Chevrolet Colorado (one of the vehicles studied), General Motors recommended using the leakdown test to find the leak path, and did not specify a threshold acceptable leakdown number.[44]

CRC used the same Snap-On® EEPV309A leakage tester for all measurements in the study. The owner's manual for the Snap-On® EEPV309A leakage tester provides a summary for its use: "*The cylinder leakage tester is a useful diagnostic test, however, it is a test for which vehicle manufacturers do not provide* *specifications. Due to standard engine tolerances and normal wear, no cylinder will maintain 0% leakage. Engines with larger cylinders diameters will tend to show a larger percentage of leakage than engines with smaller cylinder diameters, given that both engines are in the same condition. Because of these factors, this tool is best used to compare a suspect cylinder to a known good cylinder on the same engine.”*[45] The use of leakdown testing as a qualitative diagnostic tool is most valuable to identify a suspect cylinder (higher leakage than other cylinders) and locate the leak path (intake, exhaust, crankcase, water jacket, or to an adjoining cylinder) to troubleshoot the issue. Ford reinforces this diagnostic methodology in their service manual.[39]

Engines found to fail leakdown in the report were torn down and evaluated. However, since the valve seats were not inspected prior to the 500 hour/100,000 mile durability test and some of the vehicles had potentially more than 100,000 miles on them at the start of testing, it does not seem possible to determine what valve seat damage was done during the test period with the test fuel, and what was done prior to the test.

Oak Ridge National Laboratory explored the limitations of both leakdown and compression testing, concluding they are “not useful in their present forms for monitoring incremental changes in engine leakage”.[46] In contrast, CRC selected a 10% leakdown failure limit, more restrictive (50% below) than that of the lowest value specified by OEMs for engines in the study. Unfortunately, CRC did not report the leak path (intake, exhaust, crankcase, water jacket, or adjoining cylinder) for any of the engines that were deemed to have failed due to leakdown. The diagnostic values that may have linked engine failure to possible ethanol effects (intake valve) versus likely unrelated failures (water jacket or adjoining cylinder) were not reported.

Based on the factors discussed above, the conclusion that engines marginally failing emissions beyond full useful life, or showing cylinder leakdown between 10% and 25%, have experienced a fuel related mechanical failure is not supported by the study data.

The report also included a statistical analysis of the data. The purpose of the analysis was to determine whether the failure rate was associated with the ethanol content of the fuel, or some other variable. However, the values used in the analysis assumed that every vehicle that passed on E20 also passed on E15 and E0. Assumed values were put in for vehicles that were not tested, and those values had a consistent bias in relation to the question that the analysis was intended to determine. The analysis did not include testing on the 8$^{th}$ vehicle, which failed on all fuels. If all of the actual test results (i.e. including Vehicle 8), and only those values are used for the analysis, there is a 32% chance that E15 and E20 failures are completely unrelated to ethanol content, as opposed to the 7% chance that is asserted in this report. Moreover, at the very simplest level, 5 out of 16 tested vehicles failed on E20 – 31%; 5 out of 6 on E15 – 83%; and 2 out of 6 tested vehicles failed on E0 - 33%.

Almost half of the vehicles (Vehicles 4, 5, and 6) in the initial E20 tests were treated as Passed, not due to the quantitative criteria initially chosen for the study, but rather on an assessment of the engine at end-of-test (EOT) by different OEMs – which may or may not be consistent with the OEM inspections done on Vehicles 2, 3, and 8 – which Failed.  Vehicle 4 failed leakdown and was passed based on the recommendation of the OEM and noting that leakage was 11%. Vehicle 5 failed emissions and had a related DTC, however the OEM stated that there were known catalyst problems with Vehicle 5 and that the type of failure observed was not caused by increasing ethanol content of the fuel. Vehicle 6 (both engines A and B) failed for leakdown but upon engine tear down the valve seats did not show any abnormal deposits or wear and were acceptable to the OEM. Because these failures were determined by the OEM to not be fuel related, these engines would be equally likely to fail with testing on E15 or E0.

**Whole Vehicle Testing.** Two programs operated relatively large numbers of vehicles for extended times on various ethanol concentration fuels. The first, at the University of Minnesota[47], conducted from 2006 to 2007 included 40 pairs (80 total) of similar 2000 to 2006 model year vehicles with matched usage patterns. One of each pair was fueled with commercially available E0, and the second set was fueled with E20 (additional ethanol splash blended with commercially available E10). The fuels did not have the same hydrocarbon base fuel. Over the 13 month test period no additional fuel related maintenance problems emerged in the E20 fuelled vehicles. Two vehicles in the program had check-engine lights illuminate. In one case, the fuel system pressure regulator failed. The shop manager indicated that this was a common problem with the specific make and model. The other case involved mice damaging the electronic control unit. The data presented in this study does not show any performance differences between E10 and E20.

In the second program[48], the Oak Ridge National Laboratory and the National Renewable Energy Laboratory conducted an extensive aging study on 82 MY 2000-2009 vehicles. The primary purpose of the testing was to assess the effect of different fuels on catalyst aging. Four vehicle pairs were aged with E0 and E15. Five vehicle sets, each comprising four matched vehicles were aged with E0, E10, E15 and E20. The remaining eighteen vehicle models were aged with E0, E15 and E20. Vehicles were aged at least 50,000 miles using EPA's Standard Road Cycle (SRC) at three different facilities, the Southwest Research Institute, the Transportation Research Center, and Environmental Testing Corporation.

Unscheduled maintenance was logged, and affected equipment was removed and analyzed for potential fuel effects. Transmission, spark plug and radiator failures were unrelated to fuel use. Possible impacts on tailpipe emissions systems are discussed elsewhere. However, impacts on the fuel supply system include the replacement of two fuel pumps in 2001+ MY vehicles (plus a fuel pump and a fuel level sender in a 2000 MY vehicle). The first was in a 2006 Chevrolet Silverado, the second was in a 2006 Chevrolet Cobalt. Upon further inspection both failures in these used cars were determined to be unrelated to fuel effects by the researchers. In addition, an evaporative emissions hose, believed to be made of nitrile rubber, failed on a 2002 Dodge Durango. No differences could be detected between the inside and the outside of the hose, so the failure was attributed to general aging, rather than fuel effects. All three (E0, E15 and E20) 2006 Chevrolet Impalas experienced canister vent solenoid failures, that were determined to not be fuel related given that failures occurred on all fuels.

