Technical Assessment of the Feasibility of Introducing E15 Blended Fuel in U.S. Vehicle Fleet, 1994 to 2000 Model Years

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EXECUTIVE SUMMARY

Ricardo Inc., an internationally recognized automotive engineering firm, was requested by the Renewable Fuels Association to perform an analytical engineering study to determine the effects of introducing E15 (a gasoline / ethanol fuel blend containing 15% ethanol by volume) into the existing motor vehicle fleet in the United States. The study specifically focused on light duty (LD) on-road vehicles produced in the 1994 to 2000 model years (MY). The analysis concluded that the adoption and use of E15 would not adversely affect fuel system components in properly engineered vehicles, nor would it cause them to perform in a sub-optimal manner, when compared to the use of E10.

Figure E.1 shows a breakdown of the current LD U.S. vehicle fleet. Investigating the effects of E15 on 1994 to 2010 MY vehicles is a prerequisite to understanding the overall impact of introducing E15 into the marketplace, since these vehicles represent 87.6% of the total LD fleet. Vehicles manufactured between the 1994 and 2000 MY, which are still operational today, comprise 62.8 million vehicles, or approximately 25% of the overall U.S. LD vehicle fleet (EPA MOVES model). It is not feasible to carry out inspection or testing on this many vehicles, therefore an engineering analysis based on a reliable statistical sampling approach was performed.

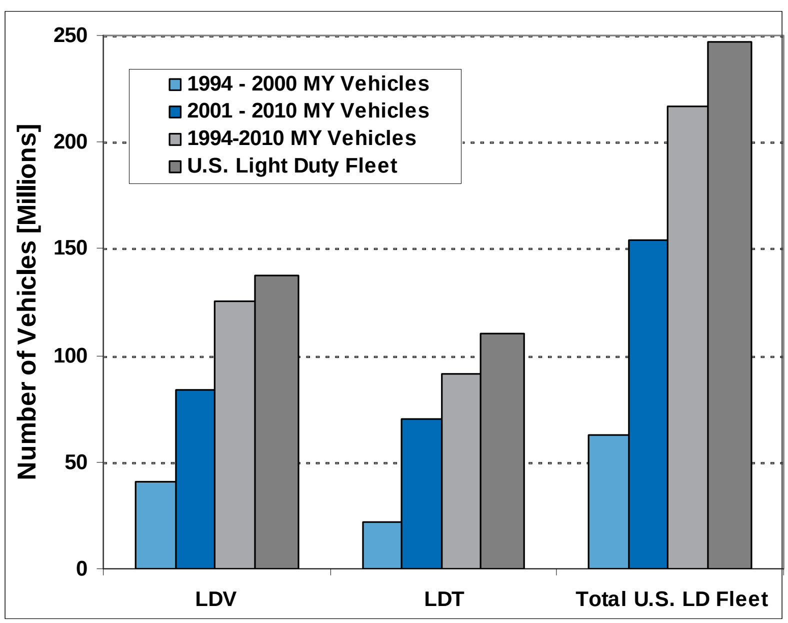

Figure E.1: U.S. Light Duty Fleet

Six automotive manufacturers were identified as representative of the majority of vehicles sales (>87%) for the study period. Top selling platforms from these manufacturers became the focus of this study (see Section 2.4). To evaluate the potential impact of using E15 in these vehicles, several technical areas were studied. Fuel system changes from 1994 to 2000 were analyzed. The introduction of various emission and diagnostic regulation levels during the studied time period was summarized. Emissions certification data from the most common vehicle platforms were collated and evaluated for current emissions outputs relative to the original legislated levels. Aftertreatment systems and vehicle calibrations from the period of interest were analyzed to determine the likelihood of deterioration due to changes in ethanol content. Properties of gasoline / ethanol blends were evaluated relative to fuel system materials commonly used during the study period, and the key degradation mechanisms of these materials were established. Finally, physical fuel system parts were procured and evaluated to identify the deterioration that would be expected for 1994 to 2000 MY parts still in service today.

Fuel systems in the 1994 to 2000 MY timeframe changed dramatically due to the onset of enhanced evaporative emissions and ORVR regulations. In general these changes increased the tolerance of fuel and vapor handling systems to ethanol blended fuels. A review of actual vehicle hardware, from vehicles manufactured prior to the onset of these regulations, indicated that these pre-enhanced evaporative emission systems were able to handle the current E10 fuel formulation and would not be expected to have further detrimental effects from the introduction of E15.

Many changes were made to EPA emissions regulations between the 1994 and 2000 MY. New tailpipe emissions legislation required all 1996 MY vehicles to meet Federal Tier I emissions legislation. Most vehicles (that were studied in this work) met the certified limits of the emissions legislation with a high compliance margin. The EPA emissions certification database was interrogated to calculate the long term deterioration factors in order to determine the expected tailpipe emissions levels that the vehicles in the study period would currently produce (in 2010). Since all of the vehicles have exceeded their useful life (100k miles or 10 years), they are no longer under legislative emissions control. Therefore, the objective of this portion of the analysis was to understand the likelihood of illuminating a Malfunction Indicator Lamp (MIL). It was determined that, in general, the vehicles from the study period were certified with relatively large compliance margins. As mileage and time have accumulated, the emissions reduction potential of the aftertreatment systems has degraded, but not to the point where the majority of the vehicles are out of compliance. Therefore, in order to trigger a MIL, a copious increase in any particular emissions species caused by a move from E10 to E15 would be required. This makes illumination of the MIL due to emissions non-compliance highly unlikely (see Section 5).

A review of vehicle calibrations from the 1994 to 2000 MY timeframe was undertaken. This was done to assist in understanding the potential effects on the drivability, catalytic converter durability, and on-board diagnostic system when E15 fuel is introduced to the vehicles. A summary of the effects is shown in the table below.

Aftertreatment / Vehicle Calibration Mechanism	Impact of Moving From E10 to E15	Comments
Fueling and Temperature Effect		
Air-Fuel Control	Low	No risk with open-loop fuel control
Exhaust and CAT temps	Low	Catalytic converters are not in close proximity to engines in the Tier I emissions timeframe
Overall Emissions Effect		
Tailpipe emissions	Low	AFR is maintained in closed loop systems, sufficient emissions margin to regulated levels to avoid MIL illumination
Evaporative emissions	Medium	Study period vehicles are no longer under legislative control. Existing data is not sufficient to predict permeability emissions from E15 relative to E10
On-board Diagnostic Impact		
Fuel system monitor	Low	Risk only if vehicle is not calibrated to standard robustness levels
Catalyst monitor	Low	No effect for vehicles with closed loop operation
Evaporative system monitor	Low	E10 is worst case for RVP, E15 generally reduces RVP. Dependent on base fuel formulation
Drivability Impact		
Cold start drivability	Medium	Can be an issue with current non-ethanol blends, final effects from E15 will be dependent on base fuel formulation
Hot fuel handling	Low	Properties controlled by ASTM D4814

Table E.1: Impact of E15 on Aftertreatment and Vehicle Calibration

Table E.1 shows that implementation of E15 into the light duty vehicle fleet will not have a significant effect on aftertreatment and calibration variables compared to E10. Further details can be found in Section 6.

A comparison of the properties of gasoline blends, E0, E10, and E15, was completed. It was found that E15 has a lower heating value (LHV) than E10 by ~1.9%. Therefore, the implementation of E15 in the passenger car fleet will cause a reduction in vehicle mileage (miles / gallon) by the same percentage.

The effect of using E15 on fuel system components in the 1994 to 2000 MY vehicles was analyzed. Degradation mechanisms for common materials used in fuel systems during the studied time period were also evaluated. The primary risk of switching from E10 to E15 fuel is the potential for gross leaks. Leaks can occur due to corrosion of metallic materials, swelling of elastomers, and hardening of plastics. Physical test results generally concluded that the materials in use during this time period would not undergo significant changes when exposed to E15 compared to when they are exposed to E10.

Some physical fuel system hardware was acquired for inspection. The hardware came from vehicles represented by the top 25 vehicle platforms from the 1994 to 2000 MY. It was found that none of the physical hardware in the fuel systems was fully compliant with enhanced evaporative emissions legislation. This was evidenced by the absence of engineered quick connects on many of the connections around the fuel tank and vapor lines. Therefore, this sample of vehicle hardware represents the vehicles that are less likely to be tolerant to ethanol blends. This is due to their significantly different material content, compared with vehicles that meet the enhanced evaporative emissions legislative requirements. However, these potentially less robust systems show no ill effects from exposure to E10. It is not expected that further degradation will be experienced when these systems are exposed to E15.

Overall, the engineering assessment completed in this report showed that the implementation of E15 in the 1994 to 2000 MY U.S. LD vehicle fleet will not have adverse effects. However, it should be noted that this analysis was focused on vehicles that fall within the normal specifications and usage profile for 1994 to 2000 MY vehicles. Vehicles falling outside these normal ranges do not have predictable reaction effects to the introduction of E15 and are therefore not represented in this study.

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1. INTRODUCTION

The United States Environmental Protection Agency (EPA) is currently considering a waiver that would allow the use of up to 15% ethanol (E15) in the light duty U.S. motor vehicle fleet. To date, research has focused on the use of an E15 fuel blend in vehicles manufactured from the 2001 model year (MY) to the current MY. However, there are a significant number of vehicles in use today that were manufactured prior to the 2001 MY. The Renewable Fuels Association (RFA) believes that limiting the use of E15 to 2001 MY and newer vehicles, will inhibit the overall market availability and acceptance of the fuel. The RFA has therefore retained Ricardo to perform a technical engineering assessment of the feasibility of E15 fuel use in vehicles manufactured between the 1994 and 2000 MY. This report will focus on the passenger car and light duty truck markets, which represents approximately 62.8 million vehicles from the studied model years that remain operational today.

While a large number of studies sponsored by the DOE and other government and industry bodies have focused on the effects of E15 on 2001 model year and newer vehicles, significant engineering analysis has not been applied to earlier model year vehicles. This study concentrated on the 1994 to 2000 MY light duty on road vehicles of which ~58% are still in operation today. The study did not include off road vehicles, marine applications, or small engine applications. In keeping with the spirit of EPA's longtime stance, a "reliable statistical sampling" of the national fleet was identified. Sales trends by both calendar year and model year were studied to identify the highest volume sales of the automotive manufacturers in years 1994 to 2000.

Ricardo, an eco-innovation technology company, is a leading independent provider of technology, product innovation, engineering solutions and strategic consulting to the world's automotive, military, transport and new energy industries. The company's skill base represents the state-of-the-art in low emissions and fuel-efficient powertrain technology.

With technical centers and offices throughout Europe, the U.S. and Asia, Ricardo provides engineering expertise ranging from vehicle systems integration, controls & electronics, hardware and software development, to the latest driveline and transmission systems and gasoline, diesel, hybrid and fuel cell powertrain technologies.

Ricardo's customers include the world's major automakers and suppliers as well as manufacturers in the military, commercial, off-highway and clean energy sectors. The company also serves in advisory roles to governmental and independent agencies. Ricardo's U.S. operation, Ricardo, Inc., is headquartered in Van Buren Township, Michigan. Ricardo plc posted sales of $394 million in financial year 2008 and is a constituent of the FTSE TechMark 100 index – a group of innovative technology companies listed on the London Stock Exchange.

2. IDENTIFICATION OF TARGET VEHICLES

In order to understand how E15 would effect vehicles manufactured between 1994 and 2000, a study was undertaken to assist in understanding the number of vehicles sold during the time period, the number of these vehicles that are still in use, and the manufacturers who sold a majority of these vehicles. This was determined by investigating total vehicle sales, major manufacturers during this time frame, model year sales, and the percentage of vehicles still registered for use.

The U.S. EPA admits that the burden of proof required by a 211(f)(4) waiver may be accomplished through a “reliable statistical sampling” of the national fleet. Researchers of this report agree that it is totally infeasible to review every make and model from each manufacturing year due to limited financial budgets, time, and resources. In keeping with the spirit of EPA’s longtime stance, a “reliable statistical sampling” of the remaining national fleet from the model years of interest needed to be identified. An extensive study to identify these remaining vehicles, specifically for the time period of 1994 to 2000, was the first priority. Both nationally and industry recognized sales trends were studied to identify the highest volume sales of the automotive manufacturers in years 1994 to 2000. Six automotive manufacturers were identified as representing the overwhelming majority of vehicles sales for each model year, >87% in all years, and the top selling platforms from those manufacturers became the focus of this study.

2.1 Total Vehicle Sales by Calendar Year

The U.S. automotive industry typically reports total vehicle sales on a month-to-month basis, with annual sales reported on a calendar year (January-December) basis. Figure 2.1.1 shows the light duty vehicles sales in the U.S. from 1990 to 2007.

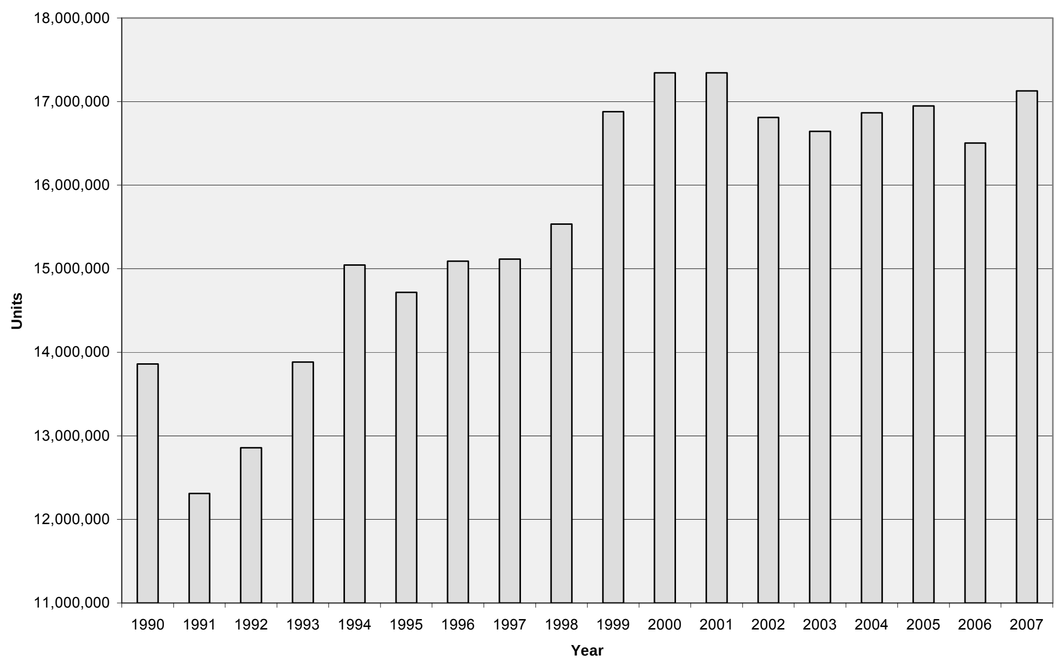


Figure 2.1.1: U.S. Light Duty Vehicle Sales per Calendar Year 1990 to 2007
(U.S. Bureau of Transportation Statistics, 2010)

Demand for new vehicles dropped dramatically in 1991, with sales recovering by 1994 and increasing to record-high levels by 2000 (over 17 million units). From 2000 to 2007, sales steadied at around 17 million units. The U.S. Bureau of Transportation Statistics reported that 109,724,000 vehicles were sold in the U.S. between 1994 and 2000.

2.2 Vehicle Sales by Manufacturer

Sales trends of light duty vehicles, by manufacturer, were analyzed using new vehicle registration data acquired from Ward's Automotive Services. This data is broken down by type of vehicle, manufacturer, make, and model. Type of vehicle is traditionally divided into automobiles and "other 2-axle, 4-tire vehicles" which includes minivans, light trucks, and sport utility vehicles (SUVs). Figure 2.2.1 shows the split of automobiles vs. other vehicles sold from 1994 to 2000.

