Appendix: Studies on the Use of E15 and E20 in Light-Duty Vehicles

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Introduction

Ethanol and gasoline fuel mixtures are in common use in the United States with E10 (10% ethanol, 90% gasoline blendstock) comprising more than 90% of the retail fuel supply in recent years.[*] In October 2010, the EPA expanded the use of this renewable fuel by granting a waiver to allow the retail sale of concentrations of up to 15% ethanol in gasoline (E15) for use in light-duty on-highway vehicles model year 2007 and later. In January 2011, the waiver was expanded to allow the use of ethanol in older light-duty vehicles, model years 2001 to 2006.

Normally, fuels and fuel additives are required to be "substantially similar" to gasoline in order to be approved for use as a motor vehicle fuel. EPA waived that requirement for E15, under the Clean Air Act[†] after ensuring that the new fuel would not "cause or contribute to the failure of any emission control device or system," and additionally that when used it would meet applicable emission standards over the life of the vehicle. To this end, a number of studies were conducted on the effects of higher ethanol content fuels on vehicle tailpipe and evaporative emissions, and long-term effects on catalyst efficiency.

In addition, several research programs have been conducted to assess the impact on materials used in the engines and fuel systems of motor vehicles, to ensure that long term impacts would not lead to reduced operating effectiveness or component failures. In separate analyses, researchers have considered the degree to which higher ethanol content fuels may trigger additional malfunction indicator light warnings for lean operation in second generation on-board diagnostic (OBD II) systems.

This document is intended as a reference list of the publicly available reports and research papers on the testing of E15 regarding these issues, as of mid-2013. Since E15 use is legally limited to vehicles MY 2001+, studies applicable only to older vehicles are not considered here. Studies conducted using non-highway vehicles or engines were also excluded. Supplementing the limited testing on E15, pertinent studies on E25, E20 or E17 are included, but studies that focused on just E85 or E10 are not. Studies focused on E15 economics, fuel economy, mis-fueling, and infrastructure are not included.

This review has been divided by subject matter, and each section is introduced with a brief review of background material intended to put the individual studies in context. This is followed by summaries of the individual studies with the results applicable to the use of E15 highlighted.

The vast majority of these studies were conducted, funded and/or supervised by the Coordinating Research Council (CRC), a research consortium funded by the American Petroleum Institute and a group of automobile manufacturer members (Chrysler, Ford, General Motors, Honda, Mitsubishi, Nissan, Toyota, and Volkswagen); the United States Department of Energy (DOE) through its national laboratories, the National Renewable Energy Laboratory (NREL) and the Oak Ridge National Laboratory (ORNL); and the Minnesota Center for Automotive Research at Minnesota State University. A table listing all of the studies is shown below.

[*] AAM Alliance of Automobile Manufacturers North American Fuel Survey, 2011.

[†] (CAA § 211(f)(4))

Studies reviewed in this document.

	Title	Source	Author Affiliation	Materials Compatibility	Fuel System Component Tests	Whole Vehicle or Engine Tests	Exhaust Emissions	Catalyst Durability	On-Board Diagnostics	Evaporative Emissions
1	SAE J1681-2000 Surface Vehicle Recommended Practice: Gasoline, Alcohol, and Diesel Fuel Surrogates for Materials Testing	SAE and http://webstore.ansi.org/RecordDetail.aspx?sku=SAE+J+1681-2000+%28SAE+J1681-2000%29#.UZpje8o0-rQ		X						
2	A Rational Approach to Qualifying Materials for Use in Fuel Systems, SAE No. 2000-01-2013	http://papers.sae.org/2000-01-2013/	Various	X						
3	Automotive Materials Engineering Challenges and Solutions for the Use of Ethanol and Methanol Blended Fuels, SAE 2010-01-0729	http://papers.sae.org/2010-01-0729/	GM	X						
4	Intermediate Ethanol Blends Infrastructure Materials Compatibility Study: Elastomers, Metals, and Sealants	http://info.ornl.gov/sites/publications/files/Pub27766.pdf	ORNL	X						
5	Effects of Mixtures of Gasoline with Methanol and Ethanol on Automotive Elastomers, SAE No. 800786	http://papers.sae.org/800786/	GM	X						
6	Fuel and Permeation Resistance of Fluoroelastomers to Ethanol Blends; presented at the Fall 170th Technical Meeting of the Rubber Division, American Chemical Society, Cincinnati, OH	http://wwwt.dupontelastomers.com/literature/viton/06ACSMini-Stevens.pdf	DuPont	X						
7	The Effects of E20 on Elastomers Used in Automotive Fuel System Components	http://www.mda.state.mn.us/news/publications/renewable/ethanol/e20onelastomers.pdf	MnCAR	X						
8	Elastomer selection for bio-fuel requires a systems approach, Sealing Technology	http://www.sciencedirect.com/science/article/pii/S1350478909700224	Various	X						
9	Performance of Elastomeric Materials in Gasoline – Ethanol Blends – A Review, NACE International Corrosion Conference & Expo, March 22-26, 2009, Atlanta , GA	http://www.onepetro.org/mslib/servlet/onepetropreview?id=NACE-09533	DNV	X						

	Title	Source	Author Affiliation	Materials Compatibility	Fuel System Component Tests	Whole Vehicle or Engine Tests	Exhaust Emissions	Catalyst Durability	On-Board Diagnostics	Evaporative Emissions
10	The Effects of E20 on Metals Used in Automotive Fuel System Components	http://www.mda.state.mn.us/news/publications/renewable/ethanol/e20onmetals.pdf	MnCAR	X						
11	EIS study of corrosion behavior of metallic materials in ethanol blended gasoline containing water as a contaminant	http://www.sciencedirect.com/science/article/pii/S0016236110006708	Various	X						
12	The Effects of E20 on Plastic Automotive Fuel System Components	http://www.mda.state.mn.us/news/publications/renewable/ethanol/e20onplastics.pdf	MnCAR	X						
13	Compatibility Study for Plastic, Elastomeric, and Metallic Fueling Infrastructure materials Exposed to Aggressive Formulations of Ethanol-Blended Gasoline	http://info.ornl.gov/sites/publications/files/Pub35074.pdf	ORNL	X						
14	The Effects of E20 on Automotive Fuel Pumps and Sending Units	http://www.mda.state.mn.us/news/publications/renewable/ethanol/320onfuelpumps.pdf	MnCAR		X					
15	An Examination of Fuel Pumps and Sending Units During a 4000 Hour Endurance Test in E20	http://www.mda.state.mn.us/news/publications/renewable/ethanol/e20endurance.pdf	MnCAR		X					
16	Durability of Automotive Fuel System Components Exposed to E20, CRC Report No. 662	http://www.crcao.org/reports/recentstudies2012/CRC%20662%20%5BAVFL-15%5D/CRC%20662%20%5BAVFL-15%5D%20Final%20Report%202011.12.30.pdf	CRC		X					
17	Durability of Fuel Pumps and Fuel Level Senders in Neat and Aggressive E15, CRC Report No. 664	http://www.crcao.org/reports/recentstudies2013/CRC%20664%20%5BAVFL-15a%5D/AVFL%2015a%20%5BCRC%20664%5D%20Final%20Report%20only.pdf	CRC		X					
18	Limitations and Recommended Practice in the Use of Compression and Leak-Down Tests to Monitor Gradual Engine Degradation, SAE 2011-01-2427	http://papers.sae.org/2011-01-2427/	ORNL			X				
19	Intermediate-Level Ethanol Blends Engine Durability Study, CRC Project No. CM-136-09-1B	http://www.crcao.com/reports/recentstudies2012/CM-136-09-1B%20Engine%20Durability/CRC%20CM-136-09-1B%20Final%20Report.pdf	CRC			X				

	Title	Source	Author Affiliation	Materials Compatibility	Fuel System Component Tests	Whole Vehicle or Engine Tests	Exhaust Emissions	Catalyst Durability	On-Board Diagnostics	Evaporative Emissions
20	Powertrain Component Inspection from mid-Level Blends Vehicle Aging Study, ORNL/TM-2011/65	http://info.ornl.gov/sites/publications/files/Pub28733.pdf	ORNL			X				
21	Lubricating Oil Consumption on the Standard Road Cycle, SAE No. 2012-01-0884	http://papers.sae.org/2013-01-0884/	ORNL			X				
22	Demonstration and Driveability Project to Determine the Feasibility of Using E20 as a Motor Fuel	http://www.mda.state.mn.us/renewable/ethanol/~/media/Files/renewable/ethanol/e20drivability.ashx	Univ. of Minnesota			X				
23	Effects of Mid-Level Ethanol Blends on Conventional Vehicle Emissions. SAE 2009-01-2723	http://www.nrel.gov/docs/fy10osti/46570.pdf	NREL/ ORNL				X			
24	Effects of Vapor Pressure, Oxygen Content, and Temperature on CO Exhaust Emissions. CRC Report No. E-74-b	http://crcao.org/reports/recentstudies2009/E-74b/E-74b%20Revised%20Final_Report_SR20090503.pdf	CRC				X			
25	EPAct/V2/E-89: Assessing the Effect of Five Gasoline Properties on Exhaust Emissions from Light-Duty Vehicles Certified to Tier 2 Standards: Final Report on Program Design and Data Collection.	http://www.epa.gov/otaq/models/moves/documents/420r13004.pdf	EPA/ NREL/ CRC				X			
26	Assessing the Effect of Five Gasoline Properties on Exhaust Emissions from Light-Duty Vehicles Certified to Tier 2 Standards: Analysis of Data from EPAct Phase 3 (EPAct/V2/E-89) Final Report	http://www.epa.gov/otaq/models/moves/documents/420r13002.pdf	EPA/ NREL/ CRC				X			
27	Statistical Analysis of the Phase 3 Emissions Data in the EPAct/V2/E-89 Program	http://www.nrel.gov/docs/fy13osti/52484.pdf	NREL				X			
28	NMOG Emissions Characterizations and Estimation for Vehicles Using Ethanol-Blended Fuels. SAE 2012-01-0883	http://info.ornl.gov/sites/publications/Files/Pub33272.pdf	ORNL				X			

	Title	Source	Author Affiliation	Materials Compatibility	Fuel System Component Tests	Whole Vehicle or Engine Tests	Exhaust Emissions	Catalyst Durability	On-Board Diagnostics	Evaporative Emissions
29	Effects of Intermediate Ethanol Blends on Legacy Vehicles and Small Non-Road Engines, Report 1-Updated. NREL/TP-540-43543 or ORNL/TM-2008/117	http://info.ornl.gov/sites/publications/Files/Pub12154.pdf	NREL/ ORNL				X			
30	Effects of E15 Ethanol Blends on HC, CO and NOx Regulated Emissions from On-Road 2001 and Later Model Year Motor Vehicles	http://ethanolrfa.3cdn.net/98cced8882a492cb49_lwm6bj5kz.pdf	RFA				X			
31	Mid-Level Ethanol Blends Catalyst Durability Study Screening. CRC Report No. E-87-1	http://crcao.org/reports/recentstudies2009/E-87-1/E-87-1%20Final%20Report%2007_06_2009.pdf	CRC					X		
32	Intermediate Ethanol Blends Catalyst Durability Program. ORNL/TM-2011/234	http://info.ornl.gov/sites/publications/Files/Pub31271.pdf	ORNL/ NREL			X	X	X		
33	Comparative Emissions Testing of Vehicles Aged on E0, E15 and E20 Fuels	http://www.nrel.gov/docs/fy12osti/55778.pdf	NREL/ETC			X	X	X		
34	Impact of E15/E20 Blends on OBDII Systems – Pilot Study CRC E-90	http://www.crcao.org/reports/recentstudies2010/E-90/E-90_Final_Report_031210.pdf	CRC						X	
35	Evaluation of Inspection and Maintenance OBD II Data to identify Vehicles that May Be Sensitive to E10+ Blends, CRC Report No. E90-2a		CRC						X	
36	Impact of Ethanol Blends on the OBDII Systems of In-Use Vehicles – Interim Report, CRC Report No. E-90-2b	http://www.crcao.org/reports/recentstudies2012/E-90-2b%20Interim%20Report/Final%20CRC%20E-90-2b%20Interim%20Report.pdf	CRC						X	
37	Investigating Malfunction Indicator Light Illumination Due to Increased Oxygenate Use in Gasoline, SAE No. 2012-01-2305	http://papers.sae.org/2012-01-2305/	ORNL/ NREL						X	
38	Fuel Permeation from Automotive Systems: E0, E6, E10, E20 and E85. CRC Report No. E-65-3	http://crcao.org/reports/recentstudies2006/E-65-3/CRC%20E-65-3%20Final%20Report.pdf	CRC							X
39	Enhanced Evaporative Emission Vehicles, CRC Report No. E-77-2	http://crcao.org/reports/recentstudies2010/E-77-2/E-77-2_Final_Report__March_2010.pdf	CRC							X

	Title	Source	Author Affiliation	Materials Compatibility	Fuel System Component Tests	Whole Vehicle or Engine Tests	Exhaust Emissions	Catalyst Durability	On-Board Diagnostics	Evaporative Emissions
40	Study to Determine Evaporative Emission Breakdown, Including Permeation Effects and Diurnal Emissions, Using E20 Fuels on Aging Enhanced Evaporative Emissions Certified Vehicles, CRC Report No. E-77-2c	http://crcao.org/reports/recentstudies2011/E-77-2c/E-77-2c%20Final%20Report%20for%20sure%201-28-11.pdf	CRC							X
41	Evaporative Emissions Characterization of E0, E10, and E15 in Support of the Fuel and Fuel Additive Registration of E15, Revised Final Report	http://www.epa.gov/otaq/regs/fuels/additive/e15/documents/e15-health-impact-data-package.pdf	RFA/ Growth							X
42	Evaporative and Exhaust Emissions Characterization of 2011 E0, E10, and E15: Comparison to Data Developed by the Section 211(b) Research Group in Support of the Fuel and Fuel Additive Registration of E15, Revised Final Report	http://www.epa.gov/otaq/regs/fuels/additive/e15/documents/e15-health-impact-data-package.pdf	RFA/ Growth							X
43	Evaporative Emissions Durability Testing. CRC Report No. E-91	http://crcao.org/reports/recentstudies2012/E-91/CRC%20E-91%20Final%20Report%20120910.pdf	CRC							X

Materials Compatibility

The fundamental problem in materials compatibility testing for automotive use is that car buyers expect their vehicles to last two decades or more, and EPA requires emissions control devices to remain effective for the full useful life of the vehicle (120,000 miles for Tier 2 vehicles) but the introduction of new fuels cannot be delayed for decades while testing is conducted. 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 seem likely to be 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.

Many of the studies reported here have used “aggressive” fuel formulas. Originally, these aggressive fuels were developed to represent one kind of worst case, but the aggressive fuels may differ in important ways from the fuels that they are intended to mimic. SAE J1681 proposes the use of an aggressive hydrocarbon base fuel, ASTM D471 Fuel C, (a 50/50 blend of toluene and isooctane) dosed with various additives (oxygenates, peroxides, chlorides) for the testing of automotive parts in contact with hydrocarbon fuels. For ethanol, J1681 suggests the use of Aggressive Ethanol (recipe from SAE J1681 and in Table 1 below) and the CRC has adjusted that recipe for its testing and used Modified Aggressive Ethanol blends (as used in CRC Reports 662 and 664, and shown in Table 1 below). Measured properties for Aggressive and Modified Aggressive Ethanol are listed in Table 2 below and compared to the applicable ASTM standard for Denatured Fuel Ethanol for Blending with Gasolines for Use as Automotive Spark-Ignition Engine Fuel, ASTM D4806.

Table 1. Recipe for Aggressive Ethanol from J1681 and for Modified Aggressive Ethanol from CRC Report No. 662

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	0	0.008 g/L
Nitric Acid	0	0.015 g/L

Table 2. Measured properties of two samples of Fuel Grade Ethanol, Aggressive Ethanol and Modified Aggressive Ethanol Compared to ASTM Standard D4806 for Blending Ethanol

Property	**Fuel Grade Ethanol Sample No. 1***	**Fuel Grade Ethanol Sample No. 2****	**Aggressive Ethanol***	**Modified Aggressive Ethanol****	**ASTM D4806-13 Limit**
Solvent Washed Gum Content, mg/100 mL	4.5	Not reported	9.8	Not reported	max. 5.0
Water, volume %	0.69%	0.79%	1.45%	0.79%	max. 1.0%
Inorganic Chloride, mass, mg/L	<0.4	<0.1	3.1	4.9	max. 8
Acidity (as acetic acid CH3COOH), mass %	0.002%	Not reported	0.014%	Not reported	max. 0.0007%
pHe	7.5	7.46	2.6	2.3	6.5 to 9.0
Sulfur, mass ppm	0.6	2	10.6	Not reported	max. 30
Total sulfate, mass ppm	0.6	<0.1	39.7	3.8	max. 4
Conductance (µs/cm)	<2	Not reported	14	Not reported	No U.S. Specification

*analysis by Midwest Laboratories, October 2009, Fuel Grade Ethanol Sample No.1 was used to make Aggressive Ethanol profiled in this table.
**CRC Report No. 662, Fuel Grade Ethanol Sample No. 2 was used to make Modified Aggressive Ethanol profiled in this table.