After vehicle aging was complete the ORNL did a tear-down study[49] of eighteen (six makes and models from the model years 2006 to 2008, each run on E0, E15 and E20) of the vehicles.  Of greatest concern with the E15 vehicles was an increase in intake valve deposits (IVD) which authors attribute to the fact that the detergent in the gasoline was diluted by ethanol. The weight of IVD in vehicles run on E15 was higher than that of those run on E0 and E20 was generally higher than both. While normally BOBs are dosed with the appropriate detergent level to account for the added ethanol that was not done for the test fuels in this study. The integrity of the emissions system was pressure checked and all of the tested systems maintained pressure. Valve seat width and valve surface contour were assessed and no differences were found between fuels. Fuel injector flow rates were equivalent to within +/- 3%. The evaporative canister working capacity shows a slight decreasing trend with higher ethanol content fuels for two of the six vehicles. Fuel tanks, fuel lines, and evaporative emissions lines were visually inspected and no "serious differences" between E0, E15 and E20 were reported. Effects on cam lobe wear, valve stem height, and valve seals were measured but the results were considered inconclusive because similar measurements were not made at the beginning of the study, before mileage accumulation.

Lubricating oil consumption was measured over the course of the testing. One of the 2007 Honda Accords was found to use excessive levels of lubricating oil when operating on E10 and the vehicle was replaced in the test program. Engine oil drain samples were monitored several times over the course of the test. There was no evidence of excessive metals in any of the engine oil samples. There were no statistically significant differences in oil consumption attributed to the ethanol level in the fuel.[50]

## Analysis

Four studies of fuel system component durability, one of engine durability, and two whole vehicle studies were reviewed.

The fact that E10 comprises more than 95% of the US commercial fuel market suggests that it is the appropriate control fuel for testing. The use of E0 in place of E10 as the control fuel is not appropriate, because various studies have demonstrated that the effects of ethanol are not linear. There is a much more significant difference between E0 and E10 than between E10 and either E15 or E20 as shown in material compatibility testing. If a study tests E15 or E20 in comparison to E0 and sees no negative effects of ethanol, then the E10 control may not be necessary. If, on the other hand, E15 or E20 cause problems, it is unclear if the problems are caused by higher levels of ethanol in the fuel or if they are caused by other factors such as test components not being compatible with E10, the dominant marketplace fuel. If a component is incompatible with E10 then it would be logical to assume that it will be equally incompatible with blends marginally higher than E10 such as E15.

Component durability studies used aggressive test fluids with undefined acceleration factors and poorly understood connection to real world fuels, as described above in the Materials Compatibility section. Two CRC studies employed a Modified Aggressive Ethanol that contained nitric and hydrochloric acids in place of sulfuric acid.[17,29] The recipe for Modified Aggressive Ethanol is shown in Table 1, and compared to commercial ethanol samples and Aggressive Ethanol in Table 2, both presented in the previous section. The stated reason for using nitric and hydrochloric acids was to reduce the sulfate content, to below that of the requirement set in D4806, and raise the chloride content to closer to the D4806 limit.

CRC stated it was essential to keep the pHe low even though the resulting value was far lower than the allowable D4806 value, and so added nitric acid instead of sulfuric.

The use of nitric acid in CRC's Modified Aggressive Ethanol is a concern, since nitric acid is both a strong acid, and an oxidizing agent. Sulfuric acid can also act as an oxidizing agent, but not at the low concentrations in J1681 Aggressive Ethanol. Copper, in particular, reacts with nitric acid, while being impervious to sulfuric acid at the low concentrations in Aggressive Ethanol. Elastomers are also consistently less resistant to nitric acid than sulfuric acid as shown in the table below. The table considers solutions several orders of magnitude more concentrated than those in Aggressive Ethanol and Modified Aggressive Ethanol, but this was the best comparison information available and is representative of the relative reactivity of the two acids in the presence of elastomers. Modified Aggressive Ethanol, with its lower pHe and the use of nitric acid in place of sulfuric acid, is expected to have more severe effects on many materials than Aggressive Ethanol.

Table 5. Compound compatibility rating with sulfuric acid (used in Aggressive Ethanol) versus nitric acid (used in Modified Aggressive Ethanol) from Parker O-Ring Handbook.[51] 1= Satisfactory, 2=Fair (usually OK for static seal), 3=Doubtful (sometimes OK for static seal), 4=unsatisfactory.

| | Nitrile NBR | Hydrogenated Nitrile HNBR | Ethylene Propylene EPDM | Fluourocarbon FKM | Hifluor FKM | Perfluoroelastomer FFKM | Neoprene/Chlorprene CR | Styrene-Butadiene SBR | Polyacrylate ACM | Polyurethane AU, EU | Butyl IIR | Hypalon CSM | Fluorosilicone FVMQ | Silicone MQ,VMQ,PVMQ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sulfuric Acid (3 Molar) | 2 | 2 | 1 | 1 | 1 | 1 | 2 | 3 | 2 | 4 | 1 | 1 | 1 | 1 |
| Nitric Acid (3 Molar) | 4 | 4 | 2 | 3 | 2 | 2 | 4 | 3 | 4 | 4 | 2 | 2 | 4 | 4 |

One engine durability study was considered in this review.[32] The study concluded that two popular gasoline engines used in 2001-2009 model year vehicles experienced mechanical failure when operated on E15. Care should be used when drawing any conclusions about the likelihood of engine failure on E15 based on this study as it employed an engine test cycle where engine speeds are not high enough to produce valve rotation. Regular valve rotation is an integral part of engine operation, intended to equalize the wear around the entire valve and thus reduce the possibility of valve failure. Moreover, it appears likely that in order to increase the likelihood of failures, vehicles were selected that were expected to be particularly sensitive to valve damage. No E10 control was used to compare the effect of E15 to the normal in-use fuel in the United States, and E0 testing was only conducted on a small subset of the vehicles in the study. The study applied a leakdown failure criterion of 10%, which is inconsistent with shop manuals for these vehicles. A more typical OEM accepted leakdown rate of 20 to 25% would have significantly reduced the number of E15 and E20 failures. More importantly, leakdown is more typically used to locate a leak or for other diagnostics and is not a common metric for mechanical engine failure. Engines failing the 10% criterion were torn down to evaluate valve wear, but no baseline data on the state of valve wear at start of test were collected. Finally, the statistical analysis was conducted using assumed data from tests that were not run, and disregarded test data from Vehicle 8.