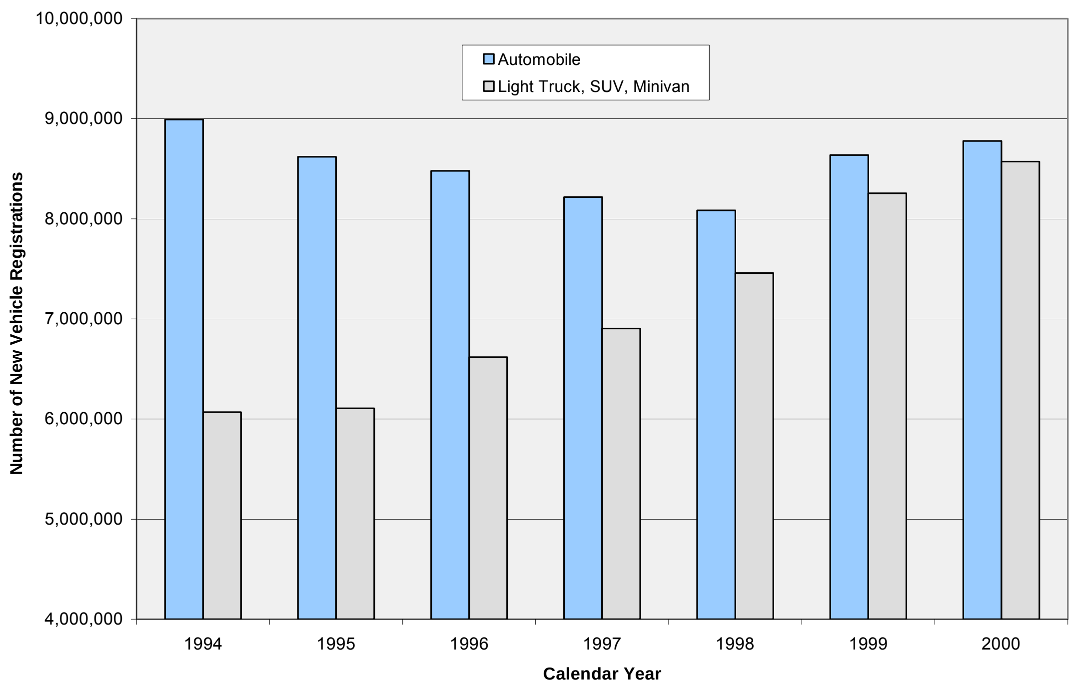


Figure 2.2.1: U.S. New Light Duty Vehicle Registrations: Automobiles & Other
(Ward's Automotive Group, 2010)

Between 1994 and 2000, overall light vehicle sales rose from their historic range of 12.5 to 15 million vehicles per year to a peak of 17.3 million (Ward's Automotive Group, 2010) in 2000. Sales of automobiles held steady between 8.2 and 9.0 million vehicles from 1994 to 2000. Sales of other 2-axle, 4-wheeled vehicles (light duty trucks, minivans and SUVs) rose dramatically during this time period, increasing from 6.0 million vehicles in 1994, to 8.5 million vehicles in 2000. The rapid sales growth of other 2-axle, 4-wheeled vehicles was caused by the increase in popularity of SUVs in the U.S. marketplace. Because of this, in 2001 the sale of light trucks, minivans, and SUVs surpassed those of automobiles for the first time in U.S. history. A breakdown of the platforms and vehicle nameplates which sold the highest volumes during this time period is shown in Section 2.4.

New vehicle registrations between 1994 and 2000 were analyzed by manufacturer to find a subset of manufacturers from the total population that represents at least 85% of all the new vehicles sold during this time frame. Figure 2.2.2 shows vehicle sales by manufacturer for 1994. Vehicle sales by manufacturer for 1995 through 2000 can be found in Appendix A.

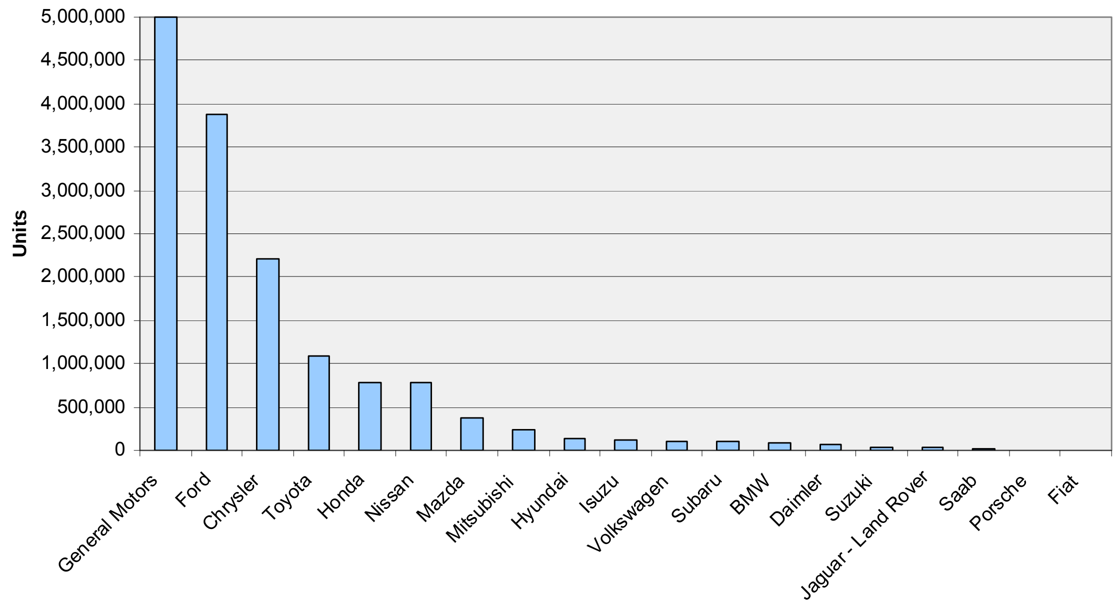


Figure 2.2.2: 1994 New U.S. Vehicle Registrations by Manufacturer

In 1994, new light duty U.S. vehicle sales from General Motors, Ford, Chrysler, Toyota, Honda and Nissan ("Big 6") represented 91.2% of all registered vehicles. Sales of the Big 6 manufacturers were significantly higher than from Mazda, Mitsubishi, Hyundai, or Isuzu. In fact, Nissan (#6) sold twice as many vehicles as Mazda (#7). General Motors (#1) sold 40 times more vehicles than Isuzu (#10).

Vehicle Manufacturer	1994 Sales
General Motors	5,005,816
Ford	3,870,408
Chrysler	2,203,995
Toyota	1,088,073
Honda	788,230
Nissan	774,406
Mazda	375,416
Mitsubishi	230,279
Hyundai	138,258
Isuzu	123,778

As shown in the year-by-year analyses (see Appendix A), the Big 6 manufacturers represented

90.1% of all light duty vehicles sold from 1994 to 2000 on a calendar year basis, with a peak market share of 91.7% in the 1995 calendar year. Therefore, vehicles from these Big 6 manufacturers will be the focus for this study because they represent the majority of vehicles sold during the time period.

2.3 Model Year Requirements

The U.S. EPA sets environmental regulations for vehicles by model year, not by calendar year. The U.S. Code of Federal Regulations defines a model year in the following manner:

40CFR85.2302: Definition of model year
Model year means the manufacturer's annual production period (as determined under §85.2304) which includes January 1 of such calendar year, provided, that if the manufacturer has no annual production period, the term “model year” shall mean the calendar year.

40CFR85.2303: Duration of model year
A specific model year must always include January 1 of the calendar year for which it is designated and may not include a January 1 of any other calendar year. Thus, the maximum duration of a model year is one calendar year plus 364 days.

40CFR85.2304: Definition of production period
(a) The “annual production period” for all models within an engine family of light-duty motor vehicles, heavy-duty motor vehicles and engines, and on-highway motorcycles begins either: when any vehicle or engine within the engine family is first produced; or on January 2 of the calendar year preceding the year for which the model year is designated, whichever date is later. The annual production period ends either: When the last such vehicle or engine is produced; or on December 31 of the calendar year for which the model year is named, whichever date is sooner.
(b) The date when a vehicle or engine is first produced is the “Job 1 date,” which is defined as that calendar date on which a manufacturer completes all manufacturing and assembling processes necessary to produce the first saleable unit of the designated model which is in all material respects the same as the vehicle or engine described in the manufacturer's application for certification. The “Job 1 date” may be a date earlier in time than the date on which the certificate of conformity is issued.

All vehicles of a specific model year must comply with the associated regulations for that year, regardless of when they were actually sold to a customer. In general, vehicle manufacturers introduce a new model year in the July-October timeframe of the previous calendar year, so calendar year sales normally include vehicles from the next model year. For example, the 1984 Corvette was introduced in March of 1983, and sold until autumn of 1984 (approximately 18 months of sales). Sales data for each of the Big 6 manufacturers, per model year, was acquired from R.L. Polk & Co.

Two data sets for new vehicle registrations per model year were acquired from R.L. Polk:

1) Total vehicles sold per manufacturer
2) Registrations by make and model

The data for total vehicles sold per manufacturer was analyzed in the same manner as the Ward’s calendar year sales data, to make sure the data sets were consistent and yielded the same general results for the large volume manufacturers under study. Figure 2.3.1 illustrates the model year sales per manufacturer for 1994 MY vehicles. Sales for 1995 MY to 2000 MY vehicles by manufacturer can be found in Figures B.1 to B.6 in Appendix B.

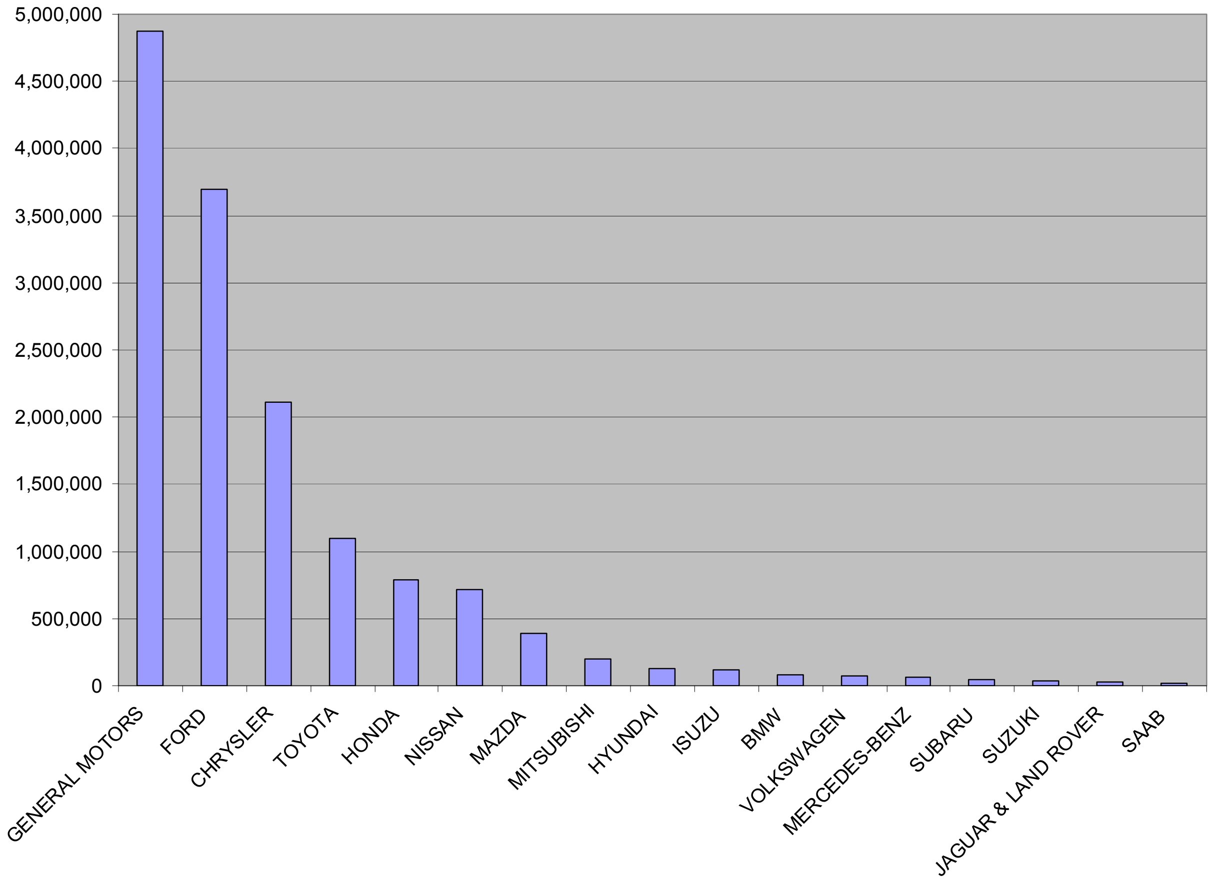


Figure 2.3.1: 1994 Model Year Sales by Manufacturer

Vehicle Manufacturer	1994 MY Sales
General Motors	4,869,168
Ford	3,695,708
Chrysler	2,107,656
Toyota	1,097,810
Honda	783,756
Nissan	712,091
Mazda	385,788
Mitsubishi	202,468
Hyundai	122,537
Isuzu	116,377

Sales by the Big 6 manufacturers represented 91.8% of all 1994 model year vehicles sold.

According to data from R.L. Polk, a total of 107,715,267 light duty vehicles were sold in the U.S. for model years 1994 through 2000. Analysis of this data shows that on a model year basis, the Big 6 manufacturers sold at least 87.5% of the U.S. light duty vehicles for this time period.

The U.S. Bureau of Transportation Statistics reported that the median age of a passenger vehicle in the U.S. in 2007 was 9.2 years and the median age for a light duty truck was 7.1 years (U.S. Bureau of Transportation Statistics, 2008). For this study, it was necessary to understand the number of vehicles from model years 1994 to 2000 that are currently registered for use. Using data derived from the U.S. EPA's Motor Vehicle Emissions Simulator (MOVES model), the following vehicle population data was calculated:

	Estimated Number of Vehicles Remaining in Population			**Size of Original Fleet**	**Percentage of Original Fleet Remaining**
Model Year	Car Population	LDT Population	Total Population	Total Population	Total (%)
1994	3,384,999	1,645,471	5,030,470	14,448,040	34.8%
1995	4,061,998	1,923,021	5,985,019	15,767,349	38.0%
1996	4,928,558	2,388,907	7,317,465	13,700,608	53.4%
1997	5,754,498	2,854,794	8,609,291	15,159,946	56.8%
1998	6,634,597	3,479,280	10,113,877	14,935,742	67.7%
1999	7,785,497	4,252,453	12,037,950	16,127,673	74.6%
2000	8,557,277	5,124,751	13,682,027	17,575,909	77.8%

Table 2.3.1: Estimated Number of Vehicles Remaining in Population Manufactured Between 1994 and 2000 Model Years

It can be seen from the data in table 2.3.1 that 34.8% of the total vehicles sold in 1994 are still in use today. This number increases with model year to the point where 77.8% of the total vehicles sold in 2000 are still in operation today. Overall, 58% of the total number of light duty vehicles sold between the 1994 - 2000 MY are still in use today. This represents 62.8 million vehicles out of the 247.3 million vehicle U.S. fleet (25.4% of total fleet). Engineering analysis of the potential effects on this group of vehicles therefore is required to ensure viability of the fuel upon its introduction into the market.

2.4 Vehicle Platforms

Most manufacturers base several of their vehicles off the same basic architecture, commonly referred to as a vehicle platform. Vehicle platforms typically share the same body structure, suspension, engine family, and fuel system. These parts are typically the most expensive to design, develop, and tool for production. Building several vehicles off a common platform allows the manufacturer economies of scale.
This study focused vehicles that have the same engine family and fuel system because it is assumed that these vehicles will experience the same effect from higher ethanol fuel content. Data

from R.L. Polk was sorted by vehicle make and model, and vehicles built off the same platform were grouped together. The following table shows total sales data for the top 25 vehicle platforms from the Big 6 manufacturers during the 1994 to 2000 timeframe (top 10 selling platforms are shown in **bold**).