Missing is any published evidence that the effects of ASTM D471 Fuel C, Aggressive Ethanol, and Modified Aggressive Ethanol have effects representative of the fuels that they are intended to represent, nor is it apparent that using ASTM D471 Fuel C instead of retail gasoline has the same effect proportionally as using Aggressive or Modified Aggressive Ethanol in place of retail ethanol. It is clear that Aggressive Ethanol and Modified Aggressive Ethanol are several orders of magnitude more acidic than retail ethanol and may have higher chloride content; both are known to increase corrosivity. In choosing to use nitric and hydrochloric acids instead of sulfuric acid, the CRC introduced other variables into the results (e.g., nitric acid is also an oxidizer), as corrosiveness depends on the specific ions in the acid, and cannot be determined by pHe alone.

Also missing is any discussion of corrosion inhibitor additives that are included in virtually all fuel grade ethanol produced in the United States today.[‡] These additives chemically neutralize acids, provide a protective film on metal surfaces, and buffer the pHe of ethanol to be between 6.5 and 9.0. As noted in ASTM D4806, section X1.1.6:

[‡] Bureman, P. Good ethanol storage practices. *Biofuels International,* page 7, April 2012. Peyton, K., Bureman, P. The evolving role of ethanol corrosion inhibitors. *Biofuels International,* page 61, October 2012.

When the pHe of ethanol used as a fuel for automotive spark-ignition engines is below 6.5, fuel pumps can malfunction as a result of film forming between the brushes and commutator, fuel injectors can fail from corrosive wear, and excessive engine cylinder wear can occur. When the pHe is above 9.0, fuel pump plastic parts can fail.

The action of corrosion inhibitors/pHe buffers is not considered in the development of aggressive ethanol test fluids, nor were these included in the materials or engine component durability studies reviewed here (CRC reports 662 and 664, for example).

E10 in is in widespread use, representing more than 90% of the US market for retail fuel and should generally be considered the standard or control fuel to which new fuels are compared. In some cases, researchers have used E0 as the control fuel to exaggerate the effects of ethanol on various materials. However, as even small amounts of ethanol may impact material compatibility, one cannot assume a straight line interpolation of the differences between E0 and E15 to estimate differences between E10 and E15. If Aggressive or Modified Aggressive Ethanol is used to represent E15 or higher ethanol blends, comparisons should be made to E10 composed from the same Aggressive or Modified Aggressive Ethanol.

Acronyms

ABS – acrylonitrile butadiene styrene (plastic)
ACM – acrylic rubber elastomer
ASTM – American Society for Testing and Materials
CO - epichlorohydrin homopolymer
CR – polychloroprene elastomer
ECO - epichlorohydrin ethylene oxide copolymer
EIS – electrochemical impedance spectroscopy
FKM – fluoroelastomer
J1681 – SAE Standard for Gasoline, Alcohol, and Diesel Fuel Surrogates for Materials Testing
NBR – nitrile rubber elastomer
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
PUR – polyurethane plastic
PVC – polyvinyl chloride plastic
SAE – Society for Automotive Engineers
SBR – styrene- butadiene rubber

Primary Category: Material Compatibility: General	Secondary Category: NA	
Title: SAE J1681-2000 Surface Vehicle Recommended Practice: Gasoline, Alcohol, and Diesel Fuel Surrogates for Materials Testing	Author: SAE	Date: January 2000
Web link: http://webstore.ansi.org/RecordDetail.aspx?sku=SAE+J+1681-2000+%28SAE+J1681-2000%29#.UZpje8o0-rQ	Research Sponsor: SAE	
Test Fuels: NA	Fuel Notes: NA	
Test Articles: NA	Vehicle Applications: NA	
Test Protocol: NA		

This SAE standard was intended to standardize surrogate gasoline and diesel mixtures to be used in materials testing. It identifies the major and minor fuel components and potential contaminants.

ASTM D471 Fuel C or Fluid C, a 50/50 mixture of toluene and isooctane, is proposed as the base hydrocarbon because toluene and isooctane are the lowest molecular weight species of their class (aromatic and alkane) that will not vaporize readily at laboratory temperatures. The lowest molecular weight species generally create the greatest swell in typical fuel system elastomers and polymers and thus Fuel C may create a potentially exaggerated view of hydrocarbon impact on these constituents. Detailed recipes for Aggressive Methanol and Aggressive Ethanol are included. These aggressive alcohols are made using acids and water. No information as to the basis of these recipes is provided nor is any experimental data referenced as to the correlation between these severe fuels and typical fuels.

The standard proposes that the following fluids be used for qualifying materials for worldwide, typical, gasoline, and diesel fuel system applications:

C[§](M15)$_A$ = ASTM Fluid C with 15v/v% aggressive methanol

C(ME15) = ASTM Fluid C with 15v/v% methyl tertiary-butyl ether

CP = ASTM Fluid 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 Fluid C and separate aqueous phase containing 100 ppm chloride ion per liter of water

[§]A less expensive alternative, Surrogate Fluid C is also permitted. Surrogate Fluid C substitutes mixed isoparaffins for the relatively expensive isooctane, although users are warned that if results are borderline, retesting with Fluid C is recommended.

Assuming automakers have used J1681 in determining appropriate materials used in their fuel systems and engines, these materials have already been tested using 15% Aggressive Methanol in ASTM Fuel C. However, it is not clear that automakers and their component suppliers actually test with ASTM Fuel C or with ASTM Fuel C and the additional contaminants. Methanol is generally considered to be far more incompatible with materials than ethanol, (see, for example, SAE Technical Paper No. 800786), and thus materials approved using J1681 would be unlikely to fail in a similar concentration ethanol blend. Moreover, at no point does J1681 recommend the use of ASTM Fluid 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 including peroxides and chlorides and water. Despite this, ASTM Fluid C with no additions has been selected as the control fluid for materials testing in many of the studies considered here, many of which imply that J1681 is the basis for their choice of test fluids. ASTM Fluid C alone is neither a worst case as envisioned under J1681 that would ensure a safety factor was included in the testing of materials, nor representative of typical marketplace fuels. J1681 suggests that reference gasolines be used in place of ASTM Fuel C when "test fluids more representative of commercial fuels are required."

Primary Category: Material Compatibility: General	Secondary Category: NA	
Title: A Rational Approach to Qualifying Materials for Use in Fuel Systems, SAE No. 2000-01-2013	**Author:** M. Harrigan, A. Banda, B. Bonazza, P. Graham, B. Slimp	**Date:** June 2000
Web link: http://papers.sae.org/2000-01-2013/	**Research Sponsors:** Ford, General Motors, TI Group Automotive Systems, Solvay Automotive, Specified Fuels & Chemicals	
Test Fuels: NA	**Fuel Notes:** NA	
Test Articles: NA	**Vehicle Applications**: NA	
Test Protocol: NA		

This SAE paper explains the basis for the modifications to J1681 made in 2000. Authors are from automotive companies and related industries – Ford, General Motors, TI Group Automotive Systems, Solvay Automotive, Inc. Specified Fuels and Chemicals, LLC. The objective of this study was to select fuel surrogate fluids for fuel system materials testing to make testing uniform and reproducible.

For choosing test fuels, this document proposes the following selection criteria:

1. Representative of marketplace fuels
2. Creates a severe, reproducible level of a particular effect
3. Safe and easy to handle in a laboratory setting
4. Safe and easy to use at temperatures between -40 °C and +60 °C
5. Globally available to scientists and engineers
6. Available with no potentially active impurities or contaminants

For hydrocarbons, the authors propose choosing an aromatic and an isoparaffin, as they are two types of compounds that comprise the majority of gasoline. Smaller compounds are typically more reactive, so they chose the representative compound of lowest molecular weight, but which would be a liquid at room temperature, as volatile compounds are difficult to work with. Thus, the fluid they chose is a blend of 50% isooctane and 50% toluene, known as ASTM Fluid C.

The selection of components emphasizes repeatability over representativeness. For example, for ethanol, they propose 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 added reagent water to reach a consistent 1 wt% water.

Aggressive Ethanol includes sodium chloride, sulfuric acid, and glacial acetic acid. Sulfuric acid was added because the authors believe that sulfuric acid is sometimes found in some commercial biomass derived ethanol (no reference source is cited). The authors mention that acetic acid can sometimes act as a buffer for stronger acids based on work done on buffering process in methanol/gasoline fuel blends. No reason is given for the amount of added sulfuric acid, glacial acetic acid or sodium chloride. The document notes that, at the time it was written, ASTM was considering a pHe specification for ethanol, which has since been incorporated in ASTM D4806. This document does not address how a new pHe specification might change their conclusions, and it has not been updated since the pHe specification has passed.

This document recommends that all materials for worldwide, basic, gasoline and diesel fuel system applications should be tested on 4 base fluids – same fluids as in J1681 (see J1681 above), which includes testing on ASTM Fluid C, dosed with other fuel components and contaminants, including methanol, methyl tertiary-butyl ether, water and peroxides.

Primary Category: Material Compatibility: General	Secondary Category: NA	
Title: "Automotive Materials Engineering Challenges and Solutions for the Use of Ethanol and Methanol Blended Fuels, SAE 2010-01-0729	Author: P.K. Yuen, J. Beckett, W. Villaire, General Motors	Date: April 12, 2010
Web link: http://papers.sae.org/2010-01-0729/	Research Sponsor: General Motors	
Test Fuels: NA	Fuel Notes: NA	
Test Articles: NA	Vehicle Applications: NA	
Test Protocol: NA		

This review article summarizes the automotive industry concerns in selecting materials for automotive parts that will be in contact with alcohol fuels. It includes fuel blends of ethanol and/or methanol at concentrations up to nominal 100%, and so conclusions may not always be appropriate for fuels with concentrations of only 15% ethanol. Moreover, roughly a third of the citations are over 10 years old, and a quarter of the citations are over 20 years old, so the conclusions are not necessarily applicable to cars on the road today. Many of the most interesting conclusions (many included below) are stated without reference to published experiments.

Corrosion of metal components in alcohol fuels is discussed and an early paper (Yahagi, Y., Y. Mizutani, "Corrosive wear of steel in gasoline-ethanol-water mixtures," *Wear* , August 1984.) is cited which states that corrosion rates of steel reach a maximum at about 20vol% ethanol content. With the higher conductivity found in alcohol fuels corrosion can be enhanced at high voltage interfaces, sometimes found in the fuel pump module. Copper, zinc plating and aluminum are listed as particularly susceptible to attack by alcohol gasoline blends. General Motors uses stainless steel for most fuel-contacting components. While stainless steels are generally very corrosion resistant they are not corrosion-proof against alcohol containing fuels. Chloride contamination can also cause corrosion and the authors state it was potentially more prevalent in alcohol containing fuels. Various specific considerations include ensuring protective coatings are protected during manufacture and assembly, and careful evaluation of materials used for the various components of the fuel pump module, including electrical devices, commutators, fuel filters and pressure regulators are discussed, although there is no differentiation between low and high concentrations of ethanol in the fuel.

Regarding polymers the authors caution that many chemical resistance guides are intended for use only at room temperature and effects can be magnified at higher temperatures. Generally, modern fuel tanks hold up well to alternative alcohol fuels, according to this paper, however some older polymer tanks were treated with sulfonation or fluorination and have not been validated for use with alcohol fuels. Polybutylene terephthalate or polyurethane foams, both occasionally used in fuel level floats, have been found to be sensitive to higher alcohol contents, according to the authors. The authors state: "short term tests are inadequate at simulating all of the environmental conditions that the polymers may see in an automotive applications. End-of-life testing will be necessary to establish the suitability of the plastic in the application being specified."

Specific tests for elastomers are listed, and include compression stress relaxation (ability to retain sealing force under compression), fluid resistance (volume and mass change), finite element analysis, low temperature flexibility, permeation, state of cure (reach maximum cross link density for strength and function). ASTM and SAE test protocols are cited for some, but not all, of these tests. Fluorocarbon elastomers are considered the optimal choice for flex fuel (up to E85) use, and other specific polymers are listed by degree of fuel resistance. Three studies done in the 1980s and 1990, found that the most aggressive blends are in the concentration range of 15% to 35%. Methanol blends have a more severe effect than ethanol on elastomers.

Primary Category: Material Compatibility: General	**Secondary Category:** NA	
Title: Intermediate Ethanol Blends Infrastructure Materials Compatibility Study: Elastomers, Metals, and Sealants	**Author:** M. D. Kass, T. J. Theiss, C. J. Janke, S. J. Pawel, and S. A. Lewis, Oak Ridge National Laboratory	**Date:** March 2011
Web link: http://info.ornl.gov/sites/publications/files/Pub27766.pdf	**Research Sponsor:** DOE	
Test Fuels: Aggressive E10, ASTM Fuel C, Aggressive E17, Aggressive E25	**Fuel Notes:** Base fuel for ethanol blends was ASTM Fuel C	
Test Articles: (see below)	**Vehicle Applications**: NA	

Test Articles:

Metals:

Metals having unmodified coupons	Coupons having partial removal of plating to form a galvanic couple
304 stainless steel	Terne steel
1020 carbon steel	Galvanized steel
1100 aluminum	Chromium-plated brass
Cartridge brass	Chromium-plated steel
Phosphor bronze	Nickel-plated aluminum
Nickel 201	Nickel-plated steel
Terne –plated steel	
Galvanized steel	
Chromium-plated brass	
Chromium-plated steel	
Nickel-plated aluminum	
Nickel-plated steel	

Elastomers:

Fluorocarbon rubbers: A total of eight samples were evaluated—Viton A401C, Viton B601, Viton GF-600S, Viton GFLT-600S, Dyneon FE5620, Dyneon FE5840, Dyneon FPO3741, and Dyneon
NBR: A total of six samples were evaluated
Fluorosilicone rubber
Polyurethane
Neoprene
SBR
Silicone Rubber

Sealants also tested but not applicable for automotive use.

Test Protocol: Soaked for 28 days at 60 °C in constant flow tanks. Samples were exposed to both liquid and vapor phase. Metals were tested for changes in weight and appearance. Elastomers were tested for changes in weight, volume, hardness before soak, after soak and after dryout period

This study tested materials used in fuel dispensers including metals, elastomers, sealants. These materials may include some that are not in common automotive use. Further testing on plastics is in process but not included in this report. This document includes a literature review on material compatibility for these materials in ethanol fuels. Testing was done with ASTM Fuel C and three levels of Aggressive Ethanol blends, Aggressive E10, Aggressive E17 and Aggressive E25. E17 was used as a conservative estimate of actual ethanol content considering the variable nature of retail fuels.

Coupons of the materials were tested by soaking for 28 days at 60 °C in constant flow tanks. Samples were exposed to both liquid and vapor phase. Metals were tested for changes in weight and appearance. Elastomers were tested for changes in weight, volume, hardness before soak, after soak and after dryout

Metals do not provide much concern: 1020 mild steel, 1100 aluminum, 201 nickel, 304 stainless were immune to corrosion. Cartridge brass, phosphor bronze, zinc-plated galvanized steel, lead-plated (terne) steel were slightly susceptible but at levels well below the level of concern identified by these authors, 30 um/year. The highest corrosion level was in the Aggressive E10, and the lowest was in Fuel C. Galvanic coupling was tested for several pairs of metals, but resulted in no excessive corrosion levels.

For most elastomers, the greatest amount of swell occurs with either Aggressive E10 or Aggressive E17 suggesting this likely the concentration of maxiumum mutual solubility. Results for specific elastomers listed below.

1. Fluorelastomers saw the best retention of baseline properties. Volume swell was about 20% for all fuels. No structural degradation after exposure was noted.

2. Silicone rubber showed the highest volume expansion for all fuels.

3. Eight different grades of NBR were tested and there was pronounced effect to fuels containing ethanol.

4. Polyurethane was also shown to be sensitive to fuels containing ethanol, including visual evidence of material degradation.

5. Only one grade of SBR was tested, and it showed both excessive swell and softening. It does not appear to be compatible with many sealing applications in tested formulation although authors note that there may be appropriate formulations of SBR that will be acceptable.

6. Neoprene showed relatively little softening, but large amount of volume swell which may limit its use. Increase in brittleness after drying.

<table>
<tr><td colspan="1">Primary Category: Material Compatibility: Elastomers</td><td colspan="2">Secondary Category: NA</td></tr>
<tr><td>Title: Effects of Mixtures of Gasoline with Methanol and Ethanol on Automotive Elastomers, SAE No. 800786</td><td>Author: I. A. Abu-Isa, General Motors</td><td>Date: June 1980</td></tr>
<tr><td>Web link: http://papers.sae.org/800786/</td><td colspan="2">Research Sponsor: General Motors</td></tr>
<tr><td>Test Fuels: various ethanol and methanol concentrations from 0% to 100% (not clear exactly what ethanol concentrations were tested), Indolene HO-III</td><td colspan="2">Fuel Notes: base fuel was Indolene HO-III (standard fuel which contains 29.94% aromatics)</td></tr>
<tr><td>Test Articles: (for ethanol, methanol blends tested on additional materials)
EPDM
Natural rubber
Nitrile
Fluocarbon elastomers (Viton A)
Hypalon
Polyester urethane
Fluorosilicone rubber
Acrylate rubber
Epichlorhydrin homopolymer
VAMAC</td><td colspan="2">Vehicle Applications: NA</td></tr>
<tr><td colspan="3">Test Protocol: exposed to fuel at room temperature for 72 hours, changes in elongation, tensile strength and volume measured</td></tr>
</table>

This is an early study on elastomer compatibility with ethanol and methanol blends. Data is not provided for all of the tests run and generally more information is provided for methanol than for ethanol effects. However, the authors do summarize that results on the ethanol/gasoline systems are similar to those of methanol except that the ethanol mixtures have slightly less severe effects, with the exception of Viton A which showed a greatly reduced effect with ethanol as opposed to methanol. For the tested materials the most severe effects occur at concentrations of ethanol of between 10 and 25%, as opposed to either E0 or E100.