Two whole vehicles tests used transparent and standard methodology.[47,48] The first was a comprehensive catalyst durability study of 82 vehicles operated for at least 50,000 miles using EPA's standard road cycle and the second was conducted on a university fleet in normal use. Neither vehicle set showed any evidence of increased maintenance or component failure associated with operation on E15 or E20. These studies were not intended to stress the engine or fuel system components, nor did they attempt to test every type of vehicle, some of which may be more sensitive to ethanol damage.

The conclusion that engines will experience mechanical engine failure when operating on E15 is not supported by the data presented in these studies.

## Findings

The CRC studies were designed to identify and test vehicles and components "potentially sensitive to gasoline fuels containing ethanol at concentrations greater than 10 volume percent".[32] Pilot testing using aggressive test fuels (including acids which are potentially more damaging than those included in J1681 Aggressive Ethanol) was used to narrow down the fuel system components most likely to be affected in the fuel system. One pump, identified as Pump N, was shown to have a greater failure rate with standard E15 in comparison to standard E10 in one study, yet did not fail on Aggressive TF10 or Aggressive TF20 in a previous study, and thus the results are inconclusive.

The conclusion that engines will experience mechanical engine failure when operating on E15 is not supported by the data presented in these studies. However, these tests did not include all existing makes and models of 2001+ MY vehicles on the road, and there may be certain components or vehicles which are more susceptible to damage from higher ethanol content fuels. Moreover, vehicle tests which include only eighty vehicles are not adequate to ensure that individual component failure rates will be below the 1 in 1000 rate that OEMs typically expect over the warranty life of a vehicle.

Over two-hundred million vehicles on the road today regularly use E10 without experiencing systemic fuel-related component or engine failures. While higher levels of ethanol may have some effect, the evidence from the material compatibility testing suggests that differences between E10 and E15 are small in proportion to the difference between E0 and E10, and yet there was little impact noted as the fuel supply changed over from 1.6 billion gallons in 2000 to over 13 billion gallons in 2012.[52]

There is insufficient data to statistically support a failure rate prediction. Also, without knowing the test methods and selection criteria used by OEMs in designing the vehicles it is difficult to extrapolate the results of these studies to real world expectations and performance. What these studies can do is to indicate whether or not E15 could cause much larger numbers of failures in a range of vehicles, and/or point out specific components or vehicles which are sensitive to higher ethanol concentrations. Overall, the results showed no evidence that E15 will cause widespread failures, and in the search for sensitive components found a single unidentified pump model which, based on an inconclusive result, may be sensitive to higher ethanol concentrations in fuel formulations.

# Emissions, On-Board Diagnostics, and Catalyst Durability

## Introduction and Background

These areas are given separate sections in the appendix, but are grouped together for this discussion because they all apply directly to the criteria for obtaining a waiver to Section 211f of the Clean Air Act.

**Tailpipe Emissions and On-Board Diagnostics.** Modern cars are able to alter engine operation in response to changes in fuel composition. From the standpoint of emissions this compensation revolves around controlling the air-to-fuel ratio to be near stoichiometric (with just enough air to burn the fuel completely). The ability of modern vehicles to be fully adaptable to E15 depends on the capabilities of the fuel system and engine control unit (ECU) to 1) maintain stoichiometric combustion under normal closed-loop operation, 2) allow adequate fuel enrichment under high-load operation to protect the exhaust catalyst (and pistons) from thermal damage, as well as enrichment to start and run smoothly during low-temperature cold-starts, and 3) do all the above gracefully without triggering diagnostic trouble codes (DTCs) and malfunction indicator lights (MILs). These overlapping concerns and criteria arise from the lower energy density of ethanol- gasoline blends at levels above E0 and E10, which require higher fuel flow rates to maintain the required air-fuel ratios for the engine operating conditions and driver demands. The largest concern is for wide-open throttle acceleration at high engine speed, when the fuel flow rate requirement is highest.

Modern vehicles use the exhaust oxygen sensor (O2S) as the primary input to the ECU for closed-loop control of the engine's air-fuel ratio at stoichiometric, during steady-state operations such as cruise and idle. Other sensor inputs to the ECU allow it to control engine transients e.g., acceleration, deceleration, and cold-start. These ECU inputs typically include throttle position sensor (TPS), manifold absolute pressure (MAP), coolant temperature (CTS) and inlet air temperature (IAT). The ECU uses these input data to continuously compute the appropriate outputs to the fuel injectors (i.e., modulates the fuel injector pulse-width) for the operating conditions. In addition, the ECU adjusts (or 'trims') the fuel injector outputs for immediate operating variances using a software learning feature known as short term fuel trim (STFT); this allows the ECU to more efficiently control air-fuel ratio over the wide dynamic range of engine operating conditions.

The ECU can also accommodate longer term adaptations using a related software learning feature known as long term fuel trim (LTFT), which can correct for variances such as fuels with different energy contents, and degradation of fuel system performance (pressure and mass flow) over time. Increasing the ethanol content in gasoline requires greater LTFT to maintain stoichiometric air-fuel ratio during closed-loop operation. OEMs have a variety of control strategies for using STFT and LTFT to adapt not only to fuel changes but to other changes in the operation of the car, such as aging of the fuel pump or fuel pressure regulator, fuel injector deposits and fuel filter fouling. Generally, if the LTFT exceeds some threshold value, the second generation on-board diagnostics (OBDII) system (integral to the ECU) will trigger a DTC, and possibly illuminate the MIL depending on other factors (the control logic is proprietary). The higher LTFT required for higher ethanol content fuels suggests that there will be some increase in related DTCs and MILs due to ECU perceived lean operation for vehicles running on E10+

fuels. Conversely, some MILs which would occur for rich operation on E0 will no longer occur, if the engine is run on higher ethanol content fuels.