Vehicle Manufacturer	Platform	1994–2000 Total Sales	Vehicle Models
General Motors	**GMT400**	**5,444,489**	**C/K & Sierra**
Ford	**P1**	**5,214,189**	**F150**
Ford	**PN105/106**	**5,116,999**	**Ranger / Explorer**
Ford	**D186**	**5,019,201**	**Taurus, Sable, Continental**
General Motors	**W**	**4,249,084**	**Lumina, Century, Regal, Intrigue, Cutlass Supreme, Grand Prix, Monte Carlo, Impala**
General Motors	**GMT300**	**4,129,464**	**S-10 truck & Blazer**
Chrysler	**AS-NS-RS**	**3,709,415**	**Minivans**
Toyota	**MCV**	**3,422,500**	**Toyota Camry, Toyota Avalon, Lexus ES300**
General Motors	**N**	**3,143,541**	**Malibu, Skylark, Achieva, Alero, Cutlass, Grand Am**
Honda	**CD-CG**	**2,924,467**	**Honda Accord, Acura CL, Acura TL**
Honda	E	2,494,624	Honda Civic, Acura Integra
General Motors	J	2,347,693	Sunbird, Sunfire, Cavalier
Chrysler	BE-BR	2,213,043	Dodge Ram Pickup
Ford	Panther	2,163,162	Crown Victoria, Grand Marquis, Lincoln Town Car
Ford	CT120	2,060,523	Tracer, Escort
Chrysler	ZJ-WJ	1,857,623	Jeep Grand Cherokee
General Motors	H	1,849,275	LeSabre, 88, 88 Regency, LSS, Bonneville
Chrysler	LH	1,808,011	Concorde, LHS, 300, New Yorker; Dodge Intrepid; Eagle Vision
General Motors	GMT800	1,741,202	Silverado, Sierra, Suburban, Tahoe, Yukon, Yukon XL, Denali, Escalade
General Motors	Z	1,713,359	Saturn S-series
Toyota	CE-ZZE	1,499,056	Toyota Corolla, Toyota Celica
Chrysler	PL	1,380,013	Neon
Ford	VN	1,264,924	Econoline
Ford	CDW27	1,102,939	Mystique, Contour
Nissan	A	1,079,121	Maxima, I30
General Motors	M/L	1,044,612	Astro, Safari

Table 2.4.1: Top 25 Vehicle Platforms from the Big 6 Manufacturers between 1994 and 2000

The Top 10 platforms manufactured for 1994 to 2000 model year vehicles comprise 39% of the total light vehicles sold during the timeframe. Five (5) out of the Big 6 manufacturers are represented in the top 10 platforms, with the exception being Nissan. During the study period Nissan did not employ significant platform sharing. Additionally, as can be seen from the yearly sales volumes, Nissan sold significantly less vehicles than the other Big 6 manufacturers, but significantly more vehicles than the 7th manufacturer by volume. Considering this information, it was determined that the top 10 platforms represented an acceptable cross section of the vehicle population from the study period, and these top 10 platforms were investigated further as discussed in Section 5 – EPA Emissions Data. The top 10 platforms are discussed in more detail below.

General Motors' (GM) full size truck platform GMT400 sold the most vehicles during this timeframe. This was GM's full-size truck and SUV platform from 1988 to1999. This platform consisted of the following vehicles:

- Chevrolet C/K pickup, Silverado, Blazer, Tahoe, GMC Sierra, Yukon, and Suburban

Over 800,000 of these vehicles were built every year the GMT400 was in production. All of these vehicles use the same engine, same fuel pump, and very similar fuel tanks. This platform was replaced with the GMT800 platform in 1999.

Ford's P1 platform consisted of the F150 pickup and Bronco. The Ford F150 has enjoyed the distinction of being the best-selling nameplate in the U.S. since 1976 (U.S. News, 2009).

Ford's P105/106 platform consisted of the Ranger pickup and Explorer SUV. The current generation of the Ford Ranger was introduced in 1994 and is still in production today. The Ford Explorer was based off the same platform and was the best-selling SUV during the 1990s (MSN Auto).

Ford's D186 platform consists of the Ford Taurus, Mercury Sable, and Lincoln Continental sedans.

GM's W-car family incorporated most of GM's mid-size coupes and sedans. The following vehicles were based off the W-car platform:

- Buick Century (1997+) and Regal
- Chevrolet Lumina coupe and sedan, Monte Carlo, Impala (1999+)
- Oldsmobile Cutlass Supreme and Intrigue
- Pontiac Grand Prix

GMT300 consisted of GM's mid-side truck and SUV platform from 1995-2002. This platform consisted of the following vehicles:

- Chevrolet S-10 pickup, S-10 Blazer
- GMC Sonoma pickup, S-10 Jimmy, Envoy
- Oldsmobile Bravada

Chrysler AN-NS-RS platforms were evolutions of their minivan platform during this timeframe. These vehicles were sold under the following names:

- Chrysler Town and Country
- Dodge Caravan
- Plymouth Voyager

Toyota's MCV mid-sized car platform consisted of the Toyota Camry, Avalon, and Lexus ES300.

GM's N-car platform consisted of the company's intermediate automobiles:

- Buick Skylark
- Chevrolet Malibu
- Oldsmobile Achieva, Alero, and Cutlass
- Pontiac Grand Am

Honda's CD-CG platform consisted of the Honda Accord, Acura CL, and Acura TL.

3. SYSTEM DESCRIPTIONS FOR TARGET PLATFORM SET

The history of evaporative emission controls and the performance of the in-use fleet as it is available suggests that the vehicle fleet can be segregated into seven subsets:

1. Pre-Control (<1971 model year cars and trucks < 6000 Lb GVW)
2. Early Basic Control (1971 to 1977 MY)
4. Basic Control - SHED Certified (1978 to1995 MY)
5. Enhanced Evaporative Emission Control (1996 to 2003 MY)
6. Vehicles with On-Board Refueling Vapor Control (1998 and later MY)
7. Tier II and better tailpipe emissions + Enhanced EVAP and ORVR

The focus of this study is on the vehicle fleet consisting of MY 1994 to 2000. These vehicles have a mix of evaporative emission regulatory requirements that phase-in at various times, as indicated in Table 3.1 below.

	Evaporative Emissions Requirements by Model Year								
			Model Year						
Class	**Vehicle Type**	**Emission Standards**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Pre-Enhanced Evap	LDV, LDT	5 Years 50k Miles	100%	100%	80% Max.	60% Max.	10% Max.	none	none
Enhanced Evap	LDV, LDT	10 Years 100k Miles			20% Min.	40% Min.	90% Min.	100%	100%
ORVR	LDV	10 Years 100k Miles					40% Min	80% Min.	100%

Table 3.1 Evaporative Emissions Requirements by Model Year (1994 to 2000)

Pre-enhanced evaporative emission control regulations of the 1970s and 1980s targeted the control of one day's diurnal emissions and one hot soak. A canister with activated carbon was fitted to absorb the diurnal vapor emissions from the fuel tank, and the carburetor bowl vapors that were generated after vehicle operation. Early evaporative control canisters were typically located in the engine compartment to provide a short path for carburetor bowl vapors. The tank vent line had a small orifice (0.055 inch diameter) fitted to limit the mass flow of vapors from the tank to the canister during rapid fuel tank heating periods. The "useful life" (and regulatory requirement) was specified to be 5 years or 50,000 miles. Carburetors (and their bowl vapors) have disappeared in the on-road fleet due to the development and increased application of fuel injection systems and were not in use during the 1994 to 2000 MY study period of this analysis.

The enhanced evaporative emission control requirements that phased in during the 1996 to 1998 MY period made significant changes to the regulatory test requirements, and the resulting vehicle materials and hardware. The regulatory requirements were doubled to 10 years or 100,000 miles. Where the diurnal test period had been one hour, with artificial fuel tank heating and a fuel liquid temperature rise from 60 to 84ºF, the new diurnal period was 24 hours with a nine hour ambient heating increase from 72 to 96ºF. These regulations recognized that not all vehicles are driven daily, and some are parked for 3 or more days. Controlling the diurnal emissions under extended park conditions required the application of higher capacity carbon canisters capable of holding at least three successive days of diurnal vapors.

Two test procedures were required, one for two days, and the second for three consecutive days of diurnal emission measurement. The permeation component of the emissions was included in the test and measured in real-time for 24 hours each day. The entire vehicle saw the variable ambient temperature, instead of just the fuel tank. The permeation of the non-fuel tank components now followed the ambient temperature cycle, not the static temperature previously used.

The high temperature hot soak test followed almost 2 hours of vehicle operation, with the last part a drive of over one hour at 95ºF. Emissions from the fuel tank cap, or the canister vent, if any, were measured during the drive, and capped at 0.05 g/mile. Again, the useful life and the emission warranty period were extended to 10 years or 100,000 miles. The allowable limits for the highest one day of diurnal emissions, plus the one hour of hot soak following the drive were limited to 2.0 g/test, or 2.5 g/test for vehicles with fuel tank rated at 30 or more gallons.

The hardware changes that resulted from the enhanced evaporative regulations were profound. Permeation of all the fuel or vapor containing elastomers had to be greatly reduced as it was now measured over a 25 hour period instead of one hour diurnal and a 1 hour hot soak. Small leaks had to be directly controlled. Hose connections throughout the entire vehicle fuel system were upgraded from a “hose over barb with clamp” to a precision o-ring in a “quick-connect” fitting. These new fittings were more robust, easier to install, and tolerant of misalignment and rotation.

Figure 3.2 shows a conventional fuel system from around 1994.

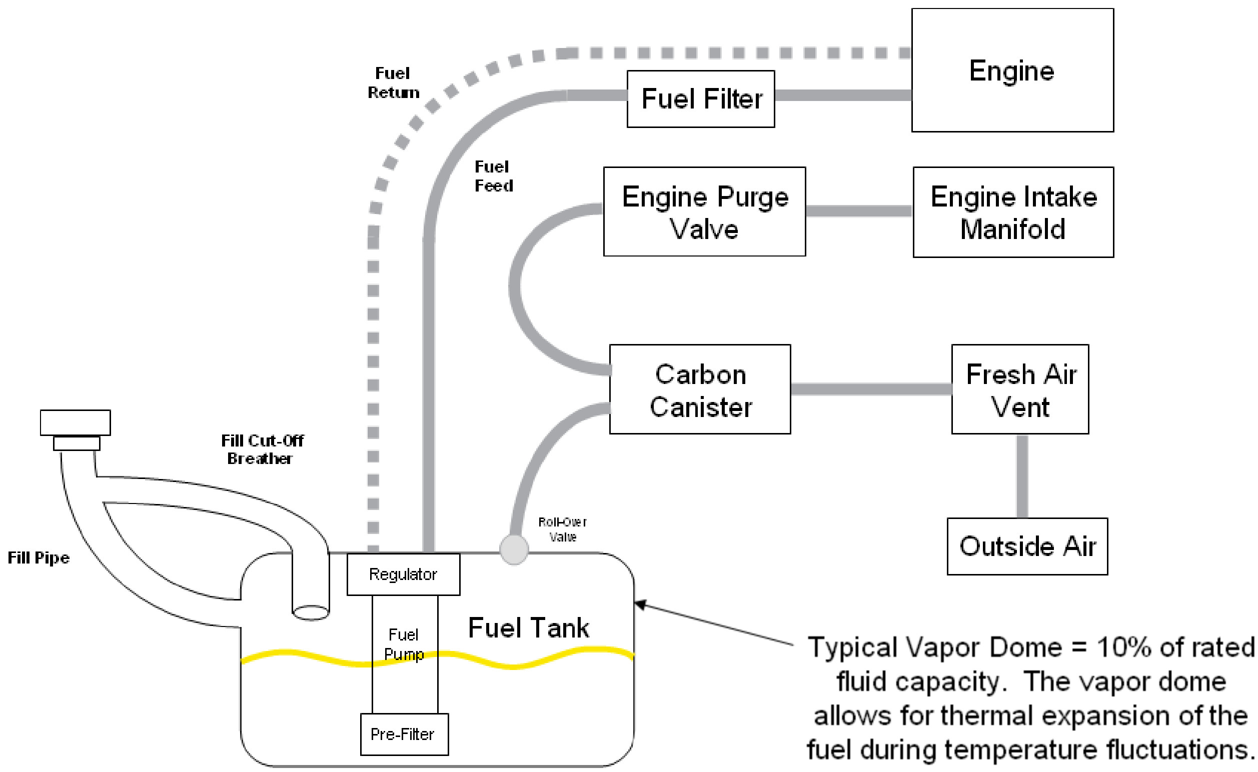


Figure 3.2: Typical Pre-ORVR Fuel System

Fuel systems such as those shown in Figure 3.2 typically consisted of the following materials:

- Fuel fill pipe: coated steel with a rubber hose to connect to tank
- Fuel tank: coated or painted steel
- Fuel lines: hot-dipped steel, plastic-coated steel or stainless steel with plastic flexible lines on each end. Many vehicles had a return fuel system, which returned unused fuel from the engine's fuel rail back to the fuel tank.
- Vapor lines: plastic or flexible rubber

On-board refueling vapor recovery (ORVR) was first required by regulation starting with passenger cars (59 FR 16262, 6 April 1994) in MY 1998. A three year phase-in was allowed. Light and heavy duty trucks (up to 8,500 pound GVW) were phased in starting in MY 2000. All light duty passenger cars and trucks were required to be controlled by the 2006 MY.

A canister that can hold three successive diurnal day's vapors has sufficient capacity to contain a 90% refueling event with 95% control, but required attention to the pressure drop during the high flow event of 10 gallons per minute (gal/min) for refueling, and larger diameter (with shorter path) hoses between the tank and the atmospheric vent. Carbon canisters are therefore located close to the tank to minimize the pressure drop during full flow refueling. With these changes, both the enhanced evaporative control requirement and the refueling control requirement could be combined into a common "integrated" system. The "integrated system" became the universal practice once the test requirements were finalized, and the design implications and principles were understood.

Two major modifications to the carbon canister were required to comply with the ORVR requirements:

1. Location
2. Internal flow restriction

The canister location in the vehicle was moved from the engine compartment and placed close to the fuel tank, and carbon particle size and shape were addressed to allow for a low pressure drop across the bed during the refueling event. Where irregular granular carbon had been used on many applications, the cylindrical particle configuration was adopted for more consistent pressure drop during refueling.

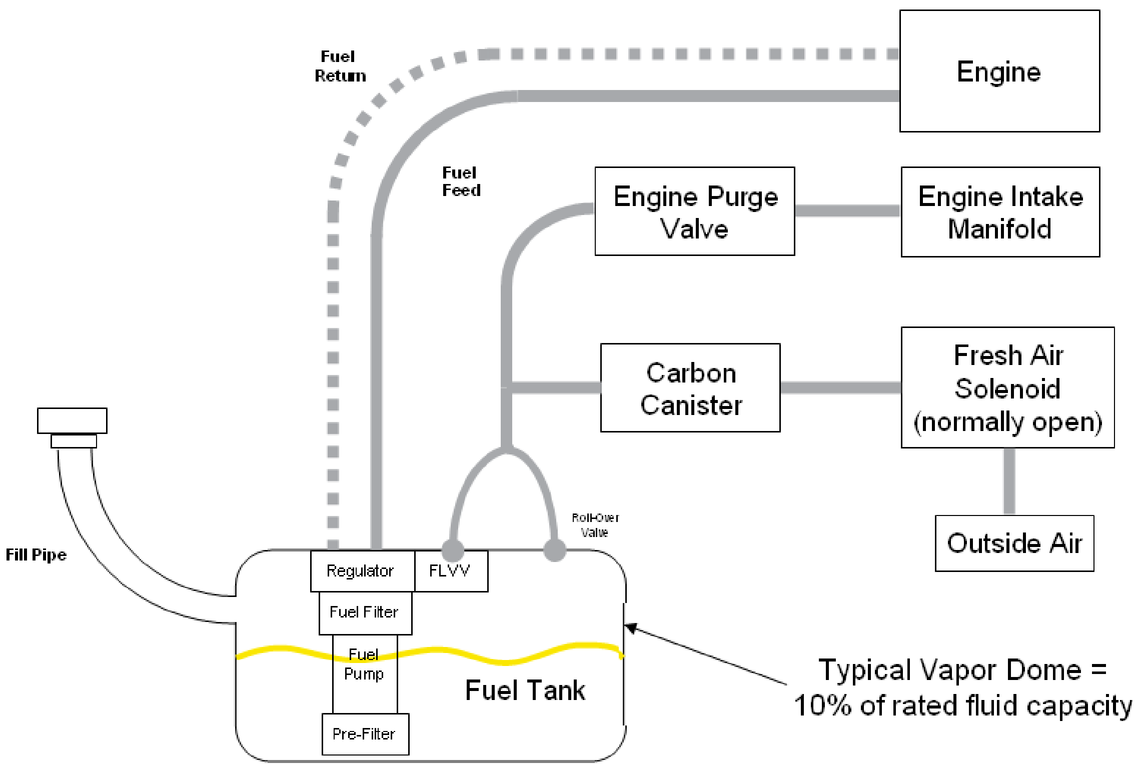


Figure 3.3: Typical ORVR Fuel System

On an ORVR system, all fuel vapors are pushed into the carbon canister during refueling. The activated charcoal adsorbs the fuel vapor, holding it in the canister until an engine purge cycle. During the engine purge cycle, the engine pulls a vacuum on the canister, which releases the fuel vapor from the activated charcoal.