Primary Category: Material Compatibility: Elastomers	Secondary Category: NA	
Title: Fuel and Permeation Resistance of Fluoroelastomers to Ethanol Blends; presented at the Fall 170th Technical Meeting of the Rubber Division, American Chemical Society, Cincinnati, OH	**Author:** R. D. Stevens, DuPont	**Date:** October 10-12, 2006
Web link: http://wwwt.dupontelastomers.com/literature/viton/06ACSMini-Stevens.pdf	**Research Sponsor:** DuPont Performance Elastomers	
Test Fuels: ASTM Fuel C, E10, E25, E50, E85, E100	**Fuel Notes:** base fuel for all ethanol blends was ASTM Fuel C	
Test Articles: 6 fluoroelastomers Viton GLT-600S Viton GBLT-600S Viton GFLT-600S Viton F-605C VTR-9209	**Vehicle Applications**: NA	
Test Protocol: soaked for 168 hours at 40 °C, measured changes in volume swell, hardness, tensile strength, and elongation		

Coupons of the six fluoroelastomers 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 straight ethanol or straight gasoline.

<table>
<tr><td>Primary Category: Material Compatibility: Elastomers</td><td colspan="2">Secondary Category: NA</td></tr>
<tr><td>Title: The Effects of E20 on Elastomers Used in Automotive Fuel System Components</td><td>Author: G. Mead, B. Jones, P. Steevens C. Connors, Minnesota Center for Automotive Research, Minnesota State University</td><td>Date: February 22, 2008</td></tr>
<tr><td>Web link: http://www.mda.state.mn.us/news/publications/renewable/ethanol/e20onelastomers.pdf</td><td colspan="2">Research Sponsor: State of Minnesota</td></tr>
<tr><td>Test Fuels: ASTM Fuel C, Aggressive E10, Aggressive E20</td><td colspan="2">Fuel Notes: ASTM Fuel C as base fuel for Aggressive E20 and Aggressive E10</td></tr>
<tr><td>Test Articles:
Elastomer
acrylic rubber (ACM)
[Hytemp®]epichlorohydrin homopolymer (CO)
epichlorohydrin ethylene oxide copolymer (ECO)
polychloroprene (CR) [Neoprene®]
nitrile rubber (NBR) [Buna N®]
nitrile rubber (NBR) with high CAN content [Buna N®]
nitrile/PVC blend (OZO) [Paracril®]
fluoroelastomer (FKM) with dipolymers of VF2/HFP and 65% fluorine [Viton A®]</td><td colspan="2">Vehicle Applications: NA</td></tr>
<tr><td colspan="3">Test Protocol: Soak 500 hours at 55 +/- 2 °C and test before and after for weight, volume, hardness, tensile strength, elongation, visual examination for materials degradation.</td></tr>
</table>

Samples of the elastomers listed above were soaked for 500 hours at 55 °C in ASTM Fuel C, Aggressive E10 made with ASTM Fuel C as the base fuel, and Aggressive E20 made with ASTM Fuel C as the base fuel. The following properties were measured before and after soaking: appearance, volume, weight, tensile strength, elongation and hardness and the elastomers considered are listed in the table above. All tests were done with 5 different samples for each fuel/material combination.

The conclusion of the authors was that in the few cases where Aggressive E20 caused a change greater than that of Aggressive E10 or Fuel C, the magnitude of the difference was not enough to merit concern. No clear standards for determining what level of difference would merit concern were provided, nor were statistical approaches used, although a look at the graphed data shows that differences between fuels were not dramatic.

All of the elastomers swelled in size and weight to some extent after soaking. CR swelled more in Fuel C than in ethanol blends. All the others swelled and increased in weight more in ethanol fuels than in

Fuel C. Only ECO swelled a noticeable extent larger in Aggressive E20 than in Aggressive E10, and only ACM increased in weight a noticeable amount more in Aggressive E20 than in Aggressive E10. After dryout period, seven of the eight elastomers shrank down below their pre-immersion size. Only FK 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, ACM became softer in Fuel C than in either of the ethanol fuels. The authors found that none of the elastomers exhibited a significant different change in hardness and tensile strength after soaking when Aggressive E10 and Aggressive E20 were compared. Only one of the elastomers ECO was affected more by E20 than E10, but the difference was small and considered unimportant. After dryout, the E20 ACM specimens exhibited higher loss in tensile strength and elongation than in E10 or Fuel C – although this loss in tensile strength and elongation was much less than the loss immediately after soaking so considered not significant by authors.

The document noted that the following compounds have already been qualified for FFV use and so should be consider compatible with any ethanol blends between E10 and E85: acrylic ethylene (AEM) [Vamac], chlorinated polyethylene (CPE), chlorsulfonated polyethylene (CSM)[Hypalon], hydrogenated nitrile rubber (HNBR), fluoroelastomer with terpolymers of VF2/HFP/TFE and 68% fluorine [Viton B], flouroelastomer (FKM) with terpolymers of VF2/HFP/TFE and 70% fluorine [Viton GFLT] and Santoprene (PVDT) (no reference provided).

Primary Category: Material Compatibility: Elastomers	**Secondary Category:** NA	
Title: Elastomer selection for bio-fuel requires a systems approach, *Sealing Technology*	**Author:** G. Micallef, M. Weimann, A. Weimann, Trelleborg Sealing Solutions	**Date:** January 2009
Web link: http://www.sciencedirect.com/science/article/pii/S1350478909700224	**Research Sponsor:** Trelleborg Sealing Solutions	
Test Fuels: ASTM Fuel C, E22	**Fuel Notes:** NA	
Test Articles: fluoropolymer (FKM)	**Vehicle Applications**: NA	
Test Protocol: polymers were tested under high pressure for 168 hours at 60° C with rapid decompression		

The point of this article was to show that elastomers can be affected by factors not addressed in standard laboratory testing for material compatibility. However, the only testing specific to gasoline ethanol blends (other testing involved biodiesel) were materials tested in a high pressure situation, followed by rapid decompression. Five O-rings were tested in ASTM Fuel C and E22. No failures were detected in Fuel C, but all O-rings tested in E22 exhibited cracking. Needed to prove the author's point that high pressure testing is necessary, are results from a similar soak test at lower pressures, showing that these results are due to primarily to the high pressure testing.

<table>
<tr><td>Primary Category: Material Compatibility: Elastomers</td><td colspan="2">Secondary Category: NA</td></tr>
<tr><td>Title: Performance of Elastomeric Materials in Gasoline – Ethanol Blends – A Review, NACE International Corrosion Conference & Expo, March 22-26, 2009, Atlanta , GA</td><td>Author: A. Ertekin, N. Sridhar, DNV Research & Innovation - USA</td><td>Date: March 2009</td></tr>
<tr><td>Web link:
http://www.onepetro.org/mslib/servlet/onepetropreview?id=NACE-09533</td><td colspan="2">Research Sponsor: DNV Research & Innovation - USA</td></tr>
<tr><td>Test Fuels: NA</td><td colspan="2">Fuel Notes: NA</td></tr>
<tr><td>Test Articles: NA</td><td colspan="2">Vehicle Applications: NA</td></tr>
<tr><td colspan="3">Test Protocol: NA</td></tr>
</table>

This review paper provides a useful summary of the properties of ethanol blends that may make them more detrimental to certain elastomers, as well as the various ASTM test methods for measuring liquid effects on various properties of elastomers. It also provides a table describing commonly observed deterioration modes of elastomers including chemical degradation, swelling, stress relaxation, creep, ultraviolet exposure and ozone cracking, fatigue crack growth, bond failure, abrasion/erosion, fracture/rapid tearing, explosive decompression and thermal contraction. Most of these have not been addressed in standard laboratory testing of the effects of different fuels. Results of various studies on the effect of ethanol blends on elastomers are summarized.

Primary Category: Material Compatibility: Metals	Secondary Category: NA	
Title: The Effects of E20 on Metals Used in Automotive Fuel System Components	**Author:** G. Mead, B. Jones, P. Steevens, M. Timanus, Minnesota Center for Automotive Research, Minnesota State University	**Date:** February 22, 2008
Web link: http://www.mda.state.mn.us/news/publications/renewable/ethanol/e20onmetals.pdf	**Research Sponsor:** State of Minnesota	
Test Fuels: ASTM Fuel C, Aggressive E10, Aggressive E20	**Fuel Notes:** Base fuel Aggressive E10 and Aggressive E20 was ASTM Fuel C	
Test Articles: brass 360 cast iron copper 110 6061 aluminum 3003 aluminum cast aluminum mic 6 60/40 tin/lead solder 1018 steel 1018 steel tin plated 1018 stell nickel plated 1018 steel zinc plated 1018 steel zinc tri-chromate plated (hexavalent) 1018 steel zinc di-chromate plated (hexavalent free) 1018 steel zinc-nickel plated terne plate Zamak 5 magnesium AZ91D Lead	**Vehicle Applications**: NA	
Test Protocol: Soak 2016 hours at 45 +/- 2 °C Weight change, visual examination for materials degradation.		

Three samples of each of 19 metals were placed in each fuel and held at 45 °C for 2016 hours. Corrosion rates below 0.0025 mm/yr or approximately 0.05 mm over a 20 year life span were considered acceptable. 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, 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). Zamak 5 showed unacceptable levels of corrosion, excessive mass loss and pitting in both Aggressive E10 and Aggressive E20 but not Fuel C. Magnesium AZ91D exhibited a mass loss higher in Fuel C than in the Aggressive E10 or Aggressive E20. Other metals showed some degree of discoloration, but no excess corrosion. Authors say Zamak 5 is a material used in some early OEM carburetors and aftermarket carburetors. Since carburetors are not used in vehicles since 1995, compatibility is not expected to be a problem in modern vehicles. Magnesium AZ91D is a die casting alloy that was commonly used in carburetors and diaphragm pumps.

<table>
<tr><td colspan="2">Primary Category: Material Compatibility: Metals</td><td colspan="2">Secondary Category: NA</td></tr>
<tr><td colspan="2">Title: EIS study of corrosion behavior of metallic materials in ethanol blended gasoline containing water as a contaminant</td><td>Author: H. Jafar, M.H. Idris, A. Ourdjini, H. Rahimi, B. Ghobadian D. K. Tanaka, A. Sinatora, various university and automotive industry</td><td>Date: December 2011</td></tr>
<tr><td colspan="2">Web link: http://www.sciencedirect.com/science/article/pii/S0016236110006708</td><td colspan="2">Research Sponsor: various university and automotive industry</td></tr>
<tr><td colspan="2">Test Fuels: E0, E5,E10 and E15</td><td colspan="2">Fuel Notes: fuels were tested with and without 1% water</td></tr>
<tr><td colspan="2">Test Articles:
Return fuel tube — Stainless steel 304
Fuel outlet tube — Low carbon steel
Transferring tube bolt — Medium-carbon steel
Main fuel delivery tube — Al 6061
Washer — Copper
Brazed part — Brazing alloy</td><td colspan="2">Vehicle Applications: NA</td></tr>
<tr><td colspan="4">Test Protocol: Electrochemical impedance spectroscopy (EIS) was performed in both water-free and water contaminated ethanol/gasoline blends to measure corrosion rates. Scanning electron microscopy (SEM) was used to visualize the corroded specimens.</td></tr>
</table>

Return fuel tube	Stainless steel 304
Fuel outlet tube	Low carbon steel
Transferring tube bolt	Medium-carbon steel
Main fuel delivery tube	Al 6061
Washer	Copper
Brazed part	Brazing alloy

Corrosion rates of various automotive components made from different materials were measured using electrochemical impedance spectroscopy (EIS). Corrosion rates were measured for ethanol concentrations from E0 to E15, with and without water, and were found to be extremely low, on the order of 10^{-5} mils per year (10^{-7} mm/year), and thus unlikely to be of concern in an automotive context. Corrosion rates were found to increase with ethanol content in most metals tested, with medium carbon steel, low carbon steel and copper showing a large increase in corrosion rate between E10 and E15 (with the exception of an anomalously low data point measured on medium carbon steel at E15 without water). Medium and low carbon steel were the most susceptible to corrosion at all levels of ethanol. Brazing alloy had the lowest corrosion rate. Contamination of ethanol blends with water reduced solution resistance in all cases, but did not increase the corrosion rate of Al 6061 and copper. The authors explained this for Al 6061, by proposing 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. The corrosion rate for all other metals in all fuel blends increased with water. There was no apparent trend for increased or decreased effect of water with ethanol content.

<table>
<tr><td>Primary Category: Material Compatibility: Plastics</td><td colspan="2">Secondary Category: NA</td></tr>
<tr><td>Title: The Effects of E20 on Plastic Automotive Fuel System Components</td><td>Author: B. Jones, G. Mead, P. Steevens, Minnesota Center for Automotive Research, Minnesota State University</td><td>Date: February 2008</td></tr>
<tr><td>Web link:
http://www.mda.state.mn.us/news/publications/renewable/ethanol/e20onplastics.pdf</td><td colspan="2">Research Sponsor: State of Minnesota</td></tr>
<tr><td>Test Fuels: ASTM Fuel C, Aggressive E10, Aggressive E20</td><td colspan="2">Fuel Notes: Base fuel in Aggressive E10 and Aggressive E20 was ASTM Fuel C</td></tr>
<tr><td>Test Articles:
acrylonitrile butadiene styrene (ABS)
polyamide 6 (PA 6)
polyamide 66 (PA 66)
polybutylene terephthalate (PBT)
polyethylene terephthalate (PET)
polyetherimide 1010 moldable (PEI)
polyurethane 55D-90 Adurameter hardness (PUR)
polyvinyl chloride flexibe version (PVC)</td><td colspan="2">Vehicle Applications: NA</td></tr>
<tr><td colspan="3">Test Protocol: Soaked for 3024 hours at 55 °C and then tested for volume, weight appearance, impact resistance, tensile strength, ultimate elongation</td></tr>
</table>

Samples of eight different plastics were soaked at 55 °C for 3024 hours, in ASTM Fuel C, and two ethanol blends in Fuel C, Aggressive E10 and Aggressive E20. Before and after soaking, the samples were tested for volume, weight appearance, impact resistance, tensile strength, ultimate elongation. ASTM D618-00, ASTM D543. The list of plastics was created from literature reviews, manuals, and recommendations from fuel system and engine manufacturers, according to authors, but then at the end they determine that they cannot identify any automotive fuel system use of ABS, PUR or PVC. Materials used in flex-fuel vehicle fuel systems were removed from the list because they have already been proven compatible with any blend of ethanol from 0% to 85%. These materials include ethyl vinyl alcohol, polyamide 12 conductive version, polyamide 46, polyphthalamide, high density polyethylene, low density polyethylene, polypropylene, polyphenylene sulfide, polyoxymethylene.

Several of the tested plastics were worse in the ethanol blends than in Fuel C, but the authors found no significant difference between the Aggressive E10 and the Aggressive E20. 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. The authors also conclude PBT is not compatible with ethanol containing fuels, although the reasoning is not clear.

<table>
<tr><td colspan="2">Primary Category: Material Compatibility: Plastics</td><td colspan="2">Secondary Category: NA</td></tr>
<tr><td colspan="2">Title: Compatibility Study for Plastic, Elastomeric, and Metallic Fueling Infrastructure materials Exposed to Aggressive Formulations of Ethanol-Blended Gasoline</td><td>Author: M. D. Kass, T.J. Theiss, C.J. Janke, S.J. Pawel</td><td>Date: May 2012</td></tr>
<tr><td colspan="2">Web link: http://info.ornl.gov/sites/publications/files/Pub35074.pdf</td><td colspan="2">Author Affiliation: Oak Ridge National Laboratory</td></tr>
<tr><td>Test Fuels: Aggressive E25, Aggressive E50 and Aggressive E85</td><td>Control Fuels: ASTM Fuel C</td><td colspan="2">Fuel Notes: Base fuel in all cases was ASTM Fuel C</td></tr>
<tr><td colspan="2">Test Articles:
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)
fluorinated high-density polyethylene (F-HDPE)
two isophthalic polyesters
terephthalic polyester
vinyl ester
two epoxies</td><td colspan="2">Vehicle Applications: NA</td></tr>
<tr><td colspan="4">Test Protocol: Soaked for 16 weeks, in a flowing tank (0.8 m/s) at 60 °C and tested before and after for volume, weight and hardness</td></tr>
</table>

Sixteen thermoplastic samples and six thermoset plastic samples were soaked for 16 weeks in a flowing tank kept at 60 °C in E0, Aggressive E25, Aggressive E50 or Aggressive E85 all made from a base fuel of ASTM Fuel C. Some specimens were held in the vapor phase and some were held in the liquid phase. Changes in mass, volume and hardness were measured immediately upon removal for the specimens from the liquid phase test fuel, and also after drying for 65 hours. The vapor phase samples were tested only for changes in hardness. Those plastics which exhibited hardness changes when exposed to the liquid phase of the test fuels were similarly sensitive to the vapor phase, although changes were of a smaller magnitude.

None of the samples were tested on E15 or E10 so this study cannot be used to determine plastics which are particularly susceptible to a shift from the use of E10 to E15, but a number of plastics showed no problems in any fluid tested including polyethylene terephthalate (PET), polyphenyline sulfide (PPS) and polytetrafluoroethylene (PTFE). Low levels of swell (on the order of 5%) were found for petroleum derived nylons and HDPE. However, both polypropylene (PP) and high density polyethylene (HDPE) had higher swell with Fuel C than with the other tested fuels. Higher levels of swell were found with thermosets, polyethylene terephthalate copolymer (PETG), nylon 11 and polypropylene (PP). Hardness changed roughly in proportion to measured swell, although the authors concluded that the extent of hardness change in all plastics was small. Polythiurea (PTU) and the epoxies were cracked by exposure to Aggressive E25, Aggressive E50 and Aggressive E85, while isophthalic polyesters cracked only in Aggressive E25 and Aggressive E50.