Some vehicles have ECUs that apply the learned LTFT to open-loop air-fuel ratio control during power enrichment operation. Fuel enrichment is used, for example, under wide-open throttle (WOT) condition to reduce combustion and exhaust gas temperatures, and thereby protect the pistons and exhaust catalyst from thermal damage. Vehicles which do not utilize learned LTFT during high power, open-loop operation might be expected to have inadequate fuel enrichment when using higher amounts of ethanol blended into gasoline, again because the fuel energy density is reduced compared to ethanol-free gasoline. The resulting leaner air-fuel ratio can increase catalyst temperatures, potentially making these vehicles more susceptible to catalyst damage, and consequently accelerate the degradation of the catalyst's emissions conversion performance.

**Evaporative Emissions.** Evaporative emissions are classified into the following types:

1. Diurnal emissions – emissions from the evaporation of gasoline due to daily temperature fluctuations
2. Running loss emissions – emissions from the engine and fuel system while the vehicle is running
3. Hot soak emissions – emissions that occur during the first hour after a vehicle is parked after normal operation
4. Refueling emissions – evaporative losses that occur as gasoline is pumped into the gas tank displacing the gasoline rich vapor

Total evaporative emissions can either come from evaporative losses where leaks or openings release vapor to the atmosphere, or permeation in which fuel molecules escape through the fuel system materials of construction.

In the past two decades, the EPA has required increasingly strict evaporative emissions systems to control emissions from all sources. By MY 1998 the EPA required Enhanced Evaporative Emissions systems on all new vehicles. These vehicles incorporate fully sealed fuel systems and minimize evaporative emissions by capturing fuel vapors generated by changing temperatures in carbon canisters. The carbon canister stores the organic compounds to be used as fuel when the engine is running. Newer vehicles are fitted with On-board Refueling Vapor Recovery (ORVR), in addition to the Enhanced Evaporative Emissions system. ORVR uses a check valve to allow the fuel system to remain sealed during refueling operations. The fuel flowing into the tank forces the tank vapors into the activated carbon canister. ORVR was required on 40% of 1998 model year cars, 80% of 1999 model year cars, and 100% of 2000 model year and later cars; light-duty trucks had a six-year phase-in period, starting in model year 2001. PZEV (Partial zero emission vehicles) standards require near zero evaporative emissions and therefore include additional technologies, including, in some cases canister scrubbers to virtually eliminate bleed emissions from the carbon canisters and air-intake HC traps to prevent engine breathing losses when the engine is shut down.

Evaporative systems are required to be compliant at full useful life mileage.  Tier 2 light-duty vehicles were required to meet evaporative emissions standards for 3-day diurnal test plus hot soak, a 2-day diurnal test plus hot soak and running loss.   Static permeation is not part of the EPA Tier 2 test requirements.  The Low Emission Vehicle II (LEVII) program was a set of California tailpipe emissions requirements similar to, but preceding EPA's Tier II program.  The LEV II program did not include any new evaporative emissions requirements but it is mentioned here because testing described below, found that the tested LEV II vehicles had lower evaporative emissions.

Under ASTM D4814 and EPA fuel volatility regulations, all fuels are required to meet vapor pressure restrictions which depend on the time of year and area of the country.  Only E10 is permitted a 1 psi waiver in some parts of the country. Because of economic factors which make it expensive to reduce the vapor pressure of the fuel, refiners generally sell fuel that is very close to the vapor pressure limit. Thus, current regulations require that the vapor pressure of E15 will be roughly 1 psi less than that of E10 during the summer gasoline volatility control season, depending on the standard applicable in the location.  Generally, emission testing is conducted with fuels with matched vapor pressures, to ensure testing is measuring the difference in emissions due to the composition of the fuel, not the vapor pressure, because historically, it was well known that evaporative emissions increase if the vapor pressure of the fuel increases.  However one of the more interesting results of recent studies has been that for newer vehicles fuel vapor pressure no longer seems to have much impact on emissions within typical vapor pressure ranges (up to about 10 psi).

Permeation occurs continuously, but the rate depends on a number of factors including the fuel system materials, the design and shape of the fuel system components, the amount of fuel, ambient temperatures and the properties of the fuel.  Other sources of volatile hydrocarbons may include tires, paint, adhesives and vinyl emissions, but have generally been considered minor.

## Discussion

**Carbon monoxide.** A 2008 study by the National Renewable Energy Laboratory and Oak Ridge National Laboratory (NREL/ORNL)[53,54] utilized 16 vehicles (13 of which were model years 2001 to 2007) and provides a demonstration of the effect of ethanol blending on CO from modern vehicles. The composite emissions analysis from this set of vehicles revealed a statistically significant reduction in CO of 10-15% from E10, E15 and E20, relative to E0. The CO reduction effect was evident at the E10 level, with little or no additional decreases from E15 and E20. When the vehicle set was differentiated based on those that applied LTFT to open-loop operation (9 of 16) versus those that did not (7 of 16), it was found that those which applied LTFT to open-loop operation produced no statistically significant changes in CO at any ethanol level, compared to E0. In other words, the applied LTFT compensated for the lower energy density ethanol blends during open-loop operation by adding more fuel, just as intended.

On the other hand, those vehicles that did not apply LTFT corrections during open-loop operation produced statistically significant CO reductions. These vehicles essentially responded to ethanol blending similar to older non-feedback controlled vehicles. It was reported that vehicles in the study engaged open-loop fuel control (i.e. power enrichment) during certain parts of the LA92 test cycle after warm-up. In addition, cold-start is an open-loop control condition.