ORVR fuel systems, such as those in Figure 3.3, typically consisted of the following materials:

- Fuel fill pipe: coated steel with a rubber hose to connect to tank
- Fuel Tank: coated steel or HDPE blow-molded plastic
- Fuel lines: hot-dipped steel, plastic-coated steel or stainless steel with plastic flexible lines on each end. Many vehicles had a return fuel system, which returned unused fuel from the engine's fuel rail back to the fuel tank.
- Vapor lines: flexible plastic (same as plastic fuel lines)

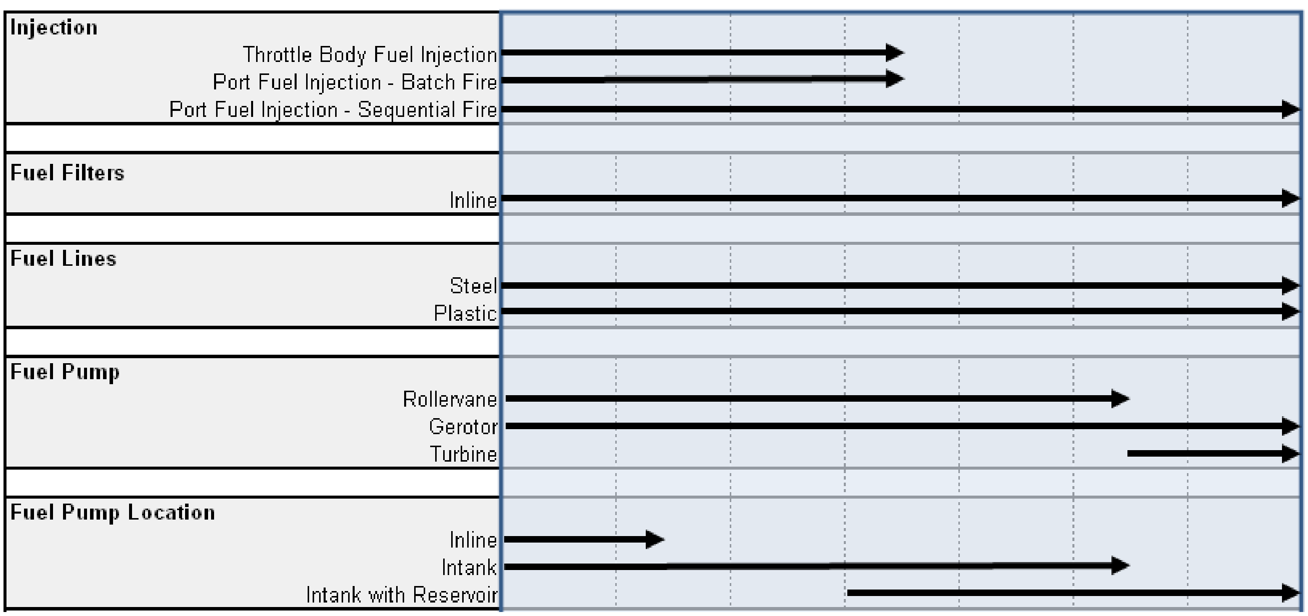
In general, the advent of enhanced evaporative emissions requirements and ORVR systems resulted in vehicle fuel systems that were more robust to ethanol blended fuels. These vehicles therefore have a much lower likelihood of experiencing significant evaporative emissions degradation than pre-enhanced EVAP vehicles. It is not anticipated that the carbon canisters in ORVR systems will experience any adverse effects from the use of E15, assuming the vapor pressure of the E15 blend is controlled to ASTM D4814 standards for volatility.

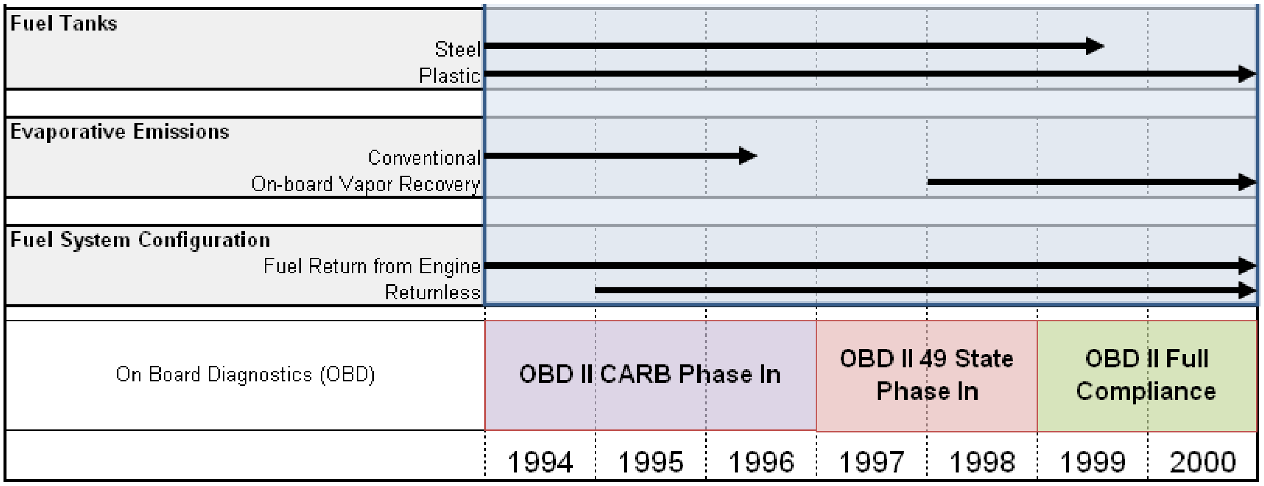
It is important to note that nearly all of the vehicles in the study period are past their useful life requirement for either tailpipe or evaporative emissions control, which results in the primary concern when moving from E10 to E15 to become gross leaks. This failure mode is discussed in detail in Section 8 (Fuel System Materials and Degradation Mechanisms). Additionally, hardware from end of life vehicles that were not initially certified to enhanced evaporative emissions requirements was also analyzed to better understand how these older systems would react to ethanol blends. The findings of this analysis are discussed in Section 9 (Hardware Observations).

4. TIMELINE OF EPA EMISSIONS REGULATIONS

The following timeline traces common fuel system components from their introduction to their phase out within the study period from 1994 to 2000. Emissions and OBD regulation milestones are cross referenced on the timeline as content drivers through the study time period. As in the evaporative emissions regulations, the tailpipe regulations during the study period were changing as more vehicles were required to hit Tier I Federal levels. It is important to note that this study period does not include any Tier II emissions level vehicles as this emissions level was not fully required until the 2004 model year. An emissions rollout schedule extending past the study period of this assessment (up to the 2003 model year) can be found in Appendix C.

	Veh. Type	Test Procedure	Emission Cat.	Emission Standards	Model Year 1994	1995	1996	1997	1998	1999	2000
Federal (non-NLEV)	LDV LDT1 & LDT2	FTP	Tier 0	Cert & In-use	60% max	20% max	0%	-	-	-	-
			Tier 1[b]	Cert[a]	40% min	80% min	100%	100%	100%	100%	100%
				Interim In-Use	40% min	80% min	60% max	20% max	0%	-	-
				Final In-Use[a]	-	-	40%	80%	100%	100%	100%
		SFTP[a]	Tier 1	Cert & In-Use[a]	-	-	-	-	-	-	40%
	LDT3 & LDT4	FTP	Tier 0	Cert & In-use	100%	100%	50% max	0%	-	-	-
			Tier 1	Cert[a]	-	-	50% min	100%	100%	100%	100%
				Interim In-Use	-	-	50% min	100%	50% max	-	-
				Final In-Use[a]	-	-	-	-	50% min	100%	100%
		SFTP[a]	Tier 1	Cert & In-Use	-	-	-	-	-	-	-
	LDV&LDT1	FTP	CARB LEV I	Cert.	-	-	-	-	-	0.148 NMOG fleet avg[f,g]	0.095 NMOG fleet avg[f]
	LDT2			Cert.	-	-	-	-	-	0.19 NMOG fleet avg.[f,g]	0.124 NMOG fleet avg.[f]





Notes:
a Small volume manufacturer exempt until last year of phase-in.
b Light-duty vehicle (LDV) may be combined with light-duty truck 1 (LDT1) and LDT2 for Tier 1 phase-in.
c LDV and LDT1 combined with LDT2 for Supplemental Federal Test Procedure phase-in.
d Other equivalent schedules allowed.
e Fleet average derived from 50,000 mile standards.
f Not applicable to small volume manufacturers.
g Early credits available.

5. EPA EMISSIONS DATA

The EPA database (www.epa.gov) was interrogated for emissions certification data for 1994 MY to 2000 MY vehicles included in the top 10 vehicle platforms (see Section 2.4: Vehicle Platforms). In the EPA database, emissions certification data is listed for the required useful life and the deterioration factor. The required useful life is either 50k miles or 100k miles, depending on the model year and certified emissions standard. The deterioration factor is either an additive or multiplicative factor, depending on the type of emissions certification being used. The EPA assumes that a vehicle travels 10k miles per year when determining deterioration factors and useful life emissions. Certification data for most 1994 MY and 1995 MY vehicles was not provided to an adequate detail in the EPA database, so extrapolation of the data to predict 2010 emissions performance was not conducted for the full range of top selling platforms for those particular model years.

Tables 5.1 and 5.2 are examples of the emissions certification data found in the EPA database. Table 5.1 shows the emissions certification data from a pre-OBDII vehicle (1994 Dodge Intrepid) and Table 5.2 shows data from a later model year (2000 Dodge Intrepid).

Vehicle Information	
Year	1994
Company	Chrysler
Brand	Dodge
Model	INTREPID
Generation	First
Platform	LH
Trim	Base/ES
# of Cyl	6
Eng Displ. (cc)	3,301
Type of FI	Gas/SEFI
EPA Engine Family	RCR3.3V8GFEA
Evap Family	N/A
OBD	I
ECS-Ev	CANISTER
ETW	3750
Cycle	FTP75
Test Procedure	N/A
Fuel Type	N/A
Sales Area	N/A
UL Certified	50
Tier	T1

Emissions Data							
CO							
Orig. Level	UL Level	Standard	Mult DF	Add DF	UL Margin	2010 Level	2010 Margin
1.01	1.34	3.4	1	0.33	60.6%	2.066	39.2%
HC Total							
Orig. Level	UL Level	Standard	Mult DF	Add DF	UL Margin	2010 Level	2010 Margin
0.147	0.196	0.41	1.335	0	52.1%	0.3046	25.7%
NOx							
Orig. Level	UL Level	Standard	Mult DF	Add DF	UL Margin	2010 Level	2010 Margin
0.08	0.106	0.4	1	0.026	73.5%	0.1632	59.2%

Table 5.1: 1994 Dodge Intrepid Emissions Data Example

In Table 5.1, the values for “UL Level”, “Standard”, “Mult DF”, and “Add DF” are found in the EPA database. The following is an explanation of these values:

- “UL Level” is the emissions level of the vehicle at its useful life (for this example the useful life of the vehicle is 50,000 miles – see “UL Certified” value)
- “Standard” is the legislated limit for the emissions species
- “Mult DF” is the multiplicative deterioration factor. If this value is equal to 1, the additive deterioration factor should be used for the emissions species
- “Add DF” is the additive deterioration factor. If this value is equal to 0, the multiplicative deterioration factor should be used for the emissions species

The “Orig. Level” value, the emissions level measured when the vehicle is at 4k miles, is not listed in the EPA database. Vehicles are supposed to be emissions certified to either 50k or 100k miles, but OEMs do not want to have to test vehicles to such high mileage in order to measure the emissions levels. Therefore, OEMs operate vehicles to 4k miles, measure their emissions levels, and then apply either a multiplicative or additive deterioration factor to determine the emissions levels at 50k or 100k miles (ie. the “UL Level”). The catalyst experiences rapid de-greening (or degradation) during the first 2k to 3k miles, so emissions levels are typically measured at 4k miles. After this time, the rate of catalyst degradation decreases significantly, but continues linearly for the life of the catalyst. In order to determine emissions levels of vehicles in 2010, both the “Orig. Level” and "UL Level" values had to be known. A linear extrapolation method could then be used to predict future emissions levels.

The "Orig. Level" value is calculated using the following method:

- If the deterioration factor is multiplicative (ie. "Mult DF" is not equal to 1),
  - Orig. Level = UL Level / Mult DF
- If the deterioration factor is additive (ie. "Add DF" is not equal to 0),
  - Orig. Level = UL Level – Add DF

The present day emissions performance values ("2010 Level") were then predicted by linearly extrapolating from the "Orig. Level" and "UL Level" data for each of the emissions species (CO, HC, NOx). Figure 5.1 shows the linear extrapolation method used to predict the present day emissions levels.

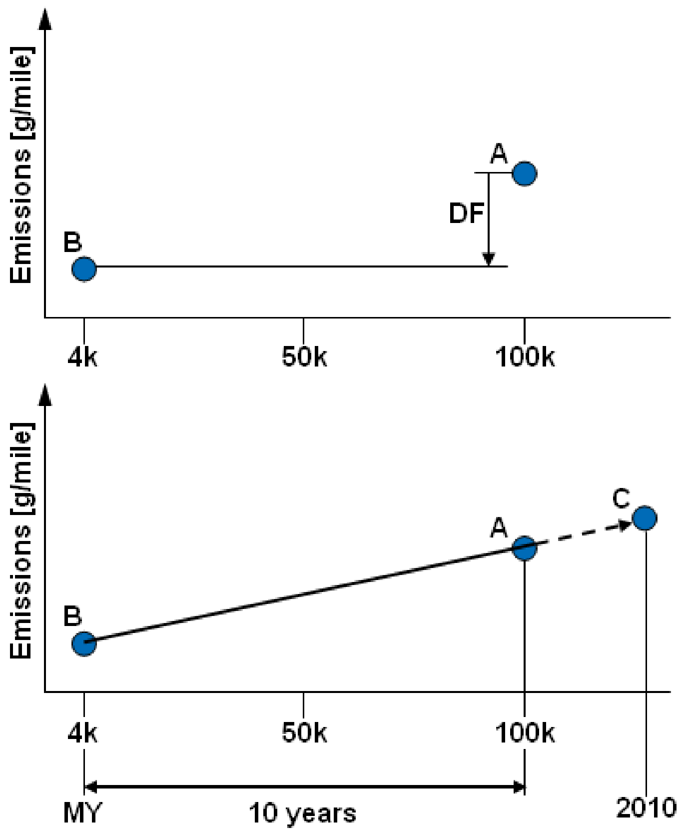


Figure 5.1: Extrapolation Method for Prediction Emissions Levels in 2010

In Figure 5.1, Point A represents the useful life emissions level at 100k miles ("UL Level"), as recorded in the EPA database. Point B represents the emissions test result recorded when the vehicle reached 4k miles ("Orig. Level"). Point C is the present day predicted emissions level ("2010 Level") that was linearly extrapolated from Points A and B by assuming that the vehicle traveled 10k miles per year.

An emissions margin was also calculated for each emissions species. The emissions margin is a measure of how far, within the original useful life emissions standard, each vehicle is predicted to be if it were tested in 2010. The 2010 emissions margin (2010 Margin) was calculated using the following formula:

$$2010 \text{ Margin} = [1 - (2010 \text{ Level} / \text{Standard})] \times 100\%$$

A 2010 emissions margin of 20% means that the vehicle's emissions performance could degrade by as much as 20% of its useful life certification standard before it would exceed that emissions standard. Similarly, a 2010 emissions margin of -10% (negative) means that the vehicle's emissions performance is 10% higher than the useful life standard to which the vehicle was originally certified.

As can be seen in Table 5.1, the emissions species that were regulated in 1994 were CO, total HC, and NOx. For this vehicle (1994 Dodge Intrepid), the UL margin for CO emissions was 60.6%, which means that at its useful life (50k miles), the vehicle was below its legislated emissions standard. Even though this vehicle was well past its useful life in 2010, its 2010 margin for CO emissions was 39.2%, therefore the vehicle still exceeded its original legislated CO emissions requirements. The methodology used to calculate CO emissions performance was also used to calculate the 2010 margins for total HC's and NOx emissions, which were both over their legislated levels.