Most of the plastics exhibited maximum swell with exposure to Aggressive E25 (as opposed to E0, E50 or E85).

Engine and Fuel System Durability

Testing of engine and fuel system durability adds a layer of complexity to the issues addressed in the section on Materials Compatibility. In addition to the problems associated with choosing appropriate test and control fluids and scaling up short term testing results to long term predictions, different materials used in each make and model, make it impossible to use individual tests to provide fleet-wide estimates of the impact of changing fuels. The value of the studies could be improved significantly if the affected materials within the components were identified, thus allowing the results to be extrapolated to components and vehicles not included in the testing. Unfortunately, because of confidentiality agreements with the OEMs, in many cases the makes and models of the tested vehicles are not associated with specific results, nor are specific materials identified, perhaps because this might allow the identification of the failed components.

Only very low failure rates for components are acceptable. The Coordinating Research Council (CRC) states that OEMs expect individual components to fail less than once per thousand vehicles over the lifetime of the vehicle.[**] Testing to prove this level of reliability would take thousands of components, and the tests included below are all on much smaller populations. In order to find any detectable effect, the CRC has focused on vehicles and components suspected or known to be more sensitive to ethanol content than the average. The results are thus biased, although to an unknown extent, toward the most sensitive vehicles and components.

<u>Acronyms</u>

CRC – Coordinating Research Council
FTP75 – Federal Test Procedure city driving cycle
MY – model year
OEM – original equipment manufacturer
PFI – port fuel injection
TBI – throttle body fuel injection

[**] CRC Report No. 664

Fuel System Component Tests

<table>
<tr><td>Primary Category: Engine and Fuel System Durability</td><td colspan="2">Secondary Category: NA</td></tr>
<tr><td>Title: The Effects of E20 on Automotive Fuel Pumps and Sending Units</td><td>Author: G. Mead, P. Steevens, B. Jones, N. Hanson, T. Devens, C. Rohde, A. Larson, Minnesota Center for Automotive Research, Minnesota State University</td><td>Date: February 21, 2008</td></tr>
<tr><td>Web link:
http://www.mda.state.mn.us/news/publications/renewable/ethanol/320onfuelpumps.pdf</td><td colspan="2">Research Sponsor: State of Minnesota</td></tr>
<tr><td>Test Fuels:, E0 (Tier II), Aggressive E10, Aggressive E20</td><td colspan="2">Fuel Notes: Base fuel in E10A and E20A was Tier II gasoline</td></tr>
<tr><td>Test Articles: Automotive electric fuel pumps and fuel level senders</td><td colspan="2">Vehicle Applications: Fuel pumps from all of the following, and fuel level senders from the three marked with an asterisk.

Volkswagen Passat 1993-1994
*Jeep Wrangler 1999-2000
Ford truck 1990-1993
GM TBI truck 1987-1992
GM PFI early 1990s
*GM (port pump) 2000-2002
Toyota Camry 2002-2005
*Honda Accord 1998-2002</td></tr>
<tr><td colspan="3">Test Protocol:
Fuel pumps | 30 day static soak test at 20 +/-10 °C | visual inspection of pumps and test fuel; pressure, flow rate and current measured
Fuel senders | 30 day static soak test at 20 +/-10 °C | visual inspection, resistance and voltage drop over full sweep</td></tr>
</table>

This study was a soak test for vehicle components in three different fuels. The test reported here was 30 days (720 hours) as compared to soak tests in CRC 662 and CRC 664 that were about four times as long. Tests were conducted on eight different model fuel pumps; and three different model sending units, only one of each in each fuel. These were the same pumps and sending units that would be used in endurance testing (An Examination of Fuel Pumps and Sending Units During a 4000 Hour Endurance Test in E20, March 2009). All of the fuel pumps met the performance requirements (J1537) for start up before and after soak. Flow data showed a dramatic reduction, 40%, in one pump (from the GM TBI truck) soaked in Aggressive E10. All others showed an increase or decrease of less than 20%, which is within the range that is considered normal. 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. Data on sending units was not included in the report.

Notably, J1681 Aggressive Ethanol blended in to ASTM Fuel C at 20 volume percent was used as the test fluid. This formulation exhibits much lower pHe than is likely to be encountered and does not contain corrosion inhibitor/pHe buffer additives that are commonly in use.

Primary Category: Engine and Fuel System Durability	**Secondary Category:** NA	
Title: An Examination of Fuel Pumps and Sending Units During a 4000 Hour Endurance Test in E20	**Author:** G. Mead, B. Jones, P. Steevens, N. Hanson, J. Harrenstein, Minnesota Center for Automotive Research, Minnesota State University	**Date:** March 2009
Web link: http://www.mda.state.mn.us/news/publications/renewable/ethanol/e20endurance.pdf	**Research Sponsor:** State of Minnesota	
Test Fuels: E0 (Tier II), Aggressive E10, Aggressive E20	**Fuel Notes:** Base fuel in Aggressive E10 and Aggressive E20 was Tier II gasoline	
Test Articles: Automotive electric fuel pumps and fuel level senders	**Vehicle Applications:** Fuel pumps from all of the following, and fuel level senders from the three marked with an asterisk. Volkswagen Passat 1993-1994 *Jeep Wrangler 1999-2000 Ford truck 1990-1993 GM TBI truck 1987-1992 GM PFI early 1990s *GM (port pump) 2000-2002 Toyota Camry 2002-2005 *Honda Accord 1998-2002	
Test Protocol: 4000 hr endurance tests with performance measurements at 500 hr intervals; at the end of test, pumps were disassembled to measure wear and inspected visually		

This study compares the effects of Aggressive E20, Aggressive E10 and Tier II E0 on electric automotive fuel pumps and sending units. This formulation exhibits much lower pHe than is likely to be encountered and does not contain corrosion inhibitor/pHe buffer additives that are commonly in use. All units were tested by operating continuously for 4000 hours. The test procedures were derived from SAE J1537 Validation Testing of Electric Fuel Pumps for Gasoline Fuel Injections systems, but test time was lengthened to 4000 hours, fuel used for test was about doubled, and the fuel change intervals were lengthened. This study also elevated temperature from 33 +/- 3 °C, suggested in J1537 to 42 +/- °8 C. One of each of eight fuel pump models and three sending unit models were tested in three different fuels. These are the same pumps that were used in a previous pump soak study, so effects may be a combination of soaking and endurance testing. 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 E10, 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 were cycled repeatedly through a sweep of their range every 2.5 minutes, over 4000 hours. The sending units in gasoline were coated with a black residue covering, the ethanol units were not, but this did not appear to affect functionality. By the end of the study all the units that were tested had failed, regardless of which fuel they were in. No significant differences between fuels were noted. These results should be compared to those in CRC studies Nos. 662 and 664 in which similar continuous operation tests were conducted on pumps and sending units, although only for a 3000 hour period.

<table>
<tr><td>Primary Category: Engine and Fuel System Durability</td><td colspan="2">Secondary Category: NA</td></tr>
<tr><td>Title: Durability of Automotive Fuel System Components Exposed to E20, CRC Report No. 662</td><td>Author: CRC</td><td>Date: December 2011</td></tr>
<tr><td>Web link:
http://www.crcao.org/reports/recentstudies2012/CRC%20662%20%5BAVFL-15%5D/CRC%20662%20%5BAVFL-15%5D%20Final%20Report%202011.12.30.pdf</td><td colspan="2">Research Sponsor: CRC</td></tr>
<tr><td>Test Fuels: E0, E10, Modified Aggressive E20</td><td colspan="2">Fuel Notes: Modified Aggressive E20 is made from ethanol different from J1681 recipe for aggressive ethanol; it includes different acids; pHe was lower than that expected from normal J1681 recipe, base fuel is described as a commercially available gasoline. Some testing may have occurred on fuel that was past its expiration date.</td></tr>
<tr><td>Test Articles: fuel pumps, dampers, level senders, fuel injectors, entire fuel system rigs</td><td colspan="2">Vehicle Applications: specific make, model and MY of test parts were not identified, just noted that they were selected from 15 different vehicles which were listed in report. MY of all vehicles considered were 1996 to 2008. Some further clues were given in the text: fuel dampers were both from one manufacturer used on vehicles MY 1994 to 2008; fuel injectors - three different manufacturers represented MYs 2002-2009; fuel level senders - eight different manufacturers; fuel system rigs two from each of six vehicle MYs 1996-2009. Parts were from spare parts available from OEM so may actually reflect design or material changes since original manufacture.

<table>
<tr><td>Toyota</td><td>Camry</td><td>1996</td></tr>
<tr><td>Honda</td><td>Accord</td><td>1998</td></tr>
<tr><td>Jeep</td><td>Grand Cherokee</td><td>2000</td></tr>
<tr><td>Chevrolet</td><td>Cavalier</td><td>2001</td></tr>
<tr><td>Toyota</td><td>Tacoma</td><td>2001</td></tr>
<tr><td>Mitsubishi</td><td>Galant</td><td>2002</td></tr>
<tr><td>Toyota</td><td>Camry</td><td>2002+</td></tr>
<tr><td>Hyundai</td><td>Elantra</td><td>2003</td></tr>
<tr><td>Nissan</td><td>Maxima</td><td>2003</td></tr>
<tr><td>Ford</td><td>Focus</td><td>2004</td></tr>
<tr><td>Ford</td><td>Focus PZEV</td><td>2004</td></tr>
<tr><td>Ford</td><td>Ranger</td><td>2004</td></tr>
<tr><td>Dodge</td><td>Neon</td><td>2005</td></tr>
<tr><td>Nissan</td><td>Altima</td><td>2007</td></tr>
<tr><td>Honda</td><td>Accord</td><td>2009</td></tr>
</table></td></tr>
</table>

Test Protocol:

Entire fuel system rig	Hot soak 61 weeks at pressure	pressure test; visual inspection of fuel delivery module, fuel hoses, lines and tubes, fuel rail and injectors; weekly analysis of fuel
Fuel pumps	8-12 weeks at 60 °C	impeller swell, flow capacity, visual material degradation
Fuel pumps	3000 hours of operation between 40 °C and 60 °C	visible materials degradation, excessive wear, shaft bearing failure, flow capacity
Fuel senders	(250,000 cycles in and out of fuel; then soaking unpowered for one week) X 4 times	qualitative evaluation of signal
Fuel senders	5 million cycles in and out of fuel while powered	Qualitative evaluation of signal
Fuel dampers	Soak 120 hours at 120 °F	dynamic response to a pressure spike
Fuel injectors	600 million cycles	flow rate

This was a pilot test report, intended to determine where additional testing might be valuable. Modified Aggressive E20 was compared to standard E10 and E0, to find parts potentially sensitive to ethanol blend fuels. This formulation exhibits much lower pHe than is likely to be encountered, includes an oxidizing acid, and does not contain corrosion inhibitor/pHe buffer additives that are commonly in use. They looked at pumps, dampers, level senders, injectors and entire fuel system rigs. Testing did not include engines. Models were selected by OEMs from a list of 15 vehicles, MYs 1996 to 2009, although results were not associated with specific vehicles. Testing was done on new components sold as service parts and purchased from local OEM dealerships. Design changes may have occurred since the original design.

The researchers chose not to use the formula for Aggressive E20 that was in J1681. Instead the CRC version included water added in different amount (could be less or more but at a level that meets ASTM spec for ethanol), sulfuric, acetic and nitric acid in different proportions than in SAE J1681 – this led to a lower pHe, 2.3, (p. A-6) instead of the expected 2.8 for J1681 (p. 24) and higher chloride content (4 to 10 ppm (mass) for the Modified Aggressive Ethanol used for this work (p. A-6 vs. 2.73 ppm (mass)predicted for J1681 recipe, according to p. 24). It was also intended to reduce sulfate levels (25.15 ppm (mass) predicted for J1681 recipe (p.24) vs. 4 ppm (mass) (p. A-6)) . The testing strategy used in this work was such that for fuel pumps, fuel senders, fuel dampers and fuel injectors, only components which failed in Modified Aggressive E20 are further tested on E10 or E0. This assumes the failure was caused by ethanol and can lead to biased results, as perhaps other components would fail only in E10 or E0, either because of different sensitivities, or because loss of flow rate is random or due to problems unrelated to fuel.

Failure of the report to specifically identify the materials in the tested equipment which are found to be more sensitive to ethanol in gasoline limits the scientific and engineering value of this paper.

Some qualitative differences attributed to differences in fuels were found on visual inspection of fuel system rigs after testing, but nothing that led to loss of pressure over test period. Fuel pumps were tested in two ways. All ten soak durability tested fuel pump models were tested on the Modified Aggressive E20, three were tested on E10 and one on E0. None of the tested pumps failed, defined as a decline in flow rate of more than 30%. The E0 pump showed a greater decline in flow rate than either the Modified Aggressive E20 or the E10 pumps. 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 E20 pump, one showed a greater decline in flow rate. Only one pump model exceeded acceptable 30% flow rate loss, and it did this in both Modified Aggressive E20 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 E20 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 with no problems. Some testing was done in replicate, although again there is no consistent or stated strategy. The results are presented as a qualitative description, and so in some cases it is not clear what senders are exhibiting unacceptable levels. Only two out of the eight senders exhibited no problems at all in Modified Aggressive E20 in either test, but given the uneven testing strategy it is not possible to compare these results summarily to those in E10 and E0.

Only two fuel dampers, both of the same make and model, were tested by soaking for 120 hours at 120 °F in 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. No significant diminishment in performance was detected.

Primary Category: Engine and Fuel System Durability	**Secondary Category:** NA	
Title: Durability of Fuel Pumps and Fuel Level Senders in Neat and Aggressive E15, CRC Report No. 664	**Author:** CRC	**Date:** January 2013
Web link: http://www.crcao.org/reports/recentstudies2013/CRC%20664%20%5BAVFL-15a%5D/AVFL%2015a%20%5BCRC%20664%5D%20Final%20Report%20only.pdf	**Research Sponsor:** CRC	
Test Fuels: E0, E10, E15 and modified E15A, E20A in one fuel pump	**Fuel Notes:** Modified Aggressive ethanol blends made from aggressive ethanol different from J1681 recipe for aggressive ethanol; it includes different acids and pHe was lower than that expected from normal J1681 recipe, base fuel is described as a commercially available gasoline; some of the testing was done on fuel that was past its expiration date.	
Test Articles: fuel pumps, fuel dampers, fuel level senders, fuel injectors, entire fuel system rigs	**Vehicle Applications**: Nissan Altima 2007 Chevrolet Cavalier 2001 Ford Focus 2004 Nissan Maxima 2003 Ford Ranger 2004 Specific make, model and MY of test parts were not identified, just noted that they were selected from these 5 different vehicles.	

Test Protocol:

fuel pumps	12 weeks soaking	loss in flow capacity, inspection of material degradation
fuel pumps	3000 hours of operation	impeller swell
fuel senders	(250,000 cycles in and out of fuel; then soaking unpowered for one week) X 4 times	qualitative evaluation of signal from circuit
fuel senders	5,000,000 cycles in and out of fuel	qualitative evaluation of signal from circuit

This work was done on those parts of the automotive fuel system that were found to be most sensitive to Modified Aggressive Ethanol in pilot testing reported in CRC Report No. 662. This Modified Aggressive Ethanol formulation exhibits much lower pHe than is likely to be encountered, includes an oxidizing acid, and does not contain corrosion inhibitor/pHe buffer additives that are commonly in use. Specific makes and models of components were also selected based on the results from CRC Report No. 662. The parts were from five vehicle models: 2007 Nissan Altima, 2001 Chevrolet Cavalier, 2004 Ford Focus, 2003 Nissan Maxima and 2004 Ford Ranger, although specific results were not associated with specific vehicles. The tested parts cannot be considered representative of parts on the road, as they have been specifically chosen because they were expected to be more sensitive to aggressive ethanol than other potential test components.

Failure of the report to specifically identify the materials which are shown to be more sensitive to ethanol gasoline blends limits the scientific and engineering value of this paper.

There were a number of concerns about the fuel, including the use of Modified Aggressive Ethanol in some of the higher content ethanol blends but standard ethanol in E10 in some cases. The E20 fuel was from a batch of gasoline that was beyond the expiration date of the certificate of analysis, and properties were not retested (analyses in Appendix A of CRC 662), and from Modified Aggressive Ethanol made up almost two years earlier. pHe of aggressive ethanol was measured in CRC 662 and was measured to be 2.3, where ASTM spec for ethanol requires pHe of ethanol to be between 6.5 and 9.0.

Fuel pumps and fuel level senders were tested for soak durability and endurance aging in E15 and Modified Aggressive E15, as well as E10 and E0 for some tests. Modified Aggressive E20 was also used in one type of fuel pump. The same test protocols were used as had been used in the pilot study (CRC Report No. 662). One to three models of each component type were tested, 6 of each model. One fuel pump model Vehicle N (of the three tested) failed regularly in soak test with E15 and Modified Aggressive E15 but not with E0 or E10 on soak durability. Interestingly, same part did not fail in CRC 662 tested on Modified Aggressive E20 or E10. Vehicle N fuel pumps were retested after other experiments were completed in E15, Modified Aggressive E15 and Modified Aggressive E20. No control was used for this testing (i.e. no E0 or E10 was tested). In this testing, all pumps failed after 4 weeks. Authors attributed soak problems found in E15 and Modified Aggressive E15 with this pump to impacts on the impeller. During teardown they found vanes of the impeller had been damaged and greater variation in width with impellers tested on E15 and Modified Aggressive E20, 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 E15 (did not include the pump which failed in soak test). Results showed 5 out of 6 of pumps tested failed in E15, similarly in Modified Aggressive E15. No failures in E0. No testing was reported in E10 or Aggressive E10.