**NMHC and NMOG.** NMHC emissions decrease when ethanol is blended into gasoline. The 2008 NREL/ORNL study of thirteen 2001-2007 model year vehicles measured a statistically significant reduction in NMHC of 10-15% from E10, E15 and E20, relative to E0 for the composite vehicle set.[53,54] This reduction was evident at the E10 level, and little or no further decreases were measured from E15 and E20. Looking at the results in more detail, those vehicles *not* applying LTFT during open loop operation produced lower NMHC emissions. Vehicles fueled with ethanol-gasoline blends that applied LTFT during open loop operation produced NMHC emissions that were not statistically different from E0 emissions. The explanation for this observation is the same as for CO- when LTFT is not applied to open-loop conditions; the enleaned air/fuel mixture occurs because of ethanol's lower energy density, allowing more complete combustion of hydrocarbons.

The exhaust emissions of ethanol and acetaldehyde increase significantly with increasing ethanol content in the fuel. These increases are sufficient to offset the reductions in NMHC due to ethanol blending. For example, the 2008 NREL/ORNL study showed that NMOG emission levels from E10, E15 and E20 were equal to those from E0 (within the measurement error), whereas E10, E15 and E20 NMHC dropped 10-15% compared to E0.[53,54] When the vehicle set was differentiated for LTFT applied/not applied, the NMOG emissions from E10, E15 and E20 were statistically the same as those from E0.

**Oxides of Nitrogen (NOx).** In the 2008 NREL/ORNL study,[53,54] there were no statistically significant differences in $NO_x$ emissions between E0, E10, E15 and E20 fuels when considering the composite 16 vehicle set. When the results were differentiated by LTFT application during open-loop operation, there was a trend of increasing $NO_x$ with increasing ethanol content for the vehicles that do not apply LTFT corrections to open-loop, although this effect was only statistically significant at the E20 level (at 35% increase compared to E0). This $NO_x$ effect from increased ethanol can be explained as the natural thermal $NO_x$ increase that accompanies higher combustion temperature, which can be inferred from the measured higher catalyst temperatures for these vehicles.

The data from vehicles that used LTFT corrections to their open-loop air-fuel ratio control revealed slightly lower $NO_x$ from the ethanol blends; however the effect was not statistically significant. This observation is consistent with what would be expected from tighter air-fuel ratio control, i.e., combustion temperature should remain more stable, and therefore $NO_x$ levels as well.

**Catalyst Durability.** Only one robust study of catalyst durability with E15 (and other ethanol blend levels) has been performed, this is known as the DOE V4 Catalyst Durability Study.[48] Eighteen Tier 2 vehicle models MY 2005-2009 and eight pre-Tier 2 vehicle models MY 2000-2003 were selected, and then multiple matching vehicles were obtained for each model. The vehicles were qualified, designated for aging on E0, E10, E15 or E20, and then aged using EPA's standard road cycle (SRC). Vehicles were aged and tested at three different facilities, Southwest Research Institute, the Transportation Research Center, and Environmental Testing Corporation.

Four vehicle pairs were aged with E0 and E15. Five vehicle sets, each comprising four matched vehicles were aged with E0, E10, E15 and E20. The remaining eighteen vehicle models were aged with E0, E15 and E20. Of the twenty-five 2001 and newer vehicle models tested, only five were tested on E10. Emissions were measured using the FTP at the start of the project, at one or two midlife points, and at the end of scheduled aging – at least 50,000 miles. The FTP testing was performed with certification E0 in every case, as well as with certification gasoline splash blended with ethanol at the appropriate level for which the vehicle was aged on. Key results from the project are:

- Overall there were no discernible differences in aging effects (performance deterioration rate) on emissions between E0 and ethanol blends. However, results for four of six models tested by ETC/NREL showed that ethanol blends produced slower catalyst performance deterioration, possibly because of the decreased sulfur level in the fuel as the ethanol level is increased.
- The study also showed that LTFT applied to open-loop operation had no effect on catalyst aging or fuel economy

Several of the car models had over 90,000 miles at the beginning of the test and so greatly exceeded the 120,000 mile full useful life requirement at end of test. Additionally, an E10 control test was not run for the majority of the 2001 and newer vehicles. In spite of these study limitations, no negative impacts of ethanol were observed at any blend level.

**On-Board Diagnostics.** Three studies have been conducted for CRC by contractors[55,56,57] and one study by Oak Ridge National Laboratory[58] for the DOE to estimate the number of vehicles likely to generate a MIL illumination from excessive LTFT due to the change in fuel from E10 to E15. Both organizations did this by first measuring the effect of ethanol content on LTFT, and then determining the level of LTFT that was likely to trigger a MIL.

Effect of ethanol on LTFT in in-use vehicles*.* In order to determine the typical LTFT in in-use vehicles and the effects of ethanol content in the fuel, CRC funded a study in which hundreds of vehicles were recruited at Inspection and Maintenance (IM) stations and the LTFT was measured on those vehicles.[56] One of the IM stations was located in an area in which the fuel available was E0, and two of the stations were in areas where E10 was the predominant fuel. Overall, the E10 locations had LTFTs that averaged about 4 absolute percent higher than average LTFT values in the E0 location. The increase of LTFT between E0 and E10, by OEM, ranged from about 1.5% to almost 7%. These measured values correlate well with the nominal 3.5% difference in energy content between E0 and E10. Similarly, the NREL/ORNL study measured LTFT during LA92 testing of multiple vehicles, although only reported data for a single car (as representative of the vehicle set).[53] On average they reported an LTFT increase of just under 4% for each 10% increase in ethanol content. Separately, ORNL also tested 22 vehicles on fuels with ethanol contents at levels that ranged from E30 to E70 and found that the LTFT increase with each 10% increase in ethanol content varied by vehicle from 1.5% to 7.5%. The median value was 4.4% for each 10% increase in ethanol.[58]

LTFT level that triggers a MIL. CRC did not measure the MIL value that triggered a MIL, but instead polled the eight OEMs representing the vehicles tested at the IM stations.[56] Only four of the eight OEMs provided the researchers with LTFT thresholds that would trigger MILs, and of those, two of the OEMs provided a range of values that would trigger MIL illumination. Of the values provided, the minimum LTFT threshold was a 17% increase in fueling and the maximum threshold was a 30% increase in fueling. In order to objectively assess the LTFT trigger level, the ORNL study increased the oxygen content of the fuel until a MIL was triggered and found that LTFT values at the point of MIL illumination ranged from a low of 18% to a high of 38% with a median of 27%.[58]

Calculating the probability of a MIL from high LTFT level. Both the CRC and ORNL studies used the MIL trigger level and the likely distribution of LTFTs to calculate the probability of a MIL from a high LTFT level.[56,58] In order to estimate the effect of higher ethanol contents, CRC assumed that the LTFT effect was in proportion to ethanol content, i.e., the LTFT increase with E10 in relation to E0 was multiplied by 1.5 to get the estimated LTFT increase with E15 for each OEM. CRC researchers also assumed that LTFT values followed a normal distribution.