The 2000 MY vehicle example in Table 5.2 shows the same calculated emissions margin of 92.6% at useful life (UL Margin) and at present day (2010 Margin). This is because the vehicle was certified to a useful life of 100,000 miles or 10 years, which the vehicle will reach in 2010.

Vehicle Information	
Year	2000
Company	Chrysler
Brand	Dodge
Model	INTREPID
Generation	Second
Platform	LH
Trim	Base
# of Cyl	6
Eng Displ. (cc)	2,736
Type of FI	Gas/SEFI
EPA Engine Family	YCRXV0165V30
Evap Family	YCRXR0101G1D
OBD	
ECS-Ev	CANISTER
ETW	3750
Cycle	FTP75
Test Procedure	CA FUEL 3 DAY EXH (BUTANE LOAD)
Fuel Type	CARB Phase II Gasoline
Sales Area	CL
UL Certified	100
Tier	LEV

Emissions Data	Orig. Level	UL Level	Standard	Mult DF	Add DF	UL Margin	2010 Level	2010 Margin
CO	0.3	0.31	4.2	1	0.01	92.6%	0.31	92.6%
HCHO	0.002	0.002	0.018	1	5E-04	88.9%	0.002	88.9%
NMOG	0.044	0.054	0.09	1	0.01	40.0%	0.054	40.0%
NOx	0.09	0.16	0.3	1	0.07	46.7%	0.16	46.7%

Table 5.2: 2000 MY Dodge Intrepid Emissions Data Example

Figures 5.2 and 5.3 show the predicted 2010 emissions margins for each emissions species for the top 10 model year vehicle platforms from 1996 to 2000.

For both CO and NOx, all vehicles surveyed are predicted to have at least a 20% margin within the original useful life standard to which they were certified. For the HC species, the vast majority of vehicles also have at least a 20% margin over the original useful life standard to which they were certified. However, a small number of vehicles from 1996 and 1997 are predicted to exceed the original legislated standard in 2010. This result can be expected because 1996 MY and 1997 MY vehicles are significantly past their useful life in 2010.

It is important to note that nearly all of the vehicles considered in this study are past, or very near the end of their legislated useful life requirement. However, to better understand the implications of the E15 fuel blend change, it is necessary to understand how vehicles currently perform relative to their certified emissions levels. This is helpful in determining whether the vehicles will experience an illumination of the Malfunction Indicator Lamp (MIL).

Changing the fuel blend from E10 to E15 may have the following effect on emissions:

- Cold CO test – enleanment of the air-fuel ratio due to additional ethanol content versus E10. This change will most likely cause a reduction in CO emissions due to a leaner overall air-fuel mixture. Cold start and drivability / stumble concerns are addressed in more detail in Section 6 – Aftertreatment / Vehicle Calibration.
- Normal driving conditions (fully warmed up catalyst with closed loop fueling control) – no change in emissions should be expected since the engine will be running at the stoichiometric air-fuel ratio, so the catalytic converter will be converting the regulated emissions species into harmless by-products in the same way it would for E0 or E10.

As discussed in Section 6, a change from E10 to E15 is not expected to cause a significant change in emissions performance. However, if such a change were to have an effect, the effect would have to be very large to exceed the 20% margin that most of the vehicles have over 2010 emissions standards. The legislation for MIL illumination for emissions non-compliance is set at 1.5 times the applicable emissions standard, resulting in an even larger margin available prior to illumination of the MIL. Therefore, illumination of the MIL due to emissions non-compliance is considered highly unlikely.

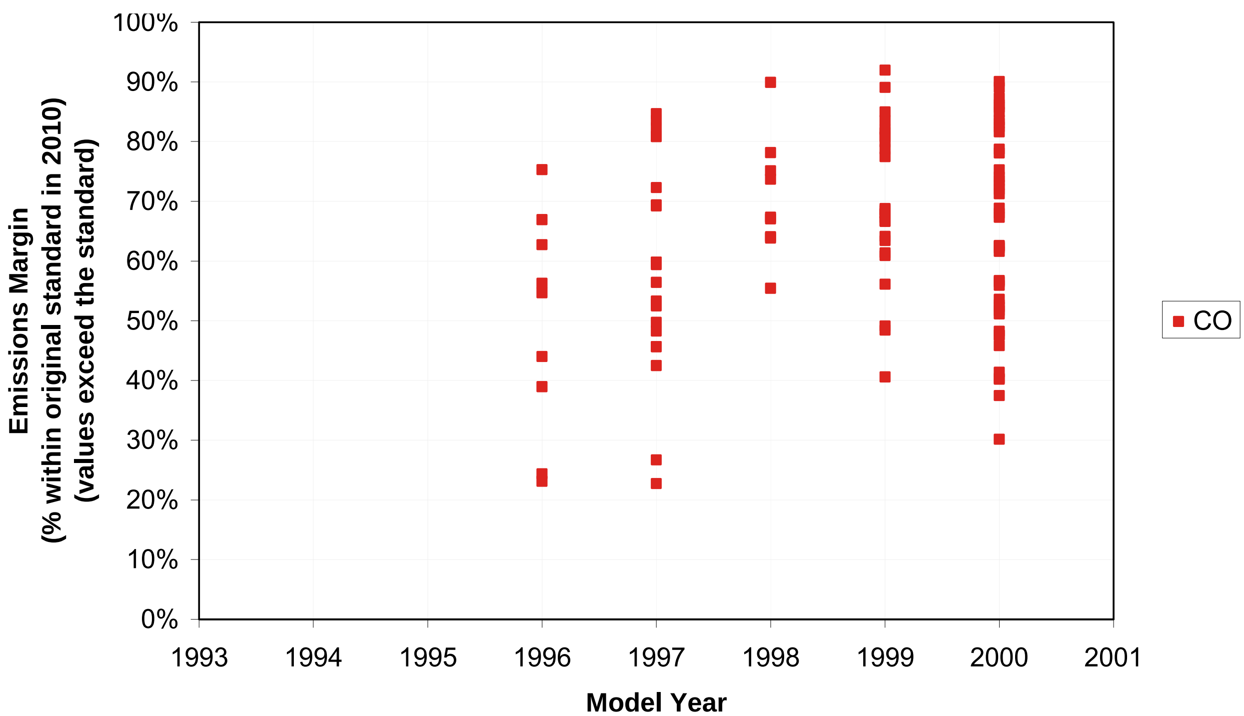
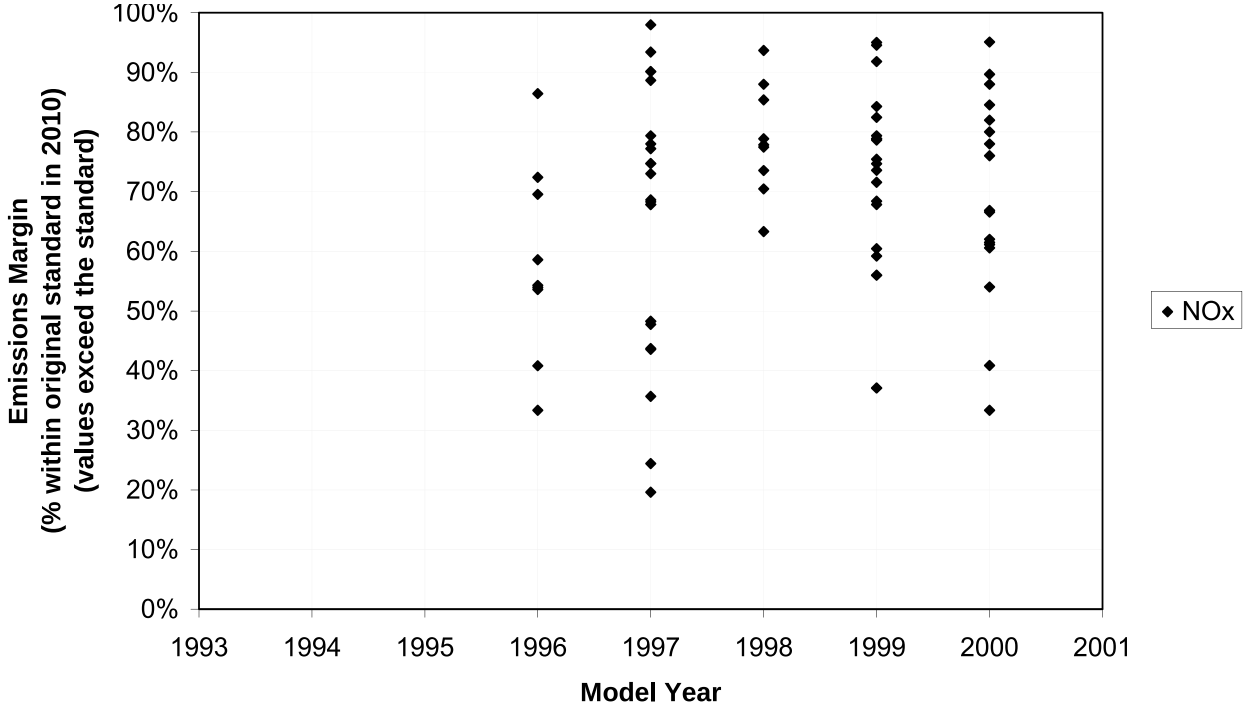


Figure 5.2: 2010 Emissions Margins for 1996 to 2000 Model Year Vehicles for CO Emissions



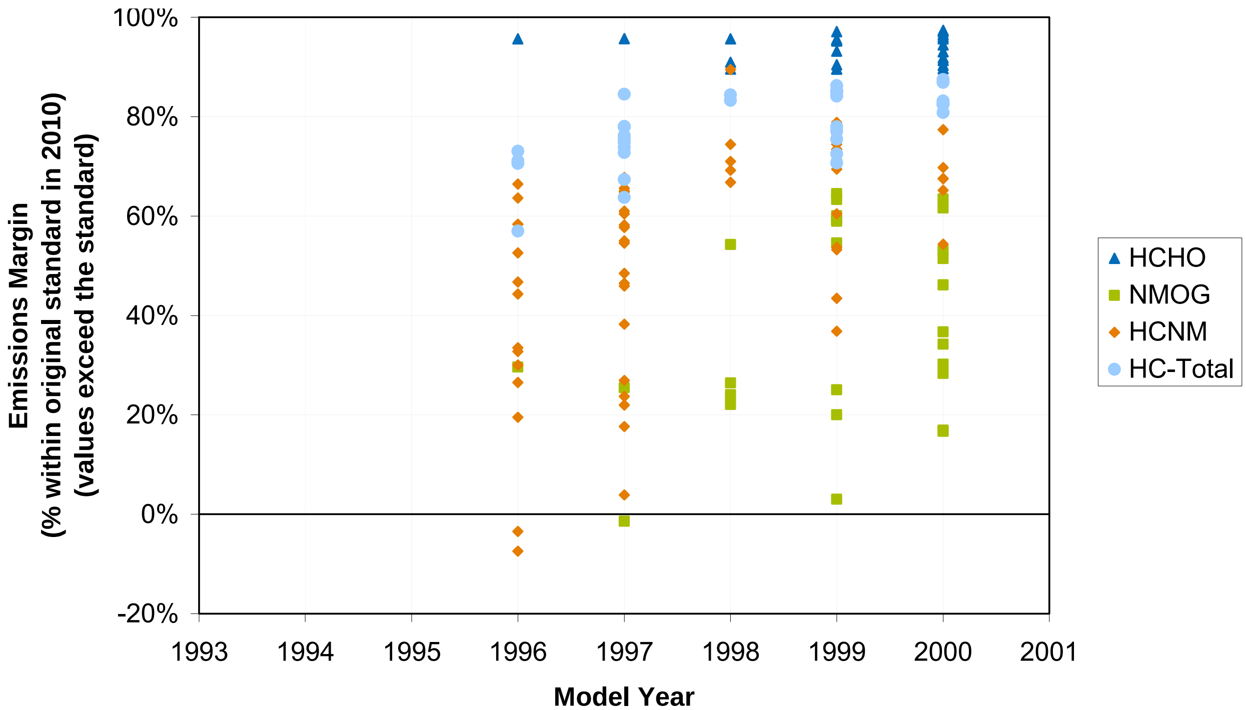


Figure 5.3: 2010 Emissions Margins for 1996 to 2000 Model Year Vehicles for NOx Emissions (upper plot) and HC Emissions Species (lower plot)

In Figure 5.3 it can be seen that there were three vehicles in the analyzed group manufactured in the 1996 MY, that fell below the 2010 emissions margins for HC emissions species. However, it is not expected that these vehicles would cause the MIL to illuminate. This is because the emissions of these vehicles were only below the 2010 emissions margin by between 5% and 10%. The MIL should not illuminate unless the vehicle emissions are more than 50% below their legislated standard. As previously stated, a significant degradation in emissions performance can be afforded before a MIL is illuminated.

6. AFTER TREATMENT / VEHICLE CALIBRATION

The following sections discuss the impact of E15 on the calibration and after treatment components in vehicles from the 1994 to 2000 MY time period.

6.1 Base Engine Calibration Impact of Increased Ethanol Blends

6.1.1 Air-Fuel Control

The primary effect of increasing the ethanol content in gasoline is the enleanment of the air-fuel ratio and the key issue is the ability of the vehicle's engine management system (EMS) to compensate for it. The stoichiometric air-fuel ratio of various ethanol blends through to E85 and the expected enleanment is shown in Table 6.1.1.1 below.

Ethanol Content (%)	Stoichiometric Air-Fuel Ratio	Shift in Stoichiometric A/F from E0 (%)
0	14.64	1
5	14.36	2
10	14.08	4
15	13.79	6
20	13.51	8
25	13.23	10
30	12.95	12
35	12.67	13
40	12.38	15
45	12.10	17
50	11.82	19
55	11.54	21
60	11.26	23
65	10.97	25
70	10.69	27
75	10.41	29
80	10.13	31
85	9.85	33

Table 6.1.1.1: Stoichiometric Air Fuel Ratio of Ethanol Blends

A modern vehicle's EMS will compensate for the enleanment caused by increased ethanol content to ensure that the vehicle will continue to operate at stoichiometric air-fuel ratios. Most vehicles in the U.S. market use switching oxygen sensors which correct fueling to the stoichiometric air-fuel ratio and learn or "adapt" the amount of extra fuel required. This is done to allow for variations in fuel system components, actual air flow through the engine, and fuel composition variation. During periods of high load operation, commonly referred to as "power enrichment", or in rich engine protection modes, such as those for catalyst or base engine protection, the engine will run an open loop fuel control based on normal control inputs.

Some vehicles have the ability to use the adapted fuel trim at part load when the engine is running at stoichiometric air-fuel ratios in open loop. This effectively creates a learned fuel composition in addition to compensating for variation in the vehicle's fuel system and air path.

Therefore, increasing the ethanol content from E10 to E15 will not affect the air-fuel control in vehicles that have a switching oxygen sensor.

6.1.2 Exhaust and Catalyst Temperatures

For vehicles that do not use part load learned fuel trims to correct open loop air-fuel ratios, there will typically be an increase in the exhaust and catalyst temperatures under high load conditions due to fueling enleanment. This can be partially offset by high ethanol fuel blends due to the increased octane content. However, this would not be the case for E15 blends, where the octane benefit is not realized, because fuel blenders typically target the minimum octane specifications for economic reasons. Increased catalyst temperatures have the potential to increase the speed of catalyst degradation. Studies by the Coordinating Research Council (CRC, Report No. E-87-1) have shown that vehicles with open loop adapted fuel trims have more consistent catalyst temperatures when using fuel blends between E0 and E20.

Recent studies by the CRC (Report No. E-87-1) have tended to focus on vehicles manufactured between 1999 and 2006, with some anomalous outliers. Despite the fact that some vehicles manufactured within this time period do not have open loop adapted fueling, the maximum inlet temperature increase seen in catalysts when comparing an E0 and E20 blend was 33°C, using the test methodology chosen. The vehicle that had the highest catalyst temperature of the group, and no open loop adapted fuel trim, showed an 8°C inlet temperature difference in the catalyst between E0 and E20. The vehicle-to-vehicle variation in catalyst inlet temperatures can be explained by the different vehicle exhaust system architectures and fueling strategies used. Of the vehicles tested in the CRC study, none exhibited abnormally high catalyst temperatures for the test protocol used. Depending on the catalyst washcoat technology, the maximum targeted temperature for exhaust gas in the catalysts was in the range of 850 to 950°C. The older vehicles tested in the CRC study (1994 to 2000 MY) tended to have lower (~850°C) exhaust gas temperatures in the catalyst. Older vehicles do not have to comply with current emissions standards, so catalytic converters in older vehicles tend to be located further from the engine. Vehicles with adapted open loop fuel trims tend to exhibit lower catalyst temperatures with higher ethanol blend fuels due to the cooling effect of ethanol in the rich fuel mixture, since ethanol has a higher latent heat of vaporization than gasoline.