Six fuel senders from each of three models were tested using two different test protocols in E15 and Modified Aggressive E15. Although some minor impacts on the senders were noted, testing was not conducted on any fuels with lesser ethanol contents, and so no conclusions regarding the impact of these fuels in comparison to typical fuels already in use can be made.

Whole Vehicle or Engine Tests

<table>
<tr><td>Primary Category: Engine and Fuel System Durability</td><td colspan="2">Secondary Category: NA</td></tr>
<tr><td>Title: Limitations and Recommended Practice in the Use of Compression and Leak-Down Tests to Monitor Gradual Engine Degradation, SAE 2011-01-2427</td><td>Author: C. Scott Sluder and B.H. West, Oak Ridge National Laboratory</td><td>Date: December 15, 2011</td></tr>
<tr><td>Web link: http://papers.sae.org/2011-01-2427/</td><td colspan="2">Research Sponsor: DOE</td></tr>
<tr><td>Test Fuels: NA</td><td colspan="2">Fuel Notes: NA</td></tr>
<tr><td>Test Articles: NA</td><td colspan="2">Vehicle Applications: NA</td></tr>
<tr><td colspan="3">Test Protocol: NA</td></tr>
</table>

The purpose of this work was to measure the uncertainty associated with compression and leak-down tests to determine if they are precise enough to monitor incremental change. Results are presented from two vehicle fleets at two different test sites. Vehicles were part of the Oak Ridge National Laboratory Intermediate Ethanol Blends Catalyst Durability Program. Random measurement uncertainty was established for each test site by conducting triplicate measurements. At both sites, the triplicate tests involved re-warming the engine, re-positioning the cylinder at Top Dead Center and re-installing the leak-down tool for each test. At site A the 95% confidence interval for leak-down testing, using the same test protocol and equipment, was +/- 2.7%. At site B the 95% confidence interval for leak-down testing was +/-0.7%. Compression test results showed 95% confidence interval of 5.7 psig at site A, and 2.7 psig at site B. However, there was a considerably larger range of uncertainty if measurements from the two sites were compared.

This document finds that there is limited information on what is an acceptable level of leak-down loss. They cite the Federal Aviation Administration, which allows a 25% leak-down rate for airplane engines, which may have little or no applicability to automotive engines. Other sources say from 20-30% is permissible in automotive engines, however the source of this information is uncited.

<table>
<tr><td>Primary Category: Engine and Fuel System Durability</td><td colspan="2">Secondary Category: NA</td></tr>
<tr><td>Title: Intermediate-Level Ethanol Blends Engine Durability Study, CRC Project No. CM-136-09-1B</td><td>Author: Henning Kleeberg
FEV, Inc.</td><td>Date: April 2012</td></tr>
<tr><td>Web link:
http://www.crcao.com/reports/recentstudies2012/CM-136-09-1B%20Engine%20Durability/CRC%20CM-136-09-1B%20Final%20Report.pdf</td><td colspan="2">Research Sponsor: CRC</td></tr>
<tr><td>Test Fuels: E0, E10, E15 and E20</td><td colspan="2">Fuel Notes: NA</td></tr>
<tr><td>Test Articles: Engines</td><td colspan="2">Vehicle Applications:

Honda CR-V 2001
Volkswagen Jetta 2002
Scion xA 2004
Chevrolet Colorado 2005
Ford Edge 2007
Dodge Ram 2007
Dodge Caliber 2009
Chevrolet Aveo 2009</td></tr>
<tr><td colspan="3">Test Protocol: Engines were run for 500 hours.
Emissions testing on vehicle and engine (FTP75); must be maintained within certification tolerance limits compared to start-of-test data
Valve clearance measurements per the OEM’s service manual or other if instructed by OEM; OEM specifications determined pass or fail
Cylinder compression per the OEM’s service manual or other if instructed by OEM; OEM specifications determined pass or fail
Leakage measurement per the OEM’s service manual or other if instructed by OEM; leak-down loss of greater than 10% was classified as a failure
Absence of fuel related diagnostic trouble code</td></tr>
</table>

Sixteen cars were purchased from used car dealerships, two of each of the eight makes and models listed above. The engines were removed from the vehicles and installed on engine dynamometers operated on E20 for 500 hours and tested before and after for compression loss, leak-down loss, valve measurements, absence of fuel-related diagnostic trouble codes, and tailpipe emissions during FTP75. The vehicle types which failed on E20 were tested (in duplicate) on E15 (different vehicles of the same make and model were recruited for the E15 testing) and those which failed on both E20 and E15 were tested (in duplicate, on a newly recruited set of vehicles) on E0. No engines were tested on E10. Emission testing was conducted using certification gasoline. Durability fuels were prepared from commercially sourced hydrocarbon gasoline and ethanol blendstocks, providing a high likelihood that corrosion inhibitor/pHe buffering additives were included. Detergent additive treat rate was three times higher than legally required for deposit control.

One engine failed leak-down measurement on at least one cylinder above 10% at end of testing on E20, E15 but not on E0. Another 1 of 2 samples failed for leak-down measurement and valve clearance measurement for E20, failed for leak-down at E15 and passed all criteria with E0. One vehicle failed for emissions, compression and leak-down for all three fuels.

The strategy of only testing engines on E0 when they already have failed on E20 presupposes that failures are related to ethanol content, as opposed to some other factor, such as their past use, or due to a problem with their design, or that failure is random.

The statistical analysis was flawed. 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. In addition, the analysis completely discarded the testing on the 8th 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%. These values suggest no clear trend of increasing failures with increasing ethanol content.

All failures are treated as equivalent. However, many of the failures in E20 and E15, were for leak-down above 10% alone, a criterion that appears to be arbitrary. Other criteria were based on OEM standards (compression and valve clearance) or EPA regulations (emissions testing).

<table>
<tr><td>Primary Category: Engine and Fuel System Durability</td><td colspan="2">Secondary Category: NA</td></tr>
<tr><td>Title: Powertrain Component Inspection from mid-Level Blends Vehicle Aging Study, ORNL/TM-2011/65</td><td>Author: B. Shoffner, R. Johnson, M. Heimrich, M. Lochte, Southwest Research Institute for the Oak Ridge National Laboratory</td><td>Date: November 2010</td></tr>
<tr><td>Web link:
http://info.ornl.gov/sites/publications/files/Pub28733.pdf</td><td colspan="2">Research Sponsor: DOE</td></tr>
<tr><td>Test Fuels: E0, E15 and E20</td><td colspan="2">Fuel Notes: base fuel for all was “retail top tier gasoline”, ethanol fuels were splash blended</td></tr>
<tr><td>Test Articles: cam lobes, valves, valve stems, intake valves, fuel pumps, fuel injectors, valve seals, evaporative canisters, fuel tanks, fuel lines, and evaporative emissions lines</td><td colspan="2">Vehicle Applications:

Honda Accord 2007
Chevrolet Silverado 2006
Nissan Altima 2008
Ford Taurus 2008
Dodge Caravan 2007
Chevrolet Cobalt 2006</td></tr>
<tr><td colspan="3">Test Protocol: Aged vehicles for between 68,000 and 102,000 miles using the Standard Road cycle.</td></tr>
</table>

emissions system	pressure test
cam lobes	heel to toe measurements
valves	measured four radial traces
valve stems	measured height
intake valves	weighed before and after aging to measure amount of deposits
engine oil drain samples	metal levels
fuel pumps	flow rate and visual inspection after disassembling
fuel injector	flow rate
valve seals	visual inspection

Six makes and models from the model years 2006 to 2008 were selected, and three used vehicles of each type were purchased. Vehicles of each type were matched for EPA engine family and transmission type and had roughly equivalent mileage. Vehicles started out with between roughly ten thousand miles (the three Nissan Altimas) and over forty thousand miles (the three Dodge Caravans and the three Chevrolet Cobalts). They were then aged for between 68,000 and 102,000 miles using the Standard Road Cycle, virtually around-the-clock. All vehicles in a set were driven roughly the same mileage. Vehicles were refueled hundreds of times during the test. The vehicles were examined before and after the aging process.

The only negative E15 finding was an increase in valve deposits which authors attribute to the fact that the detergent in the gasoline was diluted by ethanol. However, a number of the tests were inconclusive. Details are listed below.

a. The integrity of the emissions system was checked by holding under pressure, and introducing smoke into the system. All of the systems maintained pressure.
b. Cam lobe wear testing was inconclusive because the size of the cam lobes was not measured at the beginning of the program.
c. Valve seat width and valve surface contour were assessed and no differences were found between fuels.
d. Valve stem height testing was inconclusive because it was not measured at the beginning of the program.
e. Intake valve deposits were considerably greater for the E15 engines when compared to the E0, and in most cases higher for E20 than E15. The authors suggest this may be due to diluting effect of ethanol on detergent additives in gasoline.
f. 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.
g. One fuel pump feed nipple cracked in E15; for the rest there was no evidence of differences between fuels.
h. Fuel injector flow rates were equivalent to within +/- 3%. There was no evidence of any fuel related effects.
i. The valve seals were visually inspected. The authors came to no conclusions regarding these inspections and any impact of fuel ethanol content.
j. Evaporative canister working capacity shows a slight decreasing trend with higher ethanol content fuels for two of the six vehicles. Four of the six vehicles show no impact.
k. Fuel tanks, fuel lines, and evaporative emissions lines were visually inspected. There were a variety of descriptions for the different vehicles, but the authors conclude that there were no “serious differences” between E0, E15 and E20.

Primary Category: Engine and Fuel System Durability	**Secondary Category:** NA	
Title: Lubricating Oil Consumption on the Standard Road Cycle, SAE No. 2012-01-0884	**Author:** B. West and C. S. Sluder, Oak Ridge National Laboratory	**Date:** April 8, 2013
Web link: http://papers.sae.org/2013-01-0884/	**Research Sponsor:** DOE	
Test Fuels: E0, E10, E15 and E20	**Fuel Notes:** splash blended fuels	
Test Articles: NA	**Vehicle Applications**: 86 vehicles MYs 2000 to 2009	
Test Protocol: around-the-clock operation of vehicles on the Standard Road Cycle (SRC) on mileage accumulation dynamometers and track operation of vehicles for a period every day		

This study was conducted in the same vehicles as they were aged in the Intermediate Ethanol Blends Catalyst Durability Program. The vehicles were aged the equivalent of 50,000 to 120,000 miles. Oil consumption was measured over the course of the testing. There were no statistically significant differences in oil consumption attributed to the ethanol level in the fuel.

Primary Category: Engine and Fuel System Durability	Secondary Category: NA	
Title: Demonstration and Driveability Project to Determine the Feasibility of Using E20 as a Motor Fuel	**Author:** D. Kittleson, A. Tan, D. Zarling, B. Evans, C. Jewitt, University of Minnesota, Evans Research Consultants, Renewable Fuels Association	**Date:** November 2008
Web link: http://www.mda.state.mn.us/renewable/ethanol/~/media/Files/renewable/ethanol/e20drivability.ashx	**Research Sponsor:** State of Minnesota	
Test Fuels: commercially available E0, E20	**Fuel Notes:** E20 was produced from commercially available E10 up-blended with ethanol; the base fuel was not the same as the E0 used as a control	
Test Articles: NA	**Vehicle Applications**: 40 pairs from the University of Minnesota vehicle fleet; each pair had the same MY, make and model with similar usage patterns; MYs ranged from 2000 to 2006, and included 14 passenger cars, 66 light-duty trucks or vans. Included vehicles by DaimlerChrysler, Ford, General Motors and Toyota.	
Test Protocol: University fleet use for 13 months; record any check engine light illumination.		

In 2006-07, the University of Minnesota conducted a thirteen-month evaluation of 80 vehicles, consisting of 40 pairs of similar vehicles with similar usage patterns. Vehicle model years ranged from 2000 to 2006. One of each pair was fueled with commercially available E0 and the other was fueled with E20 (additional ethanol added to commercially available E10). The fuels did not have the same hydrocarbon base fuel. The primary purpose of the testing was to discover any driveability problems with the use of E20, but the use of E20 in all of these vehicles also provided some indication of whether the higher ethanol content fuel would cause maintenance problems. During that time only two of the vehicles had check-engine lights illuminate, both E20 vehicles. 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. No statistically significant driveability differences between E20 and E0 were noted by the University employees using the vehicles, or by trained driveability raters who tested vehicles during each of the four seasons.

Exhaust Emissions

Fuel composition impacts exhaust emissions; therefore it is important to know the fuel composition when comparing emissions results within a given study or results from different studies. Ethanol can be either splash-blended or match-blended into gasoline. Splash blending means that ethanol is simply added to a gasoline base-stock to the intended volumetric concentration, without regard to its effects on other fuel properties such as vapor pressure, octane number, aromatics and sulfur levels, and distillation curve. Match blending involves more effort (and therefore more expense) to adjust the properties of the base-stock gasoline(s) in order to provide fuels that hold selected fuel properties constant as ethanol level is systematically varied; constant fuel vapor pressure and octane number are examples.

Measurement of the major gaseous exhaust emissions is routine and results are available immediately. However, measurement of the oxygenated compounds in exhaust gas is less routine and labor intensive. Unburned ethanol is measured by one of two methods: 1) sampling into water impingers followed by gas chromatography (GC) analysis; or 2) on-line measurement by a specially configured Innova photoacoustic analyzer. Opinions vary on the robustness of the latter method, both have their limitations. Carbonyls are typically sampled onto pre-packaged cartridges loaded with dinitrophenylhydrazine (DNPH) impregnated silica gel, which capture and convert carbonyls to their dinitrophenylhydrazone derivatives. The carbonyl derivatives are then eluted from the cartridges with acetonitrile and the solutions are analyzed by high pressure liquid chromatography (HPLC).

Care should be taken when comparing non-methane hydrocarbons (NMHC) and non-methane organic gases (NMOG) values across different studies, because the definition and calculation of these emissions depend on whether or not oxygenated species in the vehicle exhaust are independently measured. Furthermore, in cases where oxygenate species concentrations are measured, there may be variation in how oxygenate corrections to NMHC are applied, and these variations are not always explicit. For fuels containing no oxygen, NMHC is calculated by subtraction of two flame ionization detector (FID) measurements: 1) the total hydrocarbons (THC) and 2) the strictly methane portion: NMHC = THC – CH_4. Some oxygenated fuel studies may take this NMHC value and estimate NMOG from it, because EPA continues to allow such estimation of NMOG by a multiplier [CFR 40, Part 86, subpart S, Section 86.1810-01, September 2012], i.e., NMOG = NMHC x 1.04.

Other studies use a more correct and rigorous approach to obtain NMHC and NMOG. NMHC is obtained as described above, and is then corrected for the contribution of oxygenated species to the THC measurement. The oxygenate correction is based on the concentration of ethanol and carbonyls in the exhaust, as briefly described above. The individual species concentrations are multiplied by empirically determined response factors (RF, typically < 1) and these amounts are then subtracted from the THC value. For example, NMHC = THC – CH_4 – ($RF_{ethanol}$ x Ethanol) – ($RF_{acetaldehyde}$ x Acetaldehyde). NMOG then equals the corrected NMHC + Ethanol + Acetaldehyde.

As can be seen from this comparison, the NMOG estimation method can result in over-counting NMHC, and therefore NMOG too. The California Air Resources Board (CARB) has sought to remove this ambiguity in NMHC by introducing the additional term non-oxygenated non-methane hydrocarbons (NONMHC), which corrects NMHC for the separately measured oxygenate species (as shown above). NMOG then unambiguously equals NONMHC + Ethanol + Acetaldehyde.

Acronyms

CRC- Coordinating Research Council
DNPH- Dinitrophenylhydrazine
FID- Flame ionization detector
FFV- Flex fuel vehicle
FTP- Federal Test Procedure (aka FTP75) for emissions
GC- Gas Chromatography
HPLC- High Pressure Liquid Chromatography
LTFT- Long Term Fuel Trim; learning ability of an engine controller to adjust fuel injection rates
MY- Model Year
NMHC- Non-methane hydrocarbons
NMOG- Non-methane organic gases
NONMHC- Non-oxygenated non-methane hydrocarbons
RVP- Reid vapor pressure
SRC- Standard Road Cycle
THC- Total hydrocarbons
WOT- Wide Open Throttle

Primary Category: Exhaust Emissions	Secondary Category:	
Title: Effects of Mid-Level Ethanol Blends on Conventional Vehicle Emissions. SAE 2009-01-2723	**Author:** K. Knoll, B. West, S. Huff, J. Thomas, J. Orban, C. Copper, NREL, ORNL and Battelle Memorial Institute	**Date:** 2009
Web link: http://www.nrel.gov/docs/fy10osti/46570.pdf	**Research Sponsor:** DOE	
Test Fuels: E0, E10, E15 and E20	**Fuel Notes:** Splash blends in certification gasoline	
Test Vehicles- Year, Make & Model: 16 makes / models from 1999-2007	**Test Protocol:** LA92 and modified WOT cycle to measure catalyst temperatures.	