At a MIL threshold of 30% and E15 fuel, it is estimated that the number of vehicles exhibiting a MIL for LTFT would be less than 0.00%, but 2.94% would exceed the threshold at a MIL threshold of 17%. For E10, 2.14% of the vehicles using E10 would exceed the 17%. Thus, the number of additional MILs associated with E15, but not with E10 will be quite small in percentage terms, on the order of less than 1% according to their calculations. This translates to potentially 1.6 million vehicles, given that approximately 165 million model year 2001 and newer light duty vehicles are on the road today (2013).

ORNL used a different approach; they measured the change in LTFT with increasing ethanol content in the fuel, and the LTFT threshold that would trigger a MIL for each of the 22 vehicles in their program. Even with the worst case assumptions and the most sensitive vehicle tested, these results suggest that the increase in MILs will be less than 1%. Typical vehicles appear likely to be far less sensitive to increases in ethanol content and several orders of magnitude less likely to have a MIL with either E15 or E10.

In-use MIL illuminations. In the CRC E-90 report in which 391 vehicles were tested on E10, none showed a positive MIL associated with lean operation. Moreover, no vehicles had an LTFT exceeding 14%, when one would expect at least 8, based on a normal distribution of results. One explanation is that most cars with illuminated MILs are repaired prior to IM testing. Testing conducted in California and reported in CRC Report No. E90-2a,[56] shows about 6.85 times as many cars have MILs illuminated during random roadside testing than is found in inspection stations. This number may vary by state because the conditions and costs of failing an IM inspection vary from state to state. However, it is likely that the number of MILs found at the inspection station is an underestimate of the actual prevalence of MILs.

Lean DTC and MIL results from four large IM programs in Atlanta, GA, Denver, CO, southern California and Vancouver, BC Canada, were also captured and analyzed in the CRC E-90-2a report.[56] The data were obtained before and after changes in the ethanol content in the available fuel. These data, from millions of vehicles, can be considered in understanding the impact of changing ethanol content on the probability of increased lean MILs. If one assumes that the number of measured MILs is proportional to the number of MILs in-use, then there was no apparent increasing trend of MILs with increasing ethanol content when the four IM programs are considered together. The occurrence of a lean DTC, without a MIL does not seem as likely to be affected by pre-IM maintenance and similarly provides no clear trend in increasing lean DTCs with increasing ethanol content. In summary, even with databases including millions of vehicles, the difference in MILs due to lean DTCs with increasing ethanol content is too small to be identified in practice.

Estimate of the number of sensitive vehicles. In addition to the lean DTC and MIL metadata from four IM programs, the CRC contractors collected information on the makes and models of vehicles tested and the number of each that had LTFT related MILs.[56] Based on these results for the State of Georgia, CRC Report No.E90-2a concludes that approximately 4% of all OBDII equipped light-duty vehicles could be susceptible to fuel metering-related fault codes when using E10+ fuels. The logic that leads to this conclusion is not straightforward and the supporting data was confidential and not available for review. Approximately, 0.39% of 1996 and later model cars and light-duty trucks subject to the IM program in Georgia are unable to maintain LTFT within the preprogrammed OBDII limits using E10. However, when these results were categorized by make/model/displacement/MY combinations, 4% were in categories that had at least a 1.0% increase in OBDII fault codes related to fuel trim with higher ethanol content (e.g., a 1.0% fault code rate increasing to at least 2.0%). Not reported is how many were in categories that showed a 1.0% decrease, i.e. just by random selection of the 5000 makes and models considered, there will be some combinations that show an increase and some that show a decrease. It should be noted that while 4% of the vehicles were in the sensitive make/model/displacement/MY combination only 3.4% of those vehicles actually had fuel trim-related fault codes when tested on E10.

Testing of ethanol sensitive vehicles. In CRC's E-90-2b study, widespread screening of vehicles on used car lots was performed searching for vehicles likely to exhibit MILs with higher ethanol content fuels.[57] The only limitation set on the vehicles, was that they have no existing or pending MILs and be between MYs 2001 and 2008. Seven vehicles were eventually selected. The vehicles performed ten cycles of a road-course test over three to five days (all warmer than 68 °F), and were tested on a chassis dynamometer in a temperature controlled environment, to determine if a MIL or a DTC was triggered with the tested fuel. Road testing was conducted on all seven vehicles with E20 and E0, and chassis dynamometer testing was conducted for one vehicle on E20 and two vehicles on E30. No dynamometer testing was conducted on E0.

Of the seven cars tested on the road none generated a MIL on E20 or E0, but two got warnings of pending MILs (i.e. they had lean operation DTCs) when operated on E20. One vehicle which passed the road test free of DTCs was then tested on the dynamometer with E20. It got a lean DTC when tested at 20 °F, but not when tested at three warmer temperatures. The three vehicles with pending MILs on E20 (road or dynamometer) were retested on the road-course with E30 and the MIL was illuminated for all three. There was no testing on E15 because of the lack of MILs with E20 suggested that further leaning of the fuel would be required to generate the MILs.

The results described above are consistent with those in CRC Report No. E-90, i.e., there are vehicles operating at especially high LTFTs with E10 that will trigger lean DTCs or MILs at E20 and E30, but not at E0. However, as shown by SwRI's difficulty in finding these vehicles, they are very rare.