Several reports that assess the effect of introducing E20 into the Australian market draw comparisons between U.S. vehicles and results obtained from a fleet trial conducted by the Orbital Engine Company (OEC, 2003) in Australia. While some of the vehicles, such as the 2001 Hyundai Accent, were common between the studies, it is invalid to draw a comparison between the U.S. and Australian vehicles because Australia lags the U.S. in both the stringency of emissions certification levels and on-board diagnostics (OBD). At the time of the Australian study, vehicles had to be certified to ADR37/01, which is approximately equivalent to US'83. Most vehicles in the Australian study also only had the equivalent of OBD-1 diagnostics, which are primarily used by service operators. As such, a number of the vehicles in the Australian study were generations of technology behind the U.S. vehicles in terms of the EMS, catalyst specification, and diagnostics, despite being produced in the same model year.

The results from the various studies have shown no definitive conclusion about the potential for increased catalyst temperatures to degrade emissions system performance. For the vehicles analyzed in this study, the potential for increased degradation cannot be completely ruled out, however, as stated previously, due to the distance between the engine and the catalyst for these Tier I emissions level vehicles the potential is greatly reduced in comparison to newer vehicles which have been certified at a lower tailpipe emissions level.

6.2 Emissions Effect of Increased Ethanol Blends

The effect of E15 on regulated atmospheric criteria pollutants may be broken down into two sections: emissions from the vehicle tailpipe as a result of fuel combustion and the evaporative emissions from the engine and fuel system components.

6.2.1 Tailpipe Emissions

In general, reports by varying groups, such as the CRC (Report No. E-84-1) and Reuter, R.M., et al. (1992), have concluded that increasing the amount of ethanol in gasoline will reduce non-methane hydrocarbons (NMHC) and carbon monoxide (CO), but will increase nitrogen oxides (NO_x). This is consistent with the enleanment of the fuel mixture, particularly during the critical period after the engine starts, while the catalytic converter is warming up to operational temperature. The reduction in NMHC and CO is consistent in most studies, whereas NREL (TP-540-43543) reports that the increase of NO_x emissions is not always consistent because modern EMS systems can compensate for the increased ethanol. Assuming that the EMS can maintain a stoichiometric air-fuel ratio in the engine, the catalytic converter should be able to process the engine-out emissions into non-polluting species, with no change in this capability between E10 and E15.

6.2.2 Evaporative Emissions

Evaporative emissions from a vehicle are comprised of the hydrocarbon emissions from a vehicle's engine and fuel system, as well as the static permeation, running loss, hot soak, and diurnal emissions from a vehicle's materials. The Code of Federal Regulations (CFR, 86.1824-01) states that evaporative emissions testing must be conducted with gasoline fuel that contains ethanol in the highest concentration permissible under federal law and that is commercially available in any state in the U.S.
The effect of ethanol content on Reid Vapor Pressure (RVP), or volatility of fuel, is shown in Figure 6.2.2.1. Current flex-fuel vehicles in California are required to comply with evaporative emissions

requirements on E10, as it is considered the worst case in alternating use between E0 and E85. It has been shown by GM that Low Emission Vehicles (LEV) emit approximately 12% more evaporative emissions with E10 than with gasoline (World Wide Fuels Charter edition 3), as E10 is approximately three times as permeable as straight gasoline (E0). It is important to note that the majority of the vehicles in the study period of this analysis are no longer under regulatory control relative to evaporative emissions, however the goal of this study was to determine the potential effects of increasing the ethanol content of gasoline from E10 to E15, so evaporative emissions effect were studied. Further discussion on the evaporative system monitor is provided in Section 6.3.3.

One of the key contributing factors to evaporative emissions is the vapor pressure of the fuel. It is well documented that 3v% to 10v% will increase the vapor pressure of the base gasoline to which it is added by up to 1.0 psi. However, a recent API study (April 2010) shows that the vapor pressure of E15 is actually lower than E10 (made from the same base fuels). Since vapor pressure of E15 is lower than E10, evaporative emissions related to vapor pressure would not increase and may, in some instances, decrease depending on the exact make up of the gasoline source.

Another component of evaporative emissions is permeation emissions. The limited data that is available showing the permeation effects of E15 blends does not draw a statistically relevant conclusion. CRC E65-3 showed that some vehicles have increased permeation emissions when moving from E10 to E20, while others had reduced permeation emissions. The work on E20 was conducted at the California diurnal temperature, which is important because it has been previously established that permeation emissions generally double for every 10ºC increase in temperature (CRC E65). Therefore this work can not be directly related to the rest of the U.S. light duty vehicle fleet. Overall the effect of permeation on the 1994 to 2000 MY vehicles targeted by this study will not be significant.

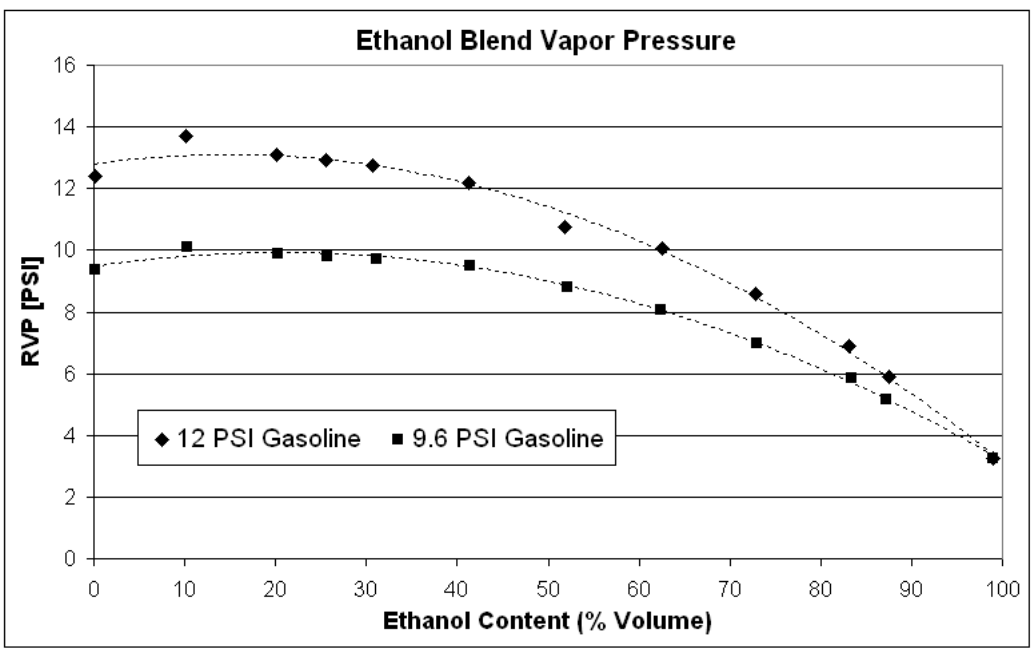


Figure 6.2.2.1: Effect of Ethanol Content on Reid Vapor Pressure (RVP)

6.3 On-Board Diagnostic Impact of Increased Ethanol Blends

A key consideration with the introduction of increased ethanol blends in the marketplace is the effect on a vehicle's on-board diagnostic system, which is designed to ensure that the vehicle's emissions control components remain effective or will alert the operator of a problem by illuminating the MIL.

6.3.1 Fuel System Monitor

The on-board diagnostic fuel system monitor is designed to detect a malfunction of a vehicle's fuel delivery system that would cause the vehicle's emissions to exceed one and a half times the applicable emissions standard. This is achieved using feedback from the vehicle's oxygen sensors which adapt the fueling when the engine is running in closed loop fueling control. When the adaption hits a pre-determined limit, the system will no longer add or subtract fuel, and the (MIL) will be activated to alert the operator. For increased ethanol blends, the system is required to add extra fuel due to the lower stoichiometric air-fuel ratio of ethanol. The threshold for MIL illumination varies between manufacturers with a range of 18 to 25% for lean side fuel trim. While some studies have expressed concern that a percentage of vehicles in service could be affected (CRC, Report No. E-90), E15 does not represent a significant shift compared to the allowable fuel trim limits, and therefore is not expected to result in fuel system monitor faults. It should also be noted that there has not been illumination of a MIL light in any of the test fleets that were operating non flex-fuel vehicles on ethanol blends up to E20.

Calibration projects that Ricardo has delivered, or is aware of, typically tend toward the high side of the lean fuel trim limit to allow sufficient margin for E10 fuel, which has been in the market for several decades. It is not unusual to implement asymmetric fuel trim limits, with a lower limit on the rich fuel trim, which effectively centers the diagnostics on a higher ethanol blend. It is possible that manufacturers that did not properly validate their diagnostics for E10 blends may have some vehicles, which currently do not exhibit a problem, illuminate the MIL due to a lean fuel system monitor when E15 is introduced into the vehicle.

6.3.2 Catalyst Monitor

For vehicles manufactured after the implementation of OBD-II (1996 MY), the EMS system has the ability to monitor the catalytic converter for proper conversion capability. This is accomplished using the pre and post converter oxygen sensors. These sensors effectively calculate the oxygen storage capacity, which indicates the level of deterioration of the washcoat—the component that contains the precious metal inside the catalytic converter. It is not expected that increased ethanol blends will directly affect the operation of the catalyst monitor, provided the engine can maintain correct closed loop operation, which is diagnosed by the fuel system monitor. The catalyst monitor would cause the MIL to illuminate if the vehicle's catalyst degrades due to extended high temperature operation caused by lean running.

6.3.3 Evaporative System Monitor

Since 2001, all vehicles in the U.S. were required to verify purge flow from the evaporative system and have a leak equivalent to a 0.040-in hole. California had even more stringent requirements. Fuel volatility has a significant effect on the ability of the system to detect leaks, particularly under high ambient conditions where the ambient temperature can exceed the initial boiling point of the fuel. The effect is similar at high altitude where the differential pressure to atmosphere is greater. High volatility fuel has a higher probability of falsely failing the evaporative system monitor due to the presence of extra vapor. This makes it difficult to pull the tank pressure down for systems that decrease the tank pressure, in order to detect leaks. Many EMS strategies have volatility detection algorithms based on fuel vapor during canister purge that will prevent the monitor from judging if the assumed vapor pressure is too high.

Since E10 was available well before the implementation of the diagnostic requirement for evaporative emissions, ethanol blends were used during development by a majority of OEMs. Since E10 is generally considered to be the worse case for alcohol-blended fuel compositions, it is not expected that E15, which has similar volatility, will have a detrimental effect on the evaporative system monitor.

6.4 Drivability Impact of Increased Ethanol Blends

6.4.1 Cold Start Drivability

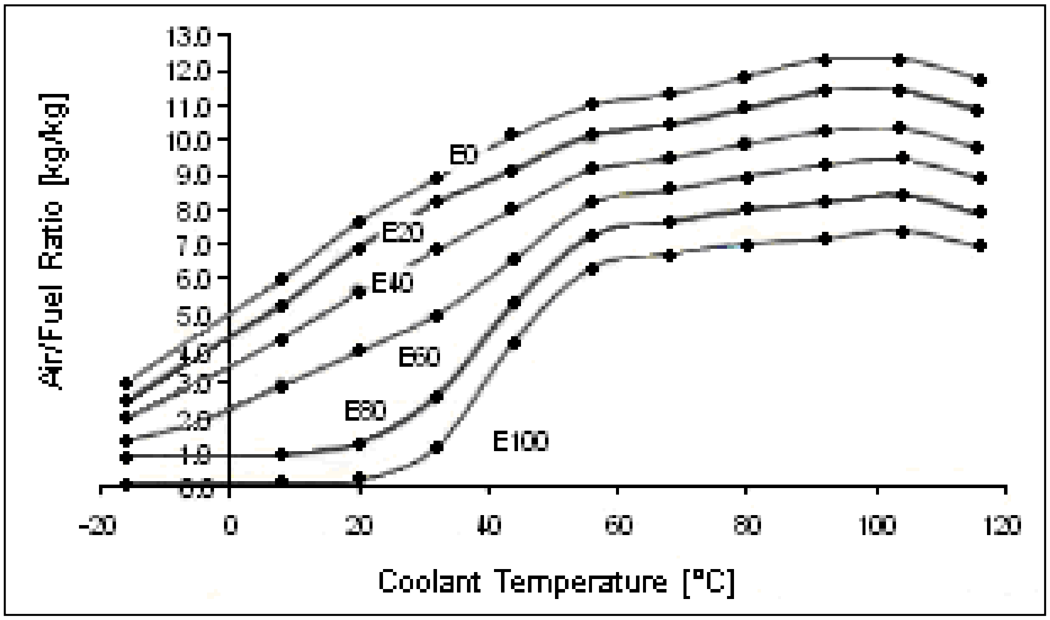


Figure 6.4.1.1: Additional Fuel Required for Cold Starting with Ethanol Blend Fuels

Increasing the ethanol content of gasoline has the potential to cause problems for engine starting and hesitation in cold climates. This is due to the lean shift caused by the lower stoichiometric air-fuel ratio, as well as the higher latent heat of vaporization of ethanol. Higher heat of vaporization means more energy in the form of heat is required to vaporize the fuel. Several fleet trials (University of Minnesota and R.I.T.) using E20 blends did not note any significant driveability issues, although the possibility exists, as it does with regular gasoline.

A significant part of any engine calibration program is to obtain good start and after-start quality which limits fuels across the full range of climatic conditions that are expected to be encountered. All OEMs have a proprietary range of fuel blends and qualities which they use to develop calibration robustness. These focus not only on RVP, which is the legislated requirement, but also on drivability index, which is calculated from the fuel's distillation curve. The calculation for the drivability index contains a correction factor for oxygenate content (up to 10% ethanol by volume) to allow for the higher latent heat of vaporization. The potential for cold start and drivability issues for vehicles using high drivability index fuels exists even for fuel blends that do not contain ethanol, and is dependent on the quality of the fuel delivered to service stations.

6.4.2 Hot Fuel Handling

While the vapor pressure of fuel containing ethanol tends to be high if not adjusted for by blending changes, the maximum RVP tends to center around E10 as stated in a recent API report (April 2010). As E10 has been available in the market for a considerable time period, it is not anticipated that a move to E15 will cause any issues with vapor lock or hot restart, provided fuel is correctly blended to existing RVP limits.

7. PROPERTIES OF GASOLINE BLENDS (E0, E10, E15)

Gasoline (E0) is a complex mixture of many chemicals spanning a range of molecular masses. By comparison, ethanol is a single compound used in fuel blends in the U.S. Typically ethanol is blended as anhydrous ethanol, denatured 2% with gasoline. There are several physical properties that can be used to characterize various blend ratios of these fuels. Some of these properties are regulated or otherwise specified, while others are used to calibrate or instrument a vehicle. Therefore, it is necessary to understand the properties of the proposed E15 fuel blend compared to currently available E0 or E10 fuel blends, in order to assess how differences in these properties may affect the performance and durability of 1994 MY to 2000 MY vehicles.

Many E0 and E10 fuel properties are regulated, with variations between summer and winter formulations as well as significant regional variations based on the Clean Air Act requirements. Adding ethanol to base reformulated gasoline significantly affects several fuel properties, including latent heat of vaporization, RVP, energy content (lower heating value, or LHV), and lubricity.

7.1 Heat of Vaporization

The latent heat of vaporization increases with increasing ethanol concentration up to E20, as shown in Figure 7.1.1 below. A higher latent heat of vaporization will improve the charge cooling benefit of the fuel. Nevertheless, this increase will make cold starts using E15 marginally more challenging, especially in cold weather conditions.