Related report: Effects of Intermediate Ethanol Blends on Legacy Vehicles and Small Non-Road Engines, Report 1- Updated. NREL/TP-540-43543 or ORNL/TM-2008/117

This study determined the short-term effects of ethanol blending (10, 15 and 20 vol %) on performance and emissions of 16 non-FFV vehicles. Exhaust ethanol was measured by Innova Photoacoustic analyzers. However, problems with these measurements at two labs led to exhaust ethanol being estimated for 10 vehicles, using a linear regression model of fuel ethanol content and exhaust ethanol concentrations at the third lab which obtained reliable measurements. Carbonyls were measured with DNPH cartridges. The exact methodology for calculating NMHC/NMOG is not explicitly stated, but given the available oxygenate measurements it is reasonable to assume NMHC/NMOG were calculated properly. For the entire vehicle set, increasing ethanol content produced no significant effect on NMOG and NO_x composite emissions, while NMHC and CO were reduced relative to E0. As expected, ethanol and acetaldehyde emissions increased. Vehicles were differentiated by fuel control strategies under high-load, open-loop operation (conditions that require fuel enrichment to protect the combustion chamber and catalyst). Vehicles that applied learned long term fuel trim (LTFT) corrections to power-enrichment air-fuel ratio control produced no ethanol effects on NMOG, NMHC, CO or NO_x composite emissions. These vehicles also showed no effect of ethanol content on catalyst temperatures during wide open throttle (WOT) operation. In contrast, vehicles that did not apply LTFT to power-enrichment fuel control produced reductions in NMHC and CO, while NO_x increased.

Primary Category: Exhaust Emissions	Secondary Category:	
Title: Effects of Vapor Pressure, Oxygen Content, and Temperature on CO Exhaust Emissions. CRC Report No. E-74-b	**Author:** R. Crawford, H. Haskew, J. Heiken, D. McClement, J. Lyons; Sierra Research, Inc.	**Date:** May 2009
Web link: http://crcao.org/reports/recentstudies2009/E-74b/E-74b%20Revised%20Final_Report_SR20090503.pdf	**Research Sponsor:** CRC	
Test Fuels: E0, E10, and E20	**Fuel Notes:** Match blended fuels to specific RVPs and specific ethanol contents.	
Test Vehicles- Year, Make & Model: 15 makes / models from MY 1994-2006; includes 11 vehicles from MY 2001-2006, of which 7 are Tier 2.	**Test Protocol:** FTP	

This project was designed to evaluate the effects of RVP and ethanol content on exhaust CO emissions. Seven fuels were created by match-blending at ethanol levels of E0, E10 and E20, with RVP targets of 7, 9 and 13.3 psig. FTP emissions tests were performed at 75°F and 50°F. Exhaust ethanol was measured by the California Air Resources Board's NMOG procedure (water impingers), but no carbonyl sample was performed.

General emissions results were that CO and total hydrocarbons (THC) decrease, and NO_x increases with increasing ethanol content. This NO_x effect among the eleven 2001 and later vehicles was reversed to a slight decrease in NO_x, if two 'sensitive' vehicles were removed from the analysis. Operation at the lower 50°F temperature produced significant increases in CO and THC. CO and NO_x increased with increasing RVP.

Key conclusions are that the EPA's MOBILE6.2 emissions factor model overestimates CO emissions for late-model vehicles under wintertime conditions, it underestimates the impact of increasing oxygenate content in reducing CO emissions, and overestimates the impact of increasing RVP in increasing CO emissions.

Primary Category: Exhaust Emissions	Secondary Category:	
Title: EPAct/V2/E-89: Assessing the Effect of Five Gasoline Properties on Exhaust Emissions from Light-Duty Vehicles Certified to Tier 2 Standards: Final Report on **Program Design and Data Collection**.	**Author:** U.S. EPA, NREL/U.S. DOE and CRC	**Date:** April 2013
Web link: http://www.epa.gov/otaq/models/moves/documents/420r13004.pdf	**Research Sponsor:**	
Test Fuels: E0, E10, E15 and E20	**Fuel Notes:** 27 match-blended fuels from a partial factorial design of five fuel parameters, of which one was ethanol concentration	
Test Vehicles- Year, Make & Model: 15 new, high sales volume cars and trucks from MY 2008: Chevrolet- Cobalt, Impala (FFV), Silverado (FFV) Saturn- Outlook Toyota- Corolla, Camry, Sienna Ford- Focus, Explorer, F-150 (FFV) Dodge- Caliber Jeep- Liberty Honda- Civic, Odyssey Nissan- Altima	**Test Protocol:** LA92	

<u>Related reports</u>: Two related reports cover data analysis and modeling of the fuel effects on exhaust emissions from the EPAct Phase 3 program (they are summarized individually in this document):

- *Assessing the Effect of Five Gasoline Properties on Exhaust Emissions from Light-Duty Vehicles Certified to Tier 2 Standards: Analysis of Data from EPAct Phase 3 (EPAct/V2/E-89) Final Report.*
- *Statistical Analysis of the Phase 3 Emissions Data Collected in the EPAct/V2/E-89 Program.*

This study was designed to provide emissions data to support development of a robust model to predict fuel effects on vehicle emissions. This report describes only the program design and data collection aspects, so no emissions results or data analysis are presented here. The designed-experiment fuel matrix varied five fuel parameters: ethanol content, T_{50}, T_{90}, dry vapor pressure equivalent (DVPE) and aromatics content:

Fuel Property	Levels		
	Low	Middle	High
Ethanol (%)	0	10, 15	20
Aromatics (%)	15		35
DVPE (psi)	7		10
T_{50} (°F)	150	165, 190, 220	240
T_{90} (°F)	300	325	340

A full factorial experimental design would have required an impractical 240 fuels, so a documented process was used to reduce the number of fuels to 27. Because covariance exists between some of the fuel properties (i.e., factors) such as ethanol content and T_{50}, the factors are not fully orthogonal. Therefore the experimental design is not truly fractional factorial, rather it is an ‘optimized’ design.

Fifteen MY 2008 vehicles were tested on the LA92 cycle; test runs were performed in duplicate (at least) on each fuel, in a partially randomized order. Alcohols and carbonyls were measured using CARB methods 1001 and 1004, respectively. These samplings only occurred during Bag 1 (cold-start phase) for all tests. Although the majority alcohol and carbonyl emissions occur during Bag 1, the fact that they were not measured for Bags 2 and 3 dictated that a mixed method of calculating NMHC and NMOG was used. For Bags 2 and 3, where NMHC could not be corrected for oxygenates, SwRI was assumed all oxygenated species levels in the exhaust were equal to zero. So for Bags 2 and 3, NMHC = NMOG = THC – CH_4 (Note however that in EPA’s analysis of these Bag 2 and 3 data, oxygenate-corrected NMHC and NMOG were estimated based on statistical correlations with measured NMHC; see *Related reports*). For Bag 1 the non-oxygenated NMHC (NONMHC) was calculated from NMHC, the available oxygenate data and oxygenate FID response factors. Then simply adding the measured oxygenate concentrations to NONMHC calculated NMOG.

It should be noted that in the fuel matrix there were:

- Only one match-blended pair of E10 and E15 fuels (fuels 28 and 16, respectively) that could be used for direct comparison of vehicle emissions. This E10 / E15 pair of fuels shared the following properties- 35 vol% aromatics, 7 psi DVPE, T_{50} = 220 F and T_{90} = 300 F
- Only one match-blended pair of E15 and E20 fuels (fuels 26 and 25, respectively) that could be used for direct comparison of vehicle emissions. This E15 /E20 pair of fuels shared the following properties-35 vol% aromatics, 10 psi DVPE, T_{50} = 165 F and T_{90} = 340 F
- No match-blended pairs that directly compare E15 and E0. However, using the models developed from the program and/or interpolation between the emissions results from two E0 fuels (fuels 5 and 13, each has one additional property varied from the E10 / E15 pair) it should be possible to develop a comparison of emissions from E0, E10 and E15

These types of analyses have not yet been reported, but could be performed in the future.

<table>
<tr><td>Primary Category: Exhaust Emissions</td><td colspan="2">Secondary Category:</td></tr>
<tr><td>Title: Assessing the Effect of Five Gasoline Properties on Exhaust Emissions from Light-Duty Vehicles Certified to Tier 2 Standards: Analysis of Data from EPAct Phase 3 (EPAct/V2/E-89) Final Report.</td><td>Author: U.S. EPA, NREL/U.S. DOE and CRC</td><td>Date: April 2013</td></tr>
<tr><td>Web link:
http://www.epa.gov/otaq/models/moves/documents/420r13002.pdf</td><td colspan="2">Research Sponsor:</td></tr>
<tr><td>Test Fuels: E0, E10, E15 and E20</td><td colspan="2">Fuel Notes: 27 match-blended fuels from a partial factorial design of five fuel parameters, of which one was ethanol concentration</td></tr>
<tr><td>Test Vehicles- Year, Make & Model: 15 new, high sales volume cars and trucks from MY 2008:

Chevrolet- Cobalt, Impala (FFV), Silverado (FFV)
Saturn- Outlook
Toyota- Corolla, Camry, Sienna
Ford- Focus, Explorer, F-150 (FFV)
Dodge- Caliber
Jeep- Liberty
Honda- Civic, Odyssey
Nissan- Altima</td><td colspan="2">Test Protocol: LA92</td></tr>
</table>

Related reports: *There are two related reports covering 1) program design and data collection, and 2) statistical data analysis of the exhaust emissions (they are summarized individually in this document):*

- *EPAct/V2/E-89: Assessing the Effect of Five Gasoline Properties on Exhaust Emissions from Light-Duty Vehicles Certified to Tier 2 Standards: Final Report on Program Design and Data Collection.*
- *Statistical Analysis of the Phase 3 Emissions Data Collected in the EPAct/V2/E-89 Program.*

This report is focused on statistical modeling and model analysis of the data collected in the EPAct/V2-E-89 program; as such most of the information is beyond the scope of this review. The data were modeled and analyzed on a per bag basis, i.e., cycle-composite data is not reported. Therefore the results are not directly comparable to most ethanol fuel-effects on emissions studies. Nevertheless, for the cold-start Bag 1 the linear-effects coefficients for CO are strongly negative with increasing ethanol, meaning that CO emission decreases with increasing ethanol level in the fuel. The linear-effects coefficients for NO_x were slightly positive, indicating a slight increase in NO_x with increasing ethanol. Both of these results are consistent with those from other studies reviewed here.

Primary Category: Exhaust Emissions	Secondary Category:	
Title: Statistical Analysis of the Phase 3 Emissions Data in the EPAct/V2/E-89 Program.	**Author:** Richard F. Gunst, Southern Methodist University	**Date:** May 2013
Web link: http://www.nrel.gov/docs/fy13osti/52484.pdf	**Research Sponsor:** NREL/U.S. DOE	
Test Fuels: E0, E10, E15 and E20	**Fuel Notes:** 27 match-blended fuels from a partial factorial design of five fuel parameters, of which one was ethanol concentration	
Test Vehicles- Year, Make & Model: 15 new, high sales volume cars and trucks from MY 2008: Chevrolet- Cobalt, Impala (FFV), Silverado (FFV) Saturn- Outlook Toyota- Corolla, Camry, Sienna Ford- Focus, Explorer, F-150 (FFV) Dodge- Caliber Jeep- Liberty Honda- Civic, Odyssey Nissan- Altima	**Test Protocol:** LA92	

Related reports: There are two related reports covering 1) program design and data collection, and 2) statistical data analysis of the exhaust emissions (they are summarized individually in this document):

- *EPAct/V2/E-89: Assessing the Effect of Five Gasoline Properties on Exhaust Emissions from Light-Duty Vehicles Certified to Tier 2 Standards: Final Report on Program Design and Data Collection.*
- *Assessing the Effect of Five Gasoline Properties on Exhaust Emissions from Light-Duty Vehicles Certified to Tier 2 Standards: Analysis of Data from EPAct Phase 3 (EPAct/V2/E-89) Final Report.*

Data from the EPAct/V2/E-89 program was independently analyzed by a statistician, the author of this report. Modeling of the emissions-fuel data using Taylor polynomials for each emission, model reductions and analysis of those models are the primary focus of the report, and is therefore beyond the scope of this review. However, Appendix XI presents charts of average measured emissions data from the vehicles tested on all 27 fuels, and the model estimates (both full Benchmark and a reduced model fits) of the emissions. The data are presented as functions of ethanol concentration for the cycle-composite (weighted) data and for individual bags (phases) data. Most relevant to this review are the cycle-composite and Bag 1 results, which both show that as fuel ethanol concentration increased from zero to 20% there was:

- A clear decrease in average CO emissions
- A slight increase in average NO_x
- A slight decrease in average NMHC most noticeably at the E20 level
- No clear effect on average NMOG

It should be noted that although the 27 fuels were match-blended, in some cases the designed fuels represent extreme limits of a fuel property or properties, and there may be 2-3 additional variables changed between fuels besides ethanol concentration. In fact, there were only a couple of fuel cases where emissions results from E15 could be directly compared with results from E10 or E20 (these types of comparisons are not explicitly made in this report). So, it is gratifying that the average emission responses from these diverse fuels align as well as they do with results from other studies of ethanol's effects on exhaust emissions.

Primary Category: Exhaust Emissions	Secondary Category:	
Title: NMOG Emissions Characterizations and Estimation for Vehicles Using Ethanol-Blended Fuels. SAE 2012-01-0883	**Author:** C. S. Sluder, B. H. West; Oak Ridge National Laboratory	**Date:** October 2011
Web link: http://info.ornl.gov/sites/publications/Files/Pub33272.pdf	**Research Sponsor:** DOE	
Test Fuels: E0, E10, E15 and E20	**Fuel Notes:** Ethanol splash blended with retail gasoline for the aging fuels, and with certification gasoline for emission measurement fuels.	
Test Vehicles- Year, Make & Model: 21 car and truck models from MY 2000-2009; tested at SwRI and TRC	**Test Protocol:** FTP	

Related reports:

The same research (with slightly less data and analysis) was also published in 2011 as an Oak Ridge National Laboratory technical report. It has the same title as and is available at: http://info.ornl.gov/sites/publications/Files/Pub33272.pdf

The data in these reports are a subset of, and come from the larger study reported as 'Intermediate Ethanol Blends Catalyst Durability Program', ORNL/TM-2011/234.

The main focus of the data analysis presented here is the development of correlations for estimating non-methane organic gases (NMOG) from non-methane hydrocarbon (NMHC) measurements. NMHC is routinely measured during emission testing by on-line, flame ionization detector (FID) instrumentation, while the oxygenated species measurement techniques needed to calculate NMOG are labor intensive and the results are not immediately available. The emissions data utilized for these correlations came from over 600 FTP emissions measurements of 21 vehicle models participating in the DOE sponsored 'Intermediate Ethanol Blends Catalyst Durability Program'; specifically those models tested at SwRI and TRC. Figure 6 is the most interesting, as it shows the effect of ethanol concentration in the fuel on the NMOG/NMHC ratio, which leads to an equation to estimate NMOG from NMHC. The figure and equation demonstrate that while the EPA approved NMOG/NMHC ratio of 1.04 is valid for E0, it is not appropriate for ethanol containing fuels.

$$NMOG_{est} = (\%\ Ethanol \times 0.0071) + 1.0302 \times NMHC$$

The discussion of the effects of ethanol blended fuels on exhaust emissions, albeit based on a vast amount of samples, is limited to comparisons of oxygenated species, and the relationship of NMOG to NMHC, as a function of fuel ethanol content. Figure 1 in the report highlights the well-known observation that ethanol inclusion in the fuel profoundly changes the composition of the oxygenated species in the exhaust (with ethanol dominant), compared to ethanol-free gasoline where formaldehyde dominates. Figure 1 also shows that the oxygenate composition from Tier 2 vehicles is essentially the same between E15 and E20; it is unfortunate that a similar comparison with E10 was not made. Other observations are that formaldehyde emissions are largely unaffected by ethanol blending (up to 20%), while acetaldehyde emissions increase with increasing ethanol content.

Primary Category: Exhaust Emissions	**Secondary Category:**	
Title: Effects of Intermediate Ethanol Blends on Legacy Vehicles and Small Non-Road Engines, Report 1- Updated. NREL/TP-540-43543 or ORNL/TM-2008/117	**Author:** K. Knoll, B. West, W. Clark, R. Graves, J. Orban, S. Przesmitzki, T. Theiss; NREL and ORNL	**Date:** February 2009
Web link: http://info.ornl.gov/sites/publications/Files/Pub12154.pdf	**Research Sponsor:** DOE	
Test Fuels: E0, E10, E15 and E20	**Fuel Notes:** Ethanol splash blended with certification gasoline.	
Test Vehicles- Year, Make & Model: 16 cars and trucks from MY 1999-2007, including 13 vehicles from MY 2001-2007.	**Test Protocol:** LA92	

Related report: SAE 2009-01-2723

Among the MY 2001 and newer vehicles the clearest emission trend with increasing ethanol content was a reduction in NMHC, with E10 and E15 producing the same amount. CO dropped sharply from E0 to E10, reaching minimum at E15. NO_x decreased slightly with increasing ethanol.

Relevant to catalyst durability, it was observed that catalyst temperatures were cooler or unchanged during closed-loop operation with the higher levels of ethanol. Vehicles that used LTFT adjustment of open-loop controlled air-fuel ratio were identified, and these vehicles had lower or unchanged catalyst temperatures at wide-open throttle.