**Evaporative Emissions.** There were four CRC studies in which evaporative emissions were measured on either E15 or E20 and a control fuel. CRC Report No. E65-3 describes a study that measured only fuel permeation emissions.[59] In this study ethanol gasoline blends were formulated to approximately equal vapor pressures including E0, E6 (two aromatic levels), E10, E20 and E85. Test rigs "included the fuel and vapor lines, and their chassis-to-engine connection hoses at the front of the vehicle. All the fuel system components (with the exception of the engine mounted injectors and hoses) that could contribute to permeation losses were kept in the original spatial relationship…. For system integrity, all components were removed and remounted on the rigs without any fuel or vapor line disconnections." Test rigs recreated the fuel systems of five 2001 to 2005 MY vehicles, two pre-ORVR, and three with ORVR systems, including one FFV. Measured permeation emissions using E20 were on average about 10% higher than those measured using E10 but the difference was not considered statistically significant. However, all of the vehicles showed a significant increase in permeation emissions with ethanol-blended fuels as compared to E0. The largest difference in permeation emissions, both in quantity and in type of emissions, occurs between E0 and E6. The differences between E6, E10 and E20 are very small in comparison. No significant effect was found for aromatic content. The average specific reactivity of E0 was about 1/3 more than all of the ethanol-blended fuels, but the difference in specific reactivity was on the order of only 3% between E10 and E20. The advanced technology LEVII and PZEV fuel system rigs had much lower permeation emissions than fuel system rigs from other vehicles.

Eight vehicles were tested on E20 (9 psi vapor pressure), E10 (7 or 10 psi vapor pressure) and E0 (7 psi and 9 psi).[60] Two of the vehicles, the 2004 Toyota Camry and 2006 Ford Taurus were Near Zero Tier 2 vehicles. The 1996 Ford Taurus was pre-Enhanced Evaporative System and the remaining vehicles were considered Enhanced Evaporative System vehicles. Static permeation, running loss, hot soak and diurnal emissions were measured.

The results were mixed when comparing the results of vehicles using E20 with those using E10, for the two sets of newer vehicles. Generally, fuels including ethanol had higher emissions than the E0 fuels, but the trend was somewhat inconsistent with variations in different tests on different vehicles. About half the vehicles had higher emissions with E20, and half had higher emissions with the two E10 fuels. The vapor pressure appeared to have a mixed, but lesser effect on emissions than the amount of ethanol. The authors conclude that the "sample size and limited data makes statistical conclusions inappropriate."

The third CRC study, CRC Report No. 77-2-c included testing only on E20, at 7 and 9 psi and not all vehicles were tested on both fuels.[61] Permeation emissions were measured on several 2000 to 2004 MY vehicles (all with ORVR) and then compared to previous testing on E0 and E10. It also included a study on the effect of leaks in various places in the fuel system, the effect of ambient temperature on permeation emissions and included speciation of emissions. Newer Tier 2 vehicles have lower permeation than Tier 1 on all fuels. Although results vary from vehicle to vehicle and test to test, permeation is on average higher with E10 or E20 than E0 and lower with E20 compared to E10. There was no clear trend in emissions with vapor pressure.

Most recently CRC Report No. E-91 has focused on evaporative emissions durability of vehicles using E20 and E0 over a prolonged test period.[62] Ten matched pairs of vehicles MY 2002 through 2010 were driven twice a day for approximately 25 miles on the EPA Standard Road Cycle (SRC), for the equivalent of 360 days of driving. The fleet was split with some vehicles aged and tested in Colorado (higher altitude), and some vehicles aged and tested in Michigan (low altitude). The vehicles were aged using the Standard Road Cycle (SRC). All of the vehicles were recruited from the public fleet with the exception of the Toyota Prius vehicles which were purchased new. Half of the vehicles (five pairs) were certified to the Federal Enhanced Evaporative Emissions Standard, three were certified to the Tier 2 2004 LDV/LLDT Standard and two models were certified to the Tier 2 2009 LDV Standard.

Two types of tests were conducted. Baseline testing was conducted using the ethanol-free certification gasoline and consisted of an LA4 prep cycle, soak and canister load, FTP75 cycle, one-hour hot soak SHED test and a two-day diurnal SHED test. The Permeation Test, included pressure test of the fuel system to identify leaks, followed by two LA92 drive cycles (no emissions testing during operation), a hot soak and then a 2-day diurnal.

Results of Baseline Test show half of the vehicles showed slightly less emissions increase (or a larger emissions decrease) after being aged on E20 than on E0, and half showed more. Evaporative emissions from three models decreased over the 360 day aging period for both fuels. Two of the vehicles aged on E20 had large increase in emissions of about 50% on the Baseline Test, while their matched E0 vehicles showed decreases in emissions over the test period. However, the results of the Permeation Tests, conducted on the same schedule, do not show the same dramatic differences in emissions for these two vehicles. Moreover, two of the ten pairs of vehicles have emissions differences of over 40% between the matched vehicles when first tested on the Baseline Test, suggesting that a 50% magnitude change in emissions may be commonplace over the lifetime of these vehicles and may not be significant. Evaporative emissions (tested on the Baseline Test) from all of the vehicles were below the federal certification standards for all tests. While these results show that some vehicles may show evaporative emissions increases associated with higher ethanol content fuels, the limited results suggest the need for additional testing.

Evaporative emissions from E15 have been characterized and compared to those from E0 and E10. In general, the same compounds were found in the head space of all three fuels, with the exception of ethanol which was found above the head space of E10 and E15 and not above the E0. Two additional compounds were found above the E0 base fuel that were not found above the ethanol containing fuels, an unidentified C6 compound and 2,2,3 -trimethylpentane.

<u>Evaporative Emissions Conclusions</u>. Even small amounts of ethanol in the fuel will increase the permeation losses and total evaporative emissions, but the evidence suggests that increases in

emissions between vehicles using E10 and E20 are small or non-existent. In modern cars, evaporative emissions are relatively insensitive to vapor pressure changes up to 10 psi. Evaporative emissions could increase over time in some vehicles when using E20 compared to E0, although current limited data are insufficient to predict the frequency of this occurrence. However in all testing, even after the equivalent of one year of aging, measured evaporative emissions remained below regulated levels.