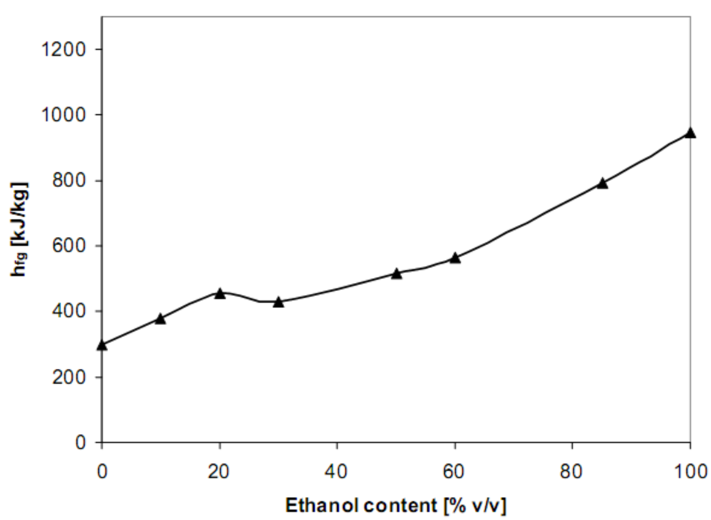


Figure 7.1.1: Heat of Vaporization versus Ethanol Concentration (mass basis) (Kar, et al, 2008)

7.2 Reid Vapor Pressure (RVP)

Reid vapor pressure (RVP) is a common measure of the volatility of gasoline. It is defined as the absolute vapor pressure exerted by a liquid at 100 °F (37.8 °C) as determined by the test method ASTM-D323. The test method applies to volatile crude oil and volatile non-viscous petroleum liquids, except liquefied petroleum gases. RVP is controlled in the U.S. dependent on season and region to values from below 7.8 psi(g) to 15.0 psi(g). These values are established to allow acceptable start up performance while minimizing vapor lock and evaporative emissions implications. A full description of RVP control can be found in ASTM standard D4814-10a.

RVP varies with ethanol concentration, but the absolute value of RVP relative to ethanol volume percentage is dependent on the base gasoline blend stock. In nearly all states (Alaska and Hawaii are notable exceptions), the U.S. EPA, in 40 CFR Part 80, allows a variation in RVP for ethanol blended fuels between May 1st and September 15th. This variation allows the RVP limit to be exceeded by 1.0 psi for gasoline ethanol blends between 9 and 10 volume % ethanol (it is well documented that 3v% to 10v% ethanol will increase the vapor pressure of the base gasoline to which it is added by up to 1.0 psi). However, a recent API study (April 2010) shows that the vapor pressure of E15 is actually lower than E10 (made from the same base fuels). API concluded that, based on the measurements made in the study, with one exception "blending ethanol into gasoline at concentrations between 10% and 30% pose no additional challenge" to meeting the volatility requirements of the ASTM D4814 Specification for Spark-Ignition Engine Fuel, version 09b.

Vapor pressure can vary significantly with ambient temperature. Figure 7.2.1 shows vapor pressure versus ethanol concentration from 86°F to 140°F. Similar to RVP data, this data is highly dependant on the vapor pressure of the base gasoline formulation, and should be used for trend identification rather than absolute values.

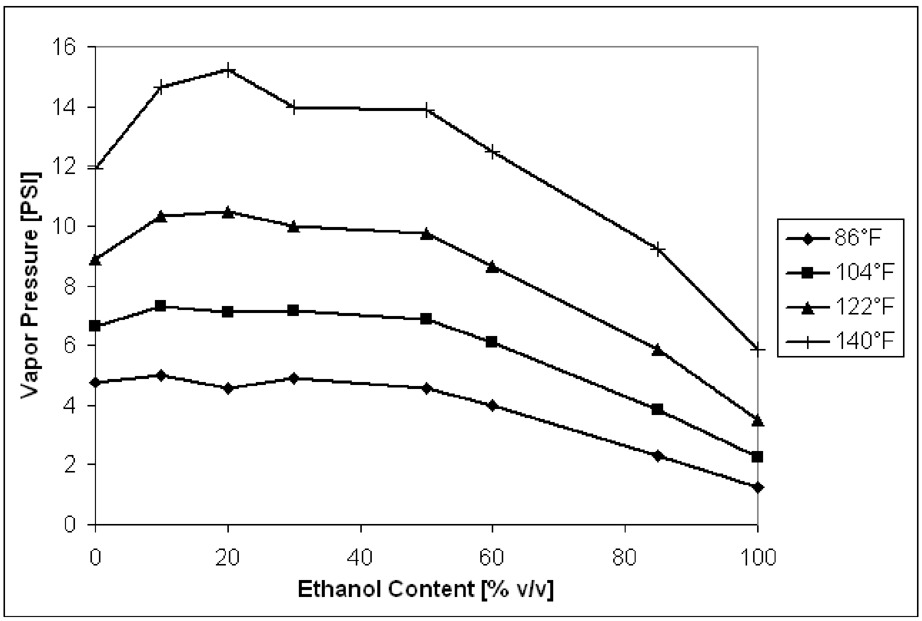


Figure 7.2.1: Vapor Pressure versus Ethanol Concentration for Several Temperatures (Kar, et al, 2008)

7.3 Fuel Energy Content

The heating value is the energy released per unit volume or mass when the fuel is burned. The lower heating value (LHV) assumes that the water created during the combustion process remains in a vapor state rather than condensing to liquid water. The higher heating value (HHV), on the other hand, assumes that the water created during the combustion process remains in the liquid state. The LHV is therefore the better measure for internal combustion engine fuels.

The LHV for neat ethanol (100% ethanol) is 26.9 MJ/kg; for E0 (gasoline), Heywood (1988) reports an LHV of 44.0 MJ/kg. Heywood (1988) also gives neat ethanol density as 0.785 kg/ℓ, and ethanol's molecular mass as 46.07 kg/kmol. For gasoline, the density is in the range of 0.72 to 0.78 kg/ℓ, and the average molecular mass is 110 kg/kmol. From this data, and assuming ideal solution behavior when mixing ethanol and gasoline, the LHV and density for E10 and E15 can be calculated and are presented in Table 7.3.1 below.

	Ethanol (neat)	Gasoline (E0)	E10 (% v/v)	E15 (% v/v)
Density (kg/liter)	0.785	0.72 - 0.78	0.73 - 0.78	0.73 - 0.78
Lower Heating Value (MJ/liter)	21.1	31.7 - 34.3	30.6 - 33.0	30.1 - 32.3
Higher Heating Value (MJ/liter)	23.3	34.1 - 36.9	33.0 - 35.5	32.4 - 34.9

Table 7.3.1: Density and Heating Values for Neat Ethanol, Gasoline, E10, and E15

On average, the LHV of E15 is 1.9% lower than that of E10. An equivalent reduction in vehicle mileage (miles / gallon) can be expected with the implementation of E15 into the passenger car fleet.

7.4 Lubricity

The few studies to date on gasoline lubricity show mixed results on the effects of ethanol, or similar oxygenate compounds, on lubricity. It appears that the constituents of the gasoline base stock more strongly influence lubricity. As of today, lubricity is not a specified property for gasoline or ethanol blends.

8. FUEL SYSTEM MATERIALS AND DEGRADATION MECHANISMS

Automakers and OEM material suppliers were studying improved materials for fuel system components as early as the late 1970s. Problems were being experienced due to the increased aromatic content of unleaded fuels and the anticipation of the increased use of alcohols (both ethanol and methanol) in fuels (SAE 790661). The automotive industry also had to consider the requirement for SHED testing, beginning in 1991.

During this time period, the effect of fuel constituents such as aromatics on fuel system material compatibility was already well understood, and researchers were developing methods to predict swelling of materials based on the solubility parameter concept (SAE 800791). Research focused primarily on the volume swell of fuel system materials (SAE 800789) as well as improvements in fuel system materials, such as re-compounding Butadiene-Acrylonitrile Rubber (NBR) Vulcanizates (SAE 790664). By 1986, research began to focus on material permeability such as re-compounding Acrylonitrile (ACN) polymers (SAE 860220). Such work continued in the mid 1990s, focusing on Permeation of Fluoropolymers (SAE 930992). It is clear from this technical literature that the auto manufacturers, and their suppliers, were conducting materials research and evaluations for materials compatibility and permeability decades ago. In many cases, this work included fuels containing methanol, which is much more aggressive to most elastomers than ethanol. This work, along with increasingly stringent evaporative emissions standards, led to the incorporation of more robust fuel system materials compared to pre-1980s vehicles.

Many materials have been used in the fuel systems of light duty vehicles, small engines, and off-road equipment. Limiting the scope to light duty vehicles, including passenger cars and light trucks, from the target range of model years (1994 to 2000), it is impractical to complete a comprehensive survey of the materials that might be exposed to liquid fuels. However, there are several materials known to be in common use in this timeframe.

It is important to note that, since the vehicles in the study period of this analysis are no longer under legislative control for evaporative emissions, the primary risk to this portion of the fleet centers around the onset of gross leaks when the general fuel formulation changes from E10 to E15. The primary drivers for leaks are corrosion of metallic materials, swelling of elastomers, and hardening of plastics. The Minnesota study, while material coupon based, still gives indicative reactions of the key fuel system materials and their reaction to changes in ethanol content. Based on the physical test results it can be generally concluded that the materials in use during this time period are unlikely to undergo significant changes when exposed to E15 compared to when they are exposed to E10, which is the most common fuel blend in most regions of the U.S.

Table 8.1 contains a list of the most common materials used in fuel system components and their compatibilities with E10 and E15. This table, although containing references similar to the Minnesota study, summarizes a broader Ricardo system and component review. It is not intended to be inclusive of all historical and in-development materials used in fuel systems, but representative of the period in review.

Common Fuel System Materials - Locations and Compatibility						
Material Class	Materials Used in Fuel Systems 1990-Present	Fuel System Component Containing this Material	Compatibility Issues			Directional Change from E10 to E15
			with E0	with E10	with E15	
Elastomers	Nitrile Rubber	Fuel pressure regulator, Hydraulic actuator seals, Hydraulic pump seals, Water pump seals, Carburetor seals, Transmission seals	Fully Compatible	Fully Compatible	Fully Compatible	None
	Viton	Fuel Injector O-ring	Fully Compatible	Fully Compatible	Fully Compatible	None
Plastics	Acetal	Fuel line Fittings, gas caps, fuel rails	Fully Compatible	**Minor swelling and mass loss**	**Minor swelling and mass loss**	None
	Glass Filled Nylon	MRA cap; sensor bodies	Fully Compatible	Fully Compatible	Fully Compatible	None
	HDPE	Fuel Tank	Fully Compatible	Fully Compatible	None	None
	Nylon 12	Fuel Lines	Fully Compatible	Fully Compatible	Fully Compatible	Minor absorption increase
	Nylon 6-6	Fuel Lines	Fully Compatible	Fully Compatible	Fully Compatible	Minor absorption increase
	PTFE	O-rings, gaskets, seals, and coatings	Fully Compatible	Fully Compatible	Fully Compatible	None
Metals	Aluminum	Fuel Injector	Fully Compatible	Fully Compatible	Minor discoloration	Increased discoloration
	Brass	Fuel level sensor	Fully Compatible	Minor discoloration	Minor discoloration	None
	Copper	Fuel Pump & Level Sensor	Fully Compatible	Minor discoloration	Minor discoloration	None
	Gold	Fuel level sensor	Fully Compatible	Fully Compatible	Fully Compatible	None
	Solder - 60% tin / 40% lead	Fuel level sensor	Fully Compatible	Minor discoloration	Minor discoloration	None
	Stainless steel	Fuel Injector Rail	Fully Compatible	Fully Compatible	Fully Compatible	None
	Steel - Hexivalent chrome plated	Fuel line Fittings	Fully Compatible	Minor discoloration	Minor discoloration	None
	Steel - phosphate plated	Fill pipe	Fully Compatible	Minor discoloration	Minor discoloration	None
	Steel - tin plate	Fuel Tank	Fully Compatible	Minor discoloration	Minor discoloration	None
	Steel - zinc plate	Fuel Tank	Fully Compatible	Minor discoloration	Minor discoloration	None

Table 8.1: Common Fuel System Materials

The materials within a fuel system can be divided up into three classes of materials — elastomers, metals, and plastics, with a fourth class of electronic components, such as fuel pumps and fuel level sensors. A research team at Minnesota State University-Mankato completed a comprehensive test program in 2008–2009 that looked at the compatibility of materials with a model gasoline (ASTM Fuel C – see table below), and so-called aggressive E10 and E20 blends. The materials chosen are representative of the materials used in various elements of a fuel system. These fuels, described in Table 8.2 below, were used throughout the test program. The aggressiveness of the ethanol blends indicates its propensity to attack materials or otherwise facilitate material degradation. Acetic acid is formed by partially oxidizing ethanol, so is a likely contaminant. The sulfuric acid is added to further increase the acidity of the ethanol blend. These aggressive blends represent a worst-case scenario for ethanol-gasoline fuel blends that are nominally compliant with the regulations, and follow standard testing protocol for verification of fuel systems for ethanol tolerance. These blends are more aggressive than what is commonly found in the marketplace.

ASTM Fuel C	50% toluene and 50% iso-octane (by volume)
Agressive Ethanol (see SAE J1681)	816.00 grams of synthetic ethanol
	8.103 grams de-ionized water
	0.061 grams glacial acetic acid
	0.021 grams sulfuric acid
	0.004 grams of sodium chloride
Gasoline (E0)	ASTM Fuel C
E10	90% ASTM Fuel C and 10% aggressive ethanol (by volume)
E20	80% ASTM Fuel C and 20% aggressive ethanol (by volume)

Table 8.2: Fuel Mixture Details

8.1 Elastomers

Jones, et al. (2008b) evaluated a number of elastomers for compatibility with increased ethanol concentrations. The testing involved soaking materials in one of the three fuels for 500 hours at 55°C and recording changes in volume, mass, hardness, or tensile strength. Their report describes their exposure test protocol in detail.

Several elastomers were tested for E20 compatibility, including:
- Acrylic rubber (ACM) [Hytemp®]
- Epichlorohydrin homopolymer (CO)
- Epichlorohydrin ethylene oxide copolymer (ECO)
- Fluoroelastomer (FKM) with dipolymers of VF2/HFP and 65% fluorine [Viton® A]
- Nitrile rubber (NBR) [Buna-N] with medium ACN content
- Nitrile rubber (NBR) [Buna-N] with high ACN content
- Polychloroprene (CR) [Neoprene®]

Several additional elastomers were not included in the testing because they were already qualified for use in flex-fuel vehicles up to E85, such as:
- Acrylic ethylene (AEM) [Vamac®]
- Chlorinated polyethylene (CPE)
- Chlorosulfonated polyethylene (CSM) [Hypalon®]
- Fluoroelastomer (FKM) with terpolymers of VF2/HFP/TFE and 68% fluorine [Viton® B]

- Fluoroelastomer (FKM) with terpolymers of VF2/HFP/TFE and 70% fluorine [Viton® GFLT]
- Hydrogenated nitrile rubber (HNBR)
- Santoprene® (PVDT)

Elastomer swelling results are shown in Figure 8.1.1. Several elastomers, such as ACM, CO, ECO, OZO, and FKM, exhibited additional swelling when the ethanol content was increased from E10 to E20. E15 is expected to give results that fall between the E10 and E20 results for these elastomers; therefore, some additional elastomer swelling is expected when ethanol concentrations increase from E10 to E15.

Figure 8.1.2 shows changes in elastomer durometer hardness, which was minimal with respect to the increase in ethanol content from E10 to E20. In almost all cases, there was no further degradation in durometer. Only CR exhibited further hardening at E20, but the increase was small.

The changes in tensile strength are shown in Figure 8.1.3. Two elastomers, ACM and FKM, showed a continued degradation in wet tensile strength after exposure to E20, although the results in Jones, et al. (2008b) indicate that these results may be statistically equivalent. None of the other materials showed a significant difference in response to E0, E10, or E20.

While there are some materials whose properties degrade as ethanol concentrations increase from E10 to E20, these changes are on the order of 5% to 10%. In most cases, the elastomers respond in a similar manner to E0, E10, and E20, suggesting that exposure to E15 will yield comparable results. While normal aging is likely a more significant contributor to the degradation of material performance, there remains some risk that existing aged components in light duty vehicles may fail when exposed to E15 instead of E10.