Primary Category: Exhaust Emissions	Secondary Category: Evaporative Emissions	
Title: Effects of E15 Ethanol Blends on HC, CO and NO_x Regulated Emissions from On-Road 2001 and Later Model Year Motor Vehicles.	**Author:** Air Improvement Resource, Inc.	**Date:** July 2011
Web link: http://ethanolrfa.3cdn.net/98cced8882a492cb49_lwm6bj5kz.pdf	**Research Sponsor:** Renewable Fuels Association	
Test Fuels: NA	**Fuel Notes:**	
Test Vehicles- Year, Make & Model:	**Test Protocol:**	

This is a 2011 literature review of regulated exhaust emissions and evaporative emissions. Three exhaust emissions studies included are:

1. Effects of Vapor Pressure, Oxygen Content, and Temperature on CO Exhaust Emissions. CRC Report No. E-74-b
2. Effects of Intermediate Ethanol Blends on Legacy Vehicles and Small Non-Road Engines, Report 1- Updated; NREL/TP-540-43543 or ORNL/TM-2008/117. *Note there appears to be a decimal point error in Table 4 (NOx) of the RFA summary of this project.*
3. Analysis of some preliminary data from the DOE Catalyst Durability Study that led to the report- "Intermediate Ethanol Blends Catalyst Durability Program"; ORNL/TM-2011/234. This summary states that only data from vehicles tested at SwRI and ETC/NREL were analyzed and discussed (i.e., TRC data were not included). However, vehicles tested at TRC are listed in Table 5 and Attachment 4.

The conclusions drawn about exhaust emissions from these studies are that NMHC and CO decrease and NO_x slightly increases, or doesn't change, as ethanol blend level goes from E10 to E15. Results from splash-blended studies align with the one match-blended study.

Catalyst Durability Studies

Only one robust vehicle level study of catalyst durability with mid-level ethanol blends (including E15) was found, the DOE V4 Catalyst Study. The Standard Road Cycle (SRC) was used to age the vehicles. The SRC was promulgated by EPA in 2006 as part of their CAP (Compliance Assurance Program) 2000 regulations, which detail how vehicle manufacturers must demonstrate emissions compliance over their full useful life (defined as 100,000 miles or 10 years for cars and light trucks). Essentially, SRC is a procedure to test emission control system durability, which includes the catalyst. The CAP 2000 rule allows manufacturers to propose custom alternatives to the SRC, however these are generally proprietary and SRC was used in DOE's studies because it was deemed adequate by EPA.

Vehicles can be differentiated on the basis of those that apply learned long term fuel trim (LTFT) to open-loop air-fuel ratio control during power enrichment operation, and vehicles that do not. 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 may be expected to have inadequate fuel enrichment when using ethanol blended gasoline, 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.

<u>Acronyms</u>

CRC- Coordinating Research Council
FTP- Federal Test Procedure (aka FTP75) for emissions
LTFT- Long Term Fuel Trim; learning ability of an engine controller to adjust fuel injection rates
MY- Model Year
NMHC- Non-methane hydrocarbons
NMOG- Non-methane organic gases
SRC- Standard Road Cycle
WOT- Wide Open Throttle

Primary Category: Catalyst Durability	Secondary Category: Exhaust Emissions	
Title: Mid-Level Ethanol Blends Catalyst Durability Study Screening. CRC Report No. E-87-1	**Author:** Walt Dudek; Transportation Research Center Inc.	**Date:** June 2009
Web link: http://crcao.org/reports/recentstudies2009/E-87-1/E-87-1%20Final%20Report%2007_06_2009.pdf	**Research Sponsor:** CRC	
Test Fuels: E0, E10, E15 and E20	**Fuel Notes:** E15 was prepared differently than other fuels, by splash blending E10 with E98.	
Test Vehicles- Year, Make & Model: 25 makes / models from MY 1995-2007	**Test Protocol:** Modified EPEFE	

Actual catalyst durability testing is not reported here. The objective of this study was to identify vehicles which do not use learned long term fuel trims (LTFT) to correct the open-loop controlled air-fuel ratio during high-load operation. Twenty-five test vehicles were screened based on FTP exhaust emissions to ensure acceptable operation, and then tested on a modified European Programme for Emission, Fuels, and Engine Technologies (EPEFE) sulfur purge test cycle, using E0, E10, E15 and E20. Eight of the twenty-five vehicles used LTFT to adjust their fueling with increasing ethanol content in open-loop operation, thirteen vehicles did not apply LTFT corrections and four vehicles gave unclear results. Ten of the thirteen vehicles identified as **not** utilizing LTFT corrections were proposed for future research with mid-level ethanol blends to test durability of the catalyst.

Primary Category: Catalyst Durability	Secondary Category: Exhaust Emissions	
Title: Intermediate Ethanol Blends Catalyst Durability Program. ORNL/TM-2011/234	**Author:** B. West, C.S. Sluder, K. Knoll, J. Orban, J. Feng; ORNL, NREL and Battelle Memorial Institute	**Date:** February 2012
Web link: http://info.ornl.gov/sites/publications/Files/Pub31271.pdf	**Research Sponsor:** DOE	
Test Fuels: E0, E10, E15 and E20	**Fuel Notes:** Ethanol splash blended with retail gasoline for the aging fuels, and with certification gasoline for emission measurement fuels.	
Test Vehicles- Year, Make & Model: 19 Tier 2 vehicle models from MY 2005-2009 and 8 pre-Tier 2 vehicle models, MY 2000-2003. Multiple matched models aged and tested in parallel.	**Test Protocol:** SRC for aging, FTP for emissions and a modified WOT cycle to measure catalyst temperatures.	

This is also known as the DOE V4 Catalyst Durability Study. It builds on CRC Project No. E-87-1, which differentiated several high-sales volume vehicle models on the basis of those that apply, or don't apply, long term fuel trim (LTFT) to open-loop air-fuel ratio control during power enrichment operating conditions. 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 (SwRI), the Transportation Research Center (TRC) and Environmental Testing Corporation (ETC).

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. 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 include:

- No discernible difference in aging effects (performance deterioration rate) on emissions between E0 and ethanol blends (however, it appears from some of the ETC/NREL results that E0 produced faster catalyst performance deterioration)
- LTFT applied to open-loop operation had no effect on catalyst aging or fuel economy
- Emissions effects of ethanol blending:
    - CO, NMHC emissions decreased with E10, E15, and E20 vs. E0
    - NO_x, formaldehyde and acetaldehyde increased with E10, E15, and E20 vs E0
    - NMOG was generally unchanged

<table>
<tr><td>Primary Category: Catalyst Durability</td><td colspan="2">Secondary Category: Exhaust Emissions</td></tr>
<tr><td>Title: Comparative Emissions Testing of Vehicles Aged on E0, E15 and E20 Fuels.</td><td>Author: K. Vertin, G. Glinsky, A. Reek, SGS Environmental Testing Corporation</td><td>Date: August 2012</td></tr>
<tr><td>Web link:
http://www.nrel.gov/docs/fy12osti/55778.pdf</td><td colspan="2">Research Sponsor: DOE</td></tr>
<tr><td>Test Fuels: E0, E15 and E20</td><td colspan="2">Fuel Notes: Ethanol splash blended with retail gasoline for the aging fuels, and with certification gasoline for emission measurement fuels.</td></tr>
<tr><td>Test Vehicles- Year, Make & Model: 18 vehicles total comprising three matched vehicles each of-
2009 Honda Odyssey 2009 Saturn Outlook
2009 Ford Focus 2000 Honda Accord
2009 Toyota Camry 2000 Ford Focus</td><td colspan="2">Test Protocol: SRC for aging, FTP for emissions and a modified WOT cycle to measure catalyst temperatures.</td></tr>
</table>

Related report: This is the ETC/NREL subset of the study reported as 'Intermediate Ethanol Blends Catalyst Durability Program', ORNL/TM-2011/234.

For each vehicle model set, one was aged on E0, another on E15 and the third on E20. The MY 2009 vehicles were aged to 120,000 miles and the MY 2000 vehicles were aged 50,000 miles past the starting mileage.

The most noteworthy result from this study is that for 4 of 6 models tested, the vehicles aged on E0 produced higher exhaust emissions at the last test than the same vehicles aged on E15 or E20. The 2009 Toyota Camry (aged 120,000 miles) and 2000 Ford Focus (aged 50,000 miles) showed no statistically significant effect of aging fuels on the final emissions level comparisons. This observation suggests that catalyst durability may be positively affected by ethanol containing fuels, possibly because fuel sulfur was diluted by the ethanol.

Effect of Ethanol Content on Second Generation On Board-Diagnostics (OBDII)

Modern vehicles control the air to fuel ratio reaching the engine, using both immediate changes (short term fuel trim or STFT) and longer term adaptations (long term fuel trim or LTFT) to fuels with different energy contents. Higher ethanol content fuels require greater LTFT to maintain stoichiometric proportions of fuel and air. OEMs have a variety of 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 injector or fuel filter fouling. Generally, if the LTFT exceeds a certain set value, the malfunction indicator lamp (MIL) is illuminated (although it may also depend on other factors that are unknown to the researchers as the control logic is proprietary). The higher LTFT required for higher ethanol content fuels suggest that there will be some increase in MILs due to 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.

Acronyms

DTC - diagnostic trouble code
IM – inspection and maintenance
LTFT – long term fuel trim
MIL – malfunction indicator light
OBDII – second generation on-board diagnostics
OEM – original equipment manufacturer
STFT – short term fuel trim

<table>
<tr><td colspan="2">Primary Category: On-Board Diagnostics II</td><td>Secondary Category: NA</td></tr>
<tr><td colspan="2">Title: Impact of E15/E20 Blends on OBDII Systems – Pilot Study CRC E-90</td><td>Author: R. Klausmeier, de la Torre Klausmeier Consulting, Inc.
Date: March 2010</td></tr>
<tr><td colspan="2">Web link: http://www.crcao.org/reports/recentstudies2010/E-90/E-90_Final_Report_031210.pdf</td><td>Research Sponsor: CRC</td></tr>
<tr><td colspan="2">Test Fuels: E0 and E10</td><td>Fuel Notes: NA</td></tr>
<tr><td colspan="2">Test Articles: NA</td><td>Vehicle Applications: Hundreds of vehicles were tested in an area in which the gasoline available did not include ethanol (E0) and in two other areas where the available gasoline included ethanol (E10)</td></tr>
<tr><td colspan="3">Test Protocol: Measured long term fuel trim at the end of a five minute or longer period of operation</td></tr>
</table>

This study attempts 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.

Hundreds of vehicles were recruited at Inspection and Maintenance (IM) stations and tested to determine Long Term Fuel Trim (LTFT) on the fuel in the vehicle at the time. 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. LTFT ranged from -14% to +14% for both E0 and E10, and was slightly negative for E0 on average and slightly positive for E10 on average. Overall, the E10 locations have LTFT about 4 absolute percent higher than average LTFT values in the E0 location, but there was a large amount of overlap. There were significant differences in the degree of change of LTFT between the fuels by OEM, although for all OEMs the average LTFT was higher with E10. The increase of LTFT between E0 and E10, by OEM, ranged from about 1.5% to almost 7%.

Extrapolating the effect on LTFT by the proportion of ethanol in the fuel and by OEM, the researchers conclude that the number of vehicles using E15 that would have an illuminated MIL due to lean operation will be about 1%, based on an intermediate threshold level of between 17 and 30%. However, by their calculations assuming a normal distribution, a number of these vehicles would also have illuminated MILs using E10 – very roughly, one half (it would depend on the threshold level). In the hundreds of E0 and E10 vehicles tested, not one had a MIL illumination due to lean operation, as indicated by the stored diagnostic trouble code (DTC), although this may be due to pre-IM test maintenance. Their analysis also predicts some MILs for rich operation would be avoided for E15. This will be a smaller percentage according to their analysis, but will reduce the number of additional MILs due to E15. 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, although potentially large in consideration of the large number of vehicles on the road.

Primary Category: On-Board Diagnostics II	Secondary Category: NA	
Title: Evaluation of Inspection and Maintenance OBD II Data to identify Vehicles that May Be Sensitive to E10+ Blends, CRC Report No. E90-2a	**Author:** D. McClement, T. Austin; Sierra Research, Inc.	**Date:** January 31, 2011
Web link: http://www.crcao.org/reports/recentstudies2011/E-90-2a/CRC_E-90-2a_021811.pdf	**Research Sponsor:** CRC	
Test Fuels: E0, E2, E6 and E10	**Fuel Notes:**	
Test Articles: NA	**Vehicle Applications**: Several million vehicles tested in various state or city Inspection and Maintenance (IM) program before and after large increases in the ethanol content of available fuel	
Test Protocol: Existing IM programs in Atlanta, Georgia; Southern California; Denver, Colorado; Vancouver, BC		

The stated objective of this study was to identify make-model-displacement-model year combinations that were more likely to experience lean operation MILs when operated with higher ethanol content fuels. This was apparently done to identify vehicles for the next phase of testing, in which the CRC chose to use the most sensitive vehicles for their vehicle testing program. Since the sensitive combinations selected are kept confidential, this objective is not met for the reader, but there is additional useful information available in this document. The results of several large IM programs, including millions of vehicles, conducted before and after a change in the ethanol content in the available fuel can be considered in understanding the impact of changing fuel on the likelihood of increased lean operation MILs. The results are summarized in the table below:

I/M Program Area	Period	Fuel	No. of Vehicles Tested	Fraction with Lean DTC but no MIL	Change in Fraction with Lean DTC but no MIL	Fraction with Lean DTC and MIL	Change in Fraction with Lean DTC and MIL
Atlanta, Georgia	2007	E2	1,436,323	NA	NA	.37%	+0.02%
	2009	E10	1,671,759	NA		.39%	
Southern California	2009	E6	1,336,317	.74%	+ 0.03%	.49%	-0.01%
	2010	E10	1,483,308	.77%		.48%	
Vancouver, BC Canada	Early 2009	E0	98,256	.57%	-0.00%	.47%	-0.05%
	Early 2010	E10	83,547	.56%		.42%	
Denver, Colorado	2006	E0 to E10 average =E6.8	179,171	NA	NA	.80%	+.20%
	2008	E10	174,601	NA		1.01%	

This data must be considered in light of the considerable motivation for vehicle owners to conduct pre-inspection maintenance when a MIL is illuminated. In random roadside testing in California, the proportion of vehicles with illuminated MILs is about 6.85 times the proportion of MILs that are found at

IM inspections. The cost-benefit of going to an IM station with a MIL illuminated varies between different programs so the number may be different in different states, but some evidence is provided to suggest in Georgia the ratio of in-use MILs to MILs found at IM stations similar to that in California. The values in the last gray column are in absolute percentage points, and should be multiplied by the ratio of in-use MILs to MILs found at IM stations to obtain a better estimate of the change in fraction of in-use MILs due to the change in fuel. However, if one assumes that the number of measured MILs is proportional to the number of MILs in-use then there is no apparent increasing trend of MILs with increasing ethanol content when the four cities 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.

CRC Report E-90 provided a good theoretical basis for understanding why MILs associated with lean operation would be more common with higher ethanol content fuels, but also showed that the value would be small, on the order of less than 1%. These data suggest that the actual value may be non-detectable in practice even in databases with millions of vehicles. No explanation is provided why the proportion of vehicles with lean DTCs is higher in Colorado than in the other test areas. One would expect that at the higher altitude of Colorado, the lower atmospheric pressure would lead to richer combustion, on average.

<table>
<tr><td>Primary Category: On-Board Diagnostics II</td><td colspan="2">Secondary Category: NA</td></tr>
<tr><td>Title: Impact of Ethanol Blends on the OBDII Systems of In-Use Vehicles – Interim Report, CRC Report No. E-90-2b</td><td>Author: B. Shoffner, M. Lochte and K. Whitney, Southwest Research, Inc.</td><td>Date: November 7, 2012</td></tr>
<tr><td>Web link: http://www.crcao.org/reports/recentstudies2012/E-90-2b%20Interim%20Report/Final%20CRC%20E-90-2b%20Interim%20Report.pdf</td><td colspan="2">Research Sponsor: CRC</td></tr>
<tr><td>Test Fuels: E0, E20 and E30</td><td colspan="2">Fuel Notes: Base fuel is EEE fuel</td></tr>
<tr><td>Test Articles: NA</td><td colspan="2">Vehicle Applications:

Acura TL 2008
BMW 325i 2004
BMW X3 2004
Cadillac Deville 2001
Dodge Caliber 2008
GMC Sonoma 2003
Mitsubishi Montero 2002</td></tr>
<tr><td colspan="3">Test Protocol: Test cycle was 23.5 miles of city and highway driving including a twenty-minute soak and fifteen minute idle, ten cycles of the course over 3 to 5 days</td></tr>
</table>

Based on the analysis in E-90-2a, recommendations from OEMs and other factors not clearly specified, the CRC selected a list of different makes and models for screening and potential selection. Various vehicles from the proposed list of makes, models and MYs were identified and screened. The screening procedure required that the vehicle had an LTFT that was between 2 and 3 standard deviations greater than the average LTFT measured in E-90-2a, i.e. a higher LTFT on E10 than 97.9% of the equivalent make and models tested. Because this screening test was so strict, they found it necessary to eventually give up on the specifically recommended makes and models and just conduct widespread screening of many vehicles on used car lots. 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.

Vehicles were operated over ten cycles of the course over three to five days (all warmer than 68 °F), and 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 on 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 DTCs) for lean operation when operated on E20. One vehicle which did not get a DTC, was retested on the dynamometer with E20 and it got a lean operation DTC warning, 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 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.

This report supports the analysis conducted in CRC Report No. E-90. There are vehicles operating at especially high LTFTs with E10, that will trigger MILs or DTCs at E20 and E30, but not at E0. However, as shown by SWRI's difficulty in finding these vehicles, they are very rare.

This was published as an interim report. Future testing is planned with different test vehicles, higher ethanol contents and will investigate the impact of varying ambient temperatures and vehicle loading.