## Analysis

We reviewed seven studies on exhaust emissions, two large studies on catalyst durability, and six studies of evaporative emissions. In general, all of these studies employed standard or regulatory test methods that were very well documented. Test subjects and fuels are well described, and controls typically included both E0 and E10 (although not in every study), or showed no significant differences between E0 and E15. Use of these test methods for comparison of emissions from the control fuels with those from E15 or E20 is fully within the intended use of these test protocols. Thus, the studies taken as a whole provide a robust database that allows an assessment of emission and catalyst durability impacts to be made with a reasonably high level of confidence.

Four studies of on-board diagnostics performance (MIL illumination) were reviewed. No standard methods for evaluating the effects of a new fuel on MIL illumination are available, as OBD-II strategies are proprietary to the manufacturer. However all four studies use well described, rational methodology. There are no issues with control fuels or accelerated test conditions. These studies also provide a strong basis for drawing conclusions that have a reasonably high level of confidence.

## Findings

A review of four relevant exhaust emissions studies,[48,53,63,64] including emission results from the DOE V4 Catalyst Durability Study, reveals the following general observations for exhaust emissions from ethanol-gasoline blends, relative to E0:

- Statistically significant reductions of carbon monoxide (CO) from E10, with little or no additional CO reduction benefit from E15 (or E20, where tested)
- Non-methane hydrocarbons (NMHC) decrease with increasing ethanol content
- Non-methane organic gases (NMOG) remain the same or slightly decrease
- Acetaldehyde and ethanol emissions increase with increasing ethanol, but not enough to override the reductions in NMHC, thus producing a neutral effect on NMOG
- $NO_x$ from E10 increases slightly, with little or no additional increase from E15
- E15 emissions remained within the cert level of the vehicle.

The DOE V4 Catalyst Durability Study aged matched sets of vehicles on E0, E10, E15 and E20 for at least 50,000 miles (and many to more than 100,000 miles) and compared their emissions over the aging period. The study employed EPA's Standard Road Cycle, which EPA deems adequate for demonstrating whether or not a new fuel will cause or contribute to the degradation of a vehicle's emission control system. Therefore, from a regulatory perspective for emissions durability this test methodology is adequate and being applied as intended. Several of the car models had over 90,000 miles at the beginning of the test and so greatly exceeded the 120,000 mile full useful life requirement at end of test. Of the twenty-five 2001 and newer vehicle models tested, only five were tested on E10. This work produced the following key findings:

- Overall there were no discernible differences in aging effects (performance deterioration rate) on emissions between E0 and ethanol blends. However, results for four of six models tested by ETC/NREL showed that ethanol blends produced slower catalyst performance deterioration, possibly because of the decreased sulfur level in the fuel as the ethanol level is increased.
- Those vehicles that did not apply learned LTFT to open-loop operation as a means to compensate for ethanol's lower energy density did not show accelerated catalyst aging.

Three studies have been conducted for CRC by contractors[55,56,57] and one study by Oak Ridge National Laboratory (ORNL)[58] for the Department of Energy (DOE) to estimate the number of vehicles likely to generate a MIL illumination from excessive LTFT due to the change in fuel from E10 to E15. Both organizations did this by first measuring the effect of ethanol content on LTFT, and then determining the level of LTFT that was likely to trigger a MIL. CRC estimated that less than 1% of all vehicles would have MILs with E15 that would not have MILs with E10. ORNL refined these values for specific vehicles by measuring the MIL threshold for each individual vehicle. They found that the number of additional lean operation MILs would be less than 1% for the most sensitive vehicles, and several orders of magnitude less for the vast majority of the vehicles in their program.

Tailpipe emissions and OBDII results taken together indicate that vehicle engine control units in 2001 and newer vehicles are adequately compensating for the higher oxygen and lower energy content of E15.

There were four CRC studies in which evaporative emissions were measured on either E15 or E20 and a control fuel.[59, 60, 61,62] Even small amounts of ethanol in the fuel will increase the permeation losses and total evaporative emissions, but the evidence suggests that increases in emissions between vehicles using E10 and E20 are small or non-existent. In modern cars, evaporative emissions are relatively insensitive to vapor pressure changes up to 10 psi. Evaporative emissions control may break down in some vehicles more when using E20 than when using E0, although the data is limited and more testing is needed to verify this result. However in all testing, even after the equivalent of one year of aging, measured evaporative emissions remained below regulated levels.

## Overall Conclusions

The project team reviewed 43 studies relevant to E15 usage in 2001 and newer model year on-highway automobiles. These included 33 unique research studies, as well as 10 related reviews, studies of methodology, or duplicate presentations of the same research data. The study does not include discussion of engines that USEPA has not approved for use with E15, such as pre-2001 cars, marine, snowmobile, motorcycle, and small non-road engines. Important observations were:

- Several of the studies tested relatively large numbers of engines or vehicles, including:
    - The Coordinating Research Council's (CRC) engine durability study (28 engines)
    - The University of Minnesota's in-use fleet study (80 vehicles)
    - The USDOE's catalyst durability study (82 vehicles).

  The data presented in these studies did not show any evidence of deterioration in engine durability or maintenance issues for E15 (or E20) in comparison to E0 and E10 (when tested).
- Because of the wide variety of control fluids and unique test protocols, especially for fuel system component, engine, and vehicle durability studies, it is difficult to combine the results into a single analysis. This document distinguishes between test fuels and test fluids. Test fluids, such as those suggested by SAE publication J1681, do not meet fuel quality standards and were not intended for comparison of the effects of different fuels because the effects of the aggressive test fluids relative to commercial fuels are unknown.
- Materials compatibility testing provides no evidence that 15 volume percent ethanol blends will cause increased rates of metal corrosion in comparison to 10 percent blends. In most cases increasing ethanol content from 10 to 15 volume percent had no significant effect on elastomer swell.
- For 2001 and newer cars emission studies also show that engine control units are able to adequately compensate for the higher oxygen and lower energy content of E15.
- The engine performance and durability expectations from the materials compatibility and emission test results are confirmed by studies of fuel system, engine, and whole vehicle durability.

E10 has been in primary use in the United States since the promulgation of the Clean Air Act Amendments of 1990. Over two-hundred million vehicles on the road today regularly use E10 without experiencing systemic fuel-related component or engine failures. The main conclusion from our analysis is that the data in the 33 unique research studies reviewed here do not show meaningful differences between E15 and E10 in any performance category.

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