<table>
<tr><td>Primary Category: On-Board Diagnostics II</td><td colspan="2">Secondary Category: NA</td></tr>
<tr><td>Title: Investigating Malfunction Indicator Light Illumination Due to Increased Oxygenate Use in Gasoline, SAE No. 2012-01-2305</td><td>Author: C. Scott Sluder, B.H. West, K. Knoll; ORNL and NREL</td><td>Date: November 15, 2012</td></tr>
<tr><td>Web link: http://papers.sae.org/2012-01-2305/</td><td colspan="2">Research Sponsor: DOE</td></tr>
<tr><td>Test Fuels: E30, E40, E50, E60 and E70</td><td colspan="2">Fuel Notes: Base fuel not specified</td></tr>
<tr><td>Test Articles: NA</td><td colspan="2">Vehicle Applications: 22 different vehicles MYs 2002-2008, subset of vehicles used in DOE Intermediate Ethanol Blends Catalyst Durability Program, vehicle results are not correlated with specific vehicles; none of the 86 vehicles used in the Catalyst Durability Program had an illuminated MIL using fuels of up to E20</td></tr>
<tr><td colspan="3">Test Protocol: Vehicles operated on standard road cycle (SRC) were monitored for LTFT and MIL illumination; four day test sequence running a total of 4 cold starts, 16 SRCs, and multiple hot soaks and extended idles</td></tr>
</table>

Twenty-two vehicles, MYs 2002 to 2008 were selected from the 86 vehicles used in the DOE Intermediate Ethanol Blends Catalyst Durability Program. Since none of the vehicles had illuminated MILs during SRC testing with E20 in the Catalyst Durability Program, testing was initiated at E30. If no MIL was encountered during the four-day test sequence, the test was repeated at E40. If that did not produce a MIL, the test was repeated at E50, then if necessary at E60 and E70. In the event that a MIL was illuminated, it was first determined if the DTC triggering the MIL was LTFT related. If so, then the LTFT was measured, assuming that the measured LTFT was necessary to illuminate the MIL. The authors note several issues associated with measuring the precise LTFT that triggers and MIL:

- The LTFT varies over time, and thus the measured LTFT may not correspond to the level at which the MIL was triggered.
- The short term fuel trim (STFT) also varies and may compensate for variations in the LTFT in an inconsistent manner
- The logic which triggers the MIL may depend on factors other than the LTFT.

However, testing of duplicate vehicles and replicate tests on the same vehicles showed good consistency in the determination of the MIL threshold. Moreover, the range and variability between OEMs agreed well with the CRC-E90 study. The MIL threshold did not appear correlated with whether or not LTFT was applied at wide open throttle.

Analysis of the increase in LTFT with fuel ethanol content shows that the LTFT increases by about 4.4% for each 10 vol% increase in ethanol in the fuel. The range of LTFTs shown to trigger MILs was between 18% and 38%. The potential for MIL illumination using E10, E15 and E20 are estimated for each make and model, and was less than 1% in all cases, and below 1 in a million for many of the vehicles even at E20. Vehicles specific results were not associated with specific makes and models and no fleetwide estimate was made.

Evaporative Emissions

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.[††]

Evaporative emissions include leaks from anywhere in the fuel system, breakthrough venting from the carbon canisters and permeation. Permeation is the molecular migration of the fuel through the elastomeric materials of the vehicle fuel system. 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.

Testing of evaporative emissions can be conducted in a variety of ways. General descriptions are below although the specifics, such as the length of the test period, ambient temperatures, and whether or not the carbon canister emissions are collected and measured can vary between test programs:

- Static permeation – emissions from cold vehicle at varying ambient temperatures; does not include canister emissions
- Dynamic permeation (running loss) - emissions from operating vehicle, not including tailpipe emissions
- Hot Soak – emissions from the vehicle while still warm from operation
- Diurnal – emissions from the vehicle as the temperature in the gasoline tank is varied to simulate warming that occurs during the course of the day.

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.

Acronyms

DVPE – Dry Vapor Pressure Equivalent
FFV- Flexible Fuel Vehicle (designed to use any fuel from E0 to E85)
LA92 – Unified Driving Cycle

[††] http://www.epa.gov/otaq/regs/ld-hwy/onboard/orvrq-a.txt
[‡‡] 40 CFR 86.127-12(d)

LEV- Low Emissions Vehicle
MY – Model Year
ORVR – On-board Refueling Vapor Recovery
psi – pounds per square inch
PZEV- Partial Zero Emissions Vehicle
SHED – Sealed Housing for Evaporative Determination

Primary Category: Evaporative Emissions	**Secondary Category:**	
Title: Fuel Permeation from Automotive Systems: E0, E6, E10, E20 and E85. CRC Report No. E-65-3	**Author:** H.M. Haskew, T.F. Liberty, D. McClement. Harold Haskew & Associates, Inc., Automotive Testing Laboratories, Inc.	**Date:** December 2006
Web link: http://crcao.org/reports/recentstudies2006/E-65-3/CRC%20E-65-3%20Final%20Report.pdf	**Research Sponsor:** CRC	
Test Fuels: E0, E6, E10, E20 and E85	**Fuel Notes:** Fuels were matched for DVPE; E6 was tested with both high aromatic and low aromatic base fuels	
Test Vehicles: Fuel systems from the following: the first two were pre-ORVR, the final three had ORVR systems; the Chevrolet Tahoe was an FFV. Toyota Tacoma 2001 Honda Odyssey 2002 Ford Taurus 2004 Chrysler Sebring 2005 Chevrolet Tahoe 2005	**Test Protocol:** Tested in SHED with tank and canister vented to outside; steady state testing: every week at for 3 to 5 hours at 105 °F in SHED diurnal testing: – California 24-hour diurnal (65 °F to 105 °F to 65°F) emission test procedure	

The objective of this program was to measure the change in permeation emissions with changing ethanol concentrations in MY 2000 to MY 2005 California vehicles. Ethanol gasoline blends were formulated to approximately equal vapor pressures including E0, E6 (two aromatic levels), E10, E20 and E85. Test rigs were built to recreate the fuel systems of five specified vehicles, and included tanks, carbon canisters, and all fuel and vapor lines. The test rigs were kept at 105 °F, until permeation emissions stabilized. Once each week, permeation was measured in a pre-heated 105 °F SHED. The tank and canister vent hoses were vented outside of the SHED, to avoid including any venting emissions in the permeation. Emissions from the rig inside the SHED were measured for either 3 (pre-ORVR rigs) to 5 hours (ORVR rigs). Stabilization was determined when the four-week average of the permeation reversed in trend. Diurnal measurements were made over 24 hours in which the temperature in the SHED varied from 65 °F to 105 °F and back to 65 °F.

The advanced technology LEV II and PZEV systems (used in the Ford Taurus and Chrysler Sebring) had much lower permeation emissions in comparison to the earlier models and the FFV (Chevrolet Tahoe). Permeation emissions using E20 were on average about 10% higher than those measured using E10 but may not be statistically significant. The greatest increase with E20 versus E10 was 47% in the 4-week average of steady-state measurements in the Honda Odyssey. In comparison, E20 led to a reduction of 23% in the Chevrolet Tahoe FFV when used instead of E10. Lesser permeation with E20, in comparison to E10 was also found in the Ford Taurus, both steady-state and diurnal. The other vehicles saw increases with E20. All of the vehicles showed a significant increase in permeation emissions with ethanol-blended fuels as compared to E0. Average specific reactivity also varied between the fuels, but the difference between E10 and E20 was only 3%, with E20 slightly more reactive. The average specific reactivity of E0 was about 1/3 more than all of the ethanol-blended fuels. 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.

Primary Category: Evaporative Emissions	**Secondary Category:**	
Title: Enhanced Evaporative Emission Vehicles, CRC Report No. E-77-2	**Author:** H.M. Haskew, T.F. Liberty. Harold Haskew & Associates, Inc.	**Date:** March 2010
Web link: http://crcao.org/reports/recentstudies2010/E-77-2/E-77-2_Final_Report__March_2010.pdf	**Research Sponsor:** CRC	
Test Fuels: E0, E10 and E20	**Fuel Notes:** E0 was blended to nominal 7 psi and 9 psi; E10 was blended to nominal 7 psi and 10 psi; E20 was blended to nominal 9 psi	
Test Vehicles: Ford Taurus 1996 Honda Accord 1999 Toyota Corolla 2001 Dodge Caravan 2001 Ford Escape 2004 Toyota Highlander 2004 Toyota Camry 2004 Ford Taurus 2006	**Test Protocol:** Four tests were conducted: static permeation rate, dynamic permeation rate, hot soak and the California three-day diurnal evaluation.	

Eight vehicles were tested on E20, E10 and E0. 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.

The static permeation rate was measured in the SHED with the canister vent connected outside of the SHED. Initially the test is conducted with the fuel system sealed but not under pressure. Then pressurized measurements are made to ensure there are no leaks. The vehicle's vapor system is pressurized to 5 inches of water for thirty minutes to quantify vapor leaks. A third set of measurements are made with the fuel pump energized to quantify any liquid leaks.

The dynamic, or running loss, test is measured with the canister vent and the vehicle exhaust vented outside of the SHED. Two cycles of the LA-92 are driven while measuring the mass emissions inside the SHED at 86 °F. The canister vent emissions are measured separately, and no tank venting emissions were measured in any of the running loss tests.

The hot soak test must immediately follow the running loss test. After the engine is turned off, the emissions are tested for 60 more minutes from the warm vehicle. Hot soak emissions were calculated by subtracting the static permeation emissions from the measured emissions during the hot soak.

The diurnal test is the three day California diurnal test. Each day the temperature is cycled between 65 °F and 105 °F and permeation emissions are 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. Looking at the results vehicle by vehicle for each test, about half the vehicles had higher emissions with E20, and half had higher emissions with the two E10 fuels (see table below). The authors conclude that the "sample size and limited data makes statistical conclusions inappropriate." The trends between E10 and E20 shown in Figure 18, p. 27 of CRC report are not correct whether by number of vehicles or by average value.

Test	Comparison of E20 and E10 Emissions for 5 Enhanced Emissions Vehicles	Comparison of E20 and E10 Emissions for 2 Near Zero Emissions Vehicles
Static permeation	2 higher emissions with E20, 2 lower with E20 and 1 mixed result	1 much higher emissions with E20 (Toyota Camry), 1 lower with E20
Dynamic or running loss	3 higher emissions with E20, 2 lower with E20	1 much higher emissions with E20 (Toyota Camry), 1 lower with E20
Hot soak	1 higher emissions with E20, 2 lower with E20, and 2 mixed results	1 higher emissions with E20, 1 lower with E20
Diurnal	2 higher emissions with E20, 2 lower emissions with E20 and 1 mixed result	1 lower emissions with E20, 1 mixed results

More information is included in this document on the impact of implanted leaks and on the very oldest vehicle the 1996 Ford Taurus, which had a fuel leak. Also, ethanol content in the vapor from various emissions tests is quantified.

Primary Category: Evaporative Emissions	Secondary Category:	
Title: Study to Determine Evaporative Emission Breakdown, Including Permeation Effects and Diurnal Emissions, Using E20 Fuels on Aging Enhanced Evaporative Emissions Certified Vehicles, CRC Report No. E-77-2c	**Author:** H.M. Haskew, T.F. Liberty, Harold Haskew & Associates, Inc.	**Date:** December 2010
Web link: http://crcao.org/reports/recentstudies2011/E-77-2c/E-77-2c%20Final%20Report%20for%20sure%201-28-11.pdf	**Research Sponsor:** CRC	
Test Fuels: E20 compared to E0 and E10 testing in CRC Report No. E-77	**Fuel Notes:** Two E20 fuels nominally 7 and 9 psi	
Test Vehicles: Mitsubishi Galant 2000 Nissan Altima 2002 Chevrolet Trailblazer 2002 Chrysler Stratus 2004 Chevrolet Impala 2004 Dodge Ram 1500 2004 Ford Focus ZX3 2004 Dodge Caravan 2001 Toyota Camry XLE 2004	**Test Protocol:** Four tests were conducted: static permeation rate, dynamic permeation rate, hot soak and the California three-day diurnal evaluation.	

Only fuel tested here was E20 at 7 and 9 psi DVPE, but not all vehicles were tested on all fuels. Evaporative emissions testing was conducted on 2000 to 2004 MY vehicles (all with ORVR) and then compared to previous testing conducted by the CRC, following the test procedures used in E-77-2. 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. Interestingly, there was no clear trend in emissions with vapor pressure.

Primary Category: Evaporative Emissions	**Secondary Category:**	
Title: Evaporative Emissions Characterization of E0, E10, and E15 in Support of the Fuel and Fuel Additive Registration of E15, Revised Final Report	**Author: E**. Robert Fanick, Southwest Research	**Date:** February 2011
Web link: http://www.epa.gov/otaq/regs/fuels/additive/e15/documents/e15-health-impact-data-package.pdf	**Research Sponsor:** Renewable Fuels Association and Growth Energy	
Test Fuels: E0, E10 and E15	**Fuel Notes:** Base fuel was EPA Tier II EEE gasoline.	
Test Vehicles: NA	**Test Protocol:** Speciation of C1 to C12 hydrocarbons, alcohols and ethers on the head space of the three different fuels.	

This report was submitted to the EPA to meet the requirements for registration of designated fuels and fuel additives and characterizes the evaporative emission products from E15, E10 and E0. In general, the same compounds were found in the head space of all three fuels. Ethanol 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.

Primary Category: Evaporative Emissions	**Secondary Category:**	
Title: Evaporative and Exhaust Emissions Characterization of 2011 E0, E10, and E15: Comparison to Data Developed by the Section 211(b) Research Group in Support of the Fuel and Fuel Additive Registration of E15, Revised Final Report	**Author:** S. Armstrong, Cambridge Environmental, Inc.	**Date:** February 17,2011
Web link: http://www.epa.gov/otaq/regs/fuels/additive/e15/documents/e15-health-impact-data-package.pdf	**Research Sponsor:** Renewable Fuels Association and Growth Energy	
Test Fuels: E0, E10 and E15	**Fuel Notes:** In 2011 data base fuel was Tier 2 EEE gasoline	
Test Vehicles: NA	**Test Protocol:** No testing just analysis.	

This analysis compares the 2011 data collected by Southwest Research on evaporative emissions speciation of E15, E10 and E0 with historical data collected in support of the registration of conventional gasoline containing 10% gasoline in 1997. Evaporative emissions profiles are similar between the 1997 data and the 2011 results. Compared to the 1997 reference fuel, evaporative emissions of the 2011 E0 contained far fewer components which may reflect differences in methodology or changes in the fuel. The 1997 Tier 1 literature searches addressed all but two components of the E15 headspace vapors, which also exist in the current E10 and E0 headspace vapors and so the author concludes a Tier 1 literature search for E15 evaporative emissions is not warranted. The author also concludes that Alternative Tier 2 health effects testing of evaporative emissions of E15 is also not warranted.

Primary Category: Evaporative Emissions	Secondary Category: Engine and Fuel System Durability	
Title: Evaporative Emissions Durability Testing. CRC Report No. E-91	**Author:** K. Vertin, G. Glinsky, J. Mickelsen, C. Morgan, M. St. Denis, J. Roeschen. SGS Environmental Testing Corp., Chrysler Corp., Revecorp Inc.	**Date:** September 2012
Web link: http://crcao.org/reports/recentstudies2012/E-91/CRC%20E-91%20Final%20Report%20120910.pdf	**Research Sponsor:** CRC	
Test Fuels: E0 and E20	**Fuel Notes:** Aging fuels splash blended with ethanol. Test fuels blended to match RVP of control fuel.	
Test Vehicles: Vehicles were tested in matched pairs. Buick Lesabre 2003 Dodge Neon 2004 Chrysler PT Cruiser 2004 VW Jetta 2002 Ford Taurus 2008 Toyota Prius 2010 Toyota Corolla 2009 Honda CRV 2008 Nissan Pathfinder 2008 Pontiac GrandAm 2004	**Test Protocol:** Baseline Test: two-day diurnal using ethanol free certification fuel and includes venting from the canister; Permeation Test: canister vent port is routed to outside of SHED, 2 hour static permeation, and 2-day diurnal as well as pressure tests to find leaks	

The objective of this study was to quantify the effects of E20 over time on evaporative emissions. Ten pairs of vehicles were matched for make, model and MY, tested for evaporative emissions and then aged for about 18,650 miles and the equivalent of 360 days of driving on different fuels and retested. 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. 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. 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).

The data showing that one of the vehicle models (Vehicles 7E0 and 7E20) showed dramatically deteriorating emissions performance on both fuels after 270 days and continuing to 360 days has been deleted from the graphs. The text explains that the purge valves were unseated and leaking on both vehicles of the pair. The valves were reseated for the 270 day test, with resultant lesser emissions that were then included in the graphs. However, this was not done for the 360-day test for unspecified reasons, and the results for 360 days is not included. The evaporative systems of both Vehicle 5E0 and 5E20 were found to be malfunctioning 31 days into the aging cycle and the researchers found it necessary to replace carbon canisters that had become clogged with dirt in both and add a carbon vent filter that was missing from both vehicles.

Results of Baseline SHED 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. As discussed above, both vehicles in the #7 matched pair showed a very large increase on both fuels (over 100%), although the researchers believe this data should not be considered, as the cause does not appear to be fuel related.

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.

Results were not associated with specific makes and models.

Also interesting was information gathered to identify the source of evaporative emissions. Tires and refrigerant were identified as a source of potentially significant volatile organic emissions for otherwise low emitting vehicles. No effect of altitude was found.

Index for Appendix