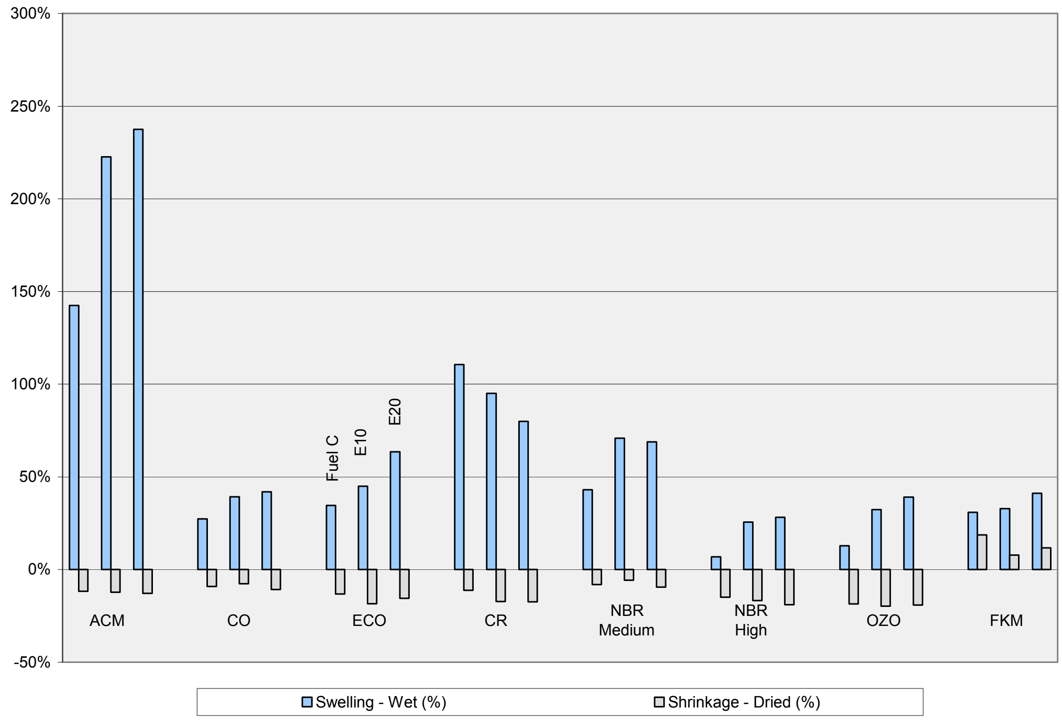


Figure 8.1.1: Elastomer Swelling

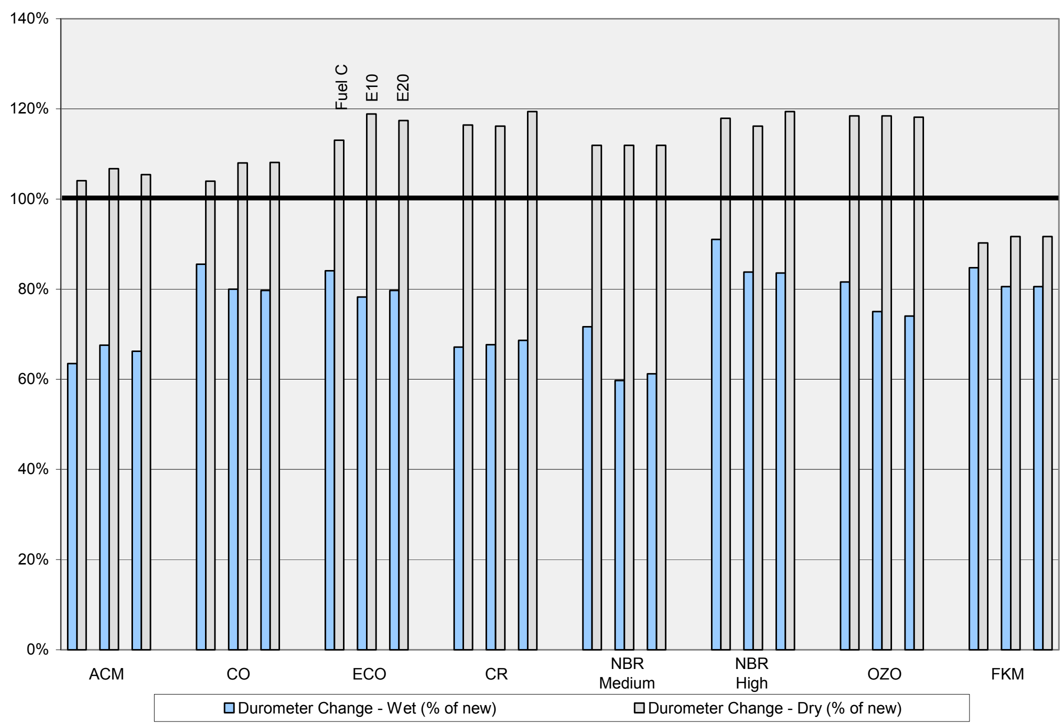


Figure 8.1.2: Elastomer Durometer Hardness

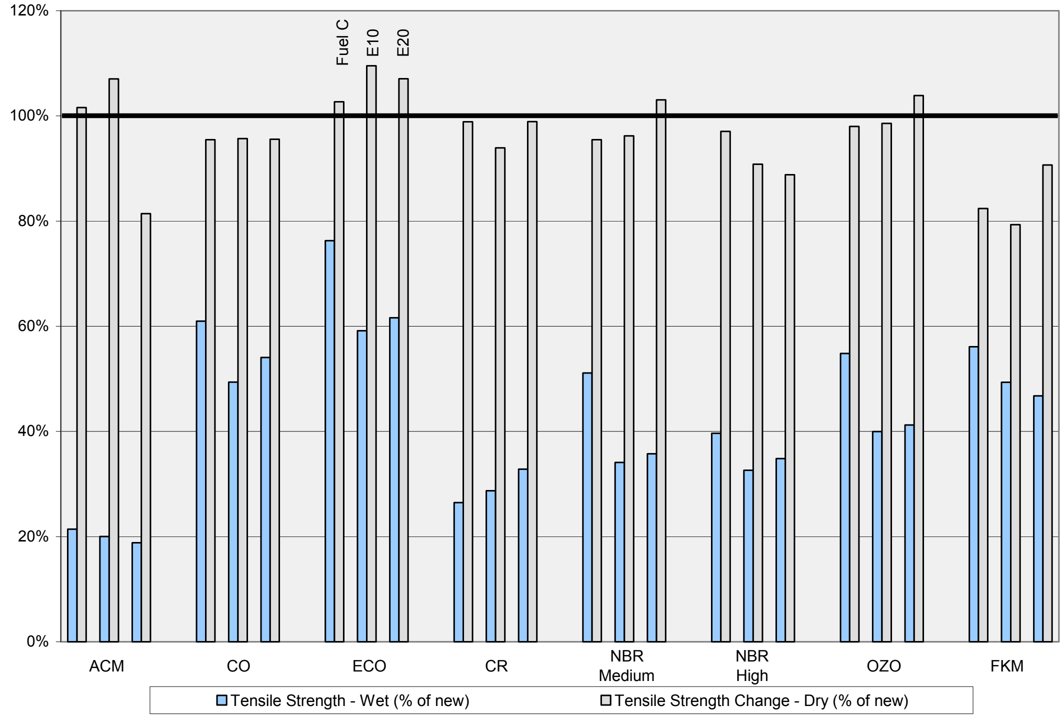


Figure 8.1.3: Elastomer Tensile Strength

8.2 Plastics

The Minnesota State University program evaluated a number of plastics for compatibility with increased ethanol concentrations. The testing involved soaking materials in one of the three fuels (E0, E10, and E20) for 18 weeks (3024 hours) at 55°C and recording changes in mass, volume, tensile strength, elongation prior to failure, and Izod impact strength. Their report provides more details on the test protocol.

Several plastics were tested for E20 compatibility, including:

- Acrylonitrile butadiene styrene (ABS)
- Polyamide 6 (PA6) [Nylon 6]
- Polyamide 66 (PA66) [Nylon 66]
- Polybutylene terephthalate (PBT)
- Polyetherimide 1010 moldable (PEI)
- Polyethylene terephthalate (PET)
- Polyurethane 55D-90A durometer (PUR)
- Polyvinyl chloride (PVC) flexible version

Of these eight plastics, the ABS, PUR, and PVC failed the testing and are not compatible with gasoline fuels of any type (with or without ethanol). These plastics are used in the automotive industry, but not in fuel systems.

In addition, several additional plastics were not included in their testing because they are already qualified for use in flex-fuel vehicles for up to E85. These ethanol-compatible plastics include:

- Ethylene vinyl alcohol (EVOH)
- Polyamide 12 (PA12) conductive version [Nylon 12]
- Polyamide 46 (PA46) [Nylon 46]
- High density polyethylene (HDPE)
- Low density polyethylene (LDPE)
- Polyoxymethylene (POM)
- Polyphthalamide (PPA)
- Polypropylene (PP)
- Polyphenylene sulfide (PPS)
- Polytetrafluoroethylene (PTFE) [Teflon®]
- Zytel® high temperature nylon (HTN)

Figure 8.2.1 shows the weight and volume change for the five plastics after soaking in the three different fuels. Both Nylons show additional ethanol absorption when exposed to E20 compared to E10, but the incremental change between E10 and E20 is quite small compared to the change between E0 and E10. Thus, additional problems arising from increasing the ethanol blend percentage from 10 to 15 are unlikely.

Figure 8.2.2 shows changes in tensile strength and Izod impact strength for the same group of plastics. None of these materials exhibit worse performance for these metrics after E20 exposure than with E10 exposure. PBT exhibited the largest effect, but the effect was positive; impact strength increased substantially.

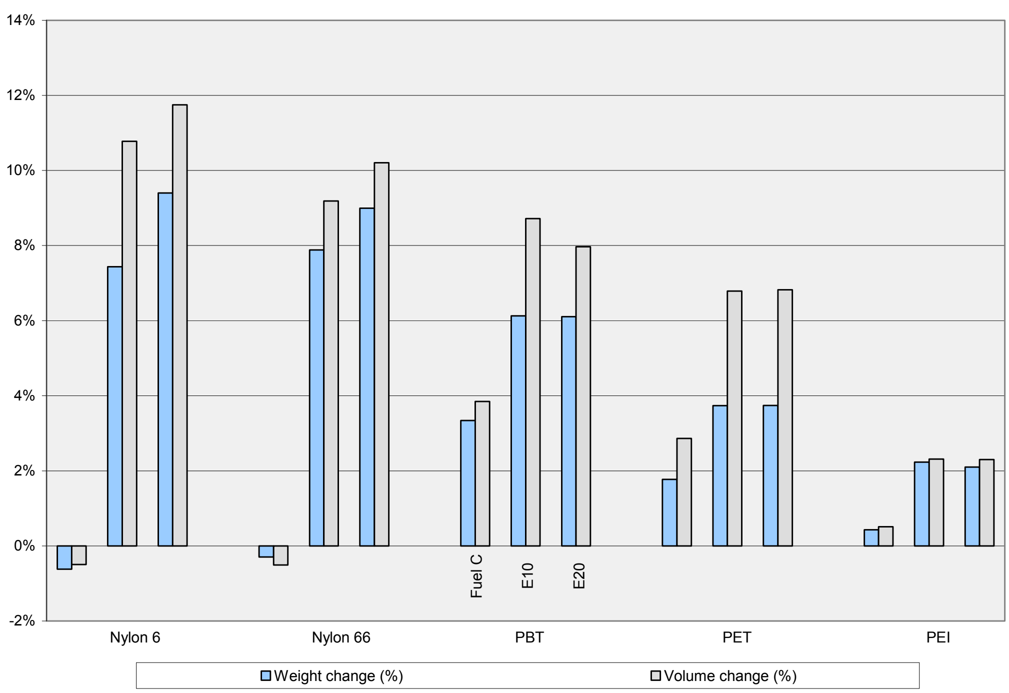


Figure 8.2.1: Plastic Weight and Volume Change

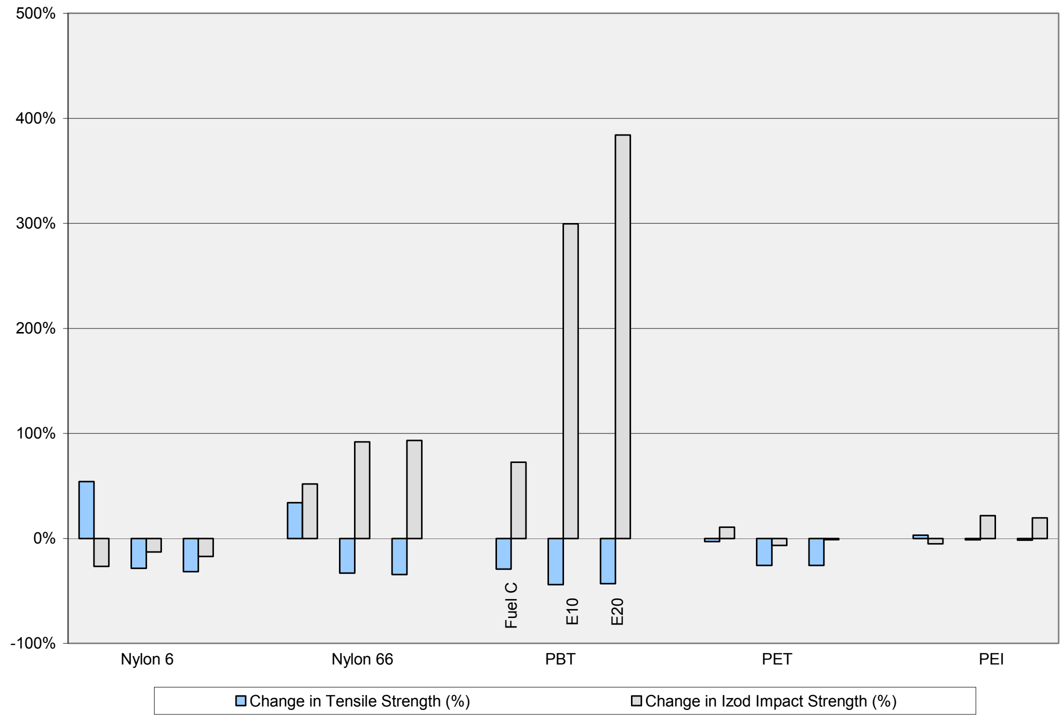


Figure 8.2.2: Plastic Tensile Strength and Izod Impact Strength

8.3 Metals

The Minnesota State University program also evaluated a number of metals for compatibility with increased ethanol concentrations. The testing involved soaking material samples in one of the three fuels for 12 weeks (2016 hours) at 45°C. Three metal samples were used for each of the three fuels: one sample was immersed in the liquid fuel, a second sample spanned the liquid-vapor plane, and a third sample remained in the vapor region. Thus, a total of nine samples were tested for each material.

Several metals were tested for E20 compatibility, including:

- 1018 steel
- 1018 steel, nickel plated
- 1018 steel, tin plated
- 1018 steel, zinc plated
- 1018 steel, zinc tri-chromate plated (hexavalent)
- 1018 steel, zinc tri-chromate plated (hexavalent free)
- 1018 steel, zinc-nickel plated
- 3003 aluminum
- 6061 aluminum
- Cast aluminum mic 6
- Brass 260
- Brass 360
- Cast iron

- Copper 110
- Lead
- 60/40 tin/lead solder
- Magnesium AZ91D
- Terne plate
- Zamak 5

All but three of the metals had corrosion rates less than 0.0025 mm/year. The three exceptions were magnesium AZ91D, Terne Plate, and Zamak 5.

Magnesium AZ91D displayed corrosion rates that increased with ethanol vapor concentration, but corrosion rates decreased with increased ethanol liquid concentration. The increase in corrosion from E10 to E20 is less than the increase from Fuel-C to E10, as shown in Figure 8.3.1, therefore an increase from E10 to E15 will not negatively affect this material.

Zamak 5 displayed mass loss rates that were more significant, and were non-linear with ethanol concentration, as shown in Figure 8.3.2. The mass loss rate when exposed to E10 was less than 1% per year but increased over 5% per year when exposed to E20 liquid. Minnesota reported visible pitting in both E10 and E20 samples, indicating this material is not completely compatible with existing ethanol mixtures.

Lastly, Terne plate showed significant mass loss rates. The mass loss rate reached 0.3% per year for E10 and 0.5% per year for E20. The corrosion rates increase fairly linearly with increased ethanol content, as shown in Figure 8.3.3, unlike the Zamak.

Based on Ricardo's experience, Magnesium AZ91D, Terne Plate (uncoated or unplated), and Zamak 5 are not found in vehicle fuel systems from the time period of 1994 to 2000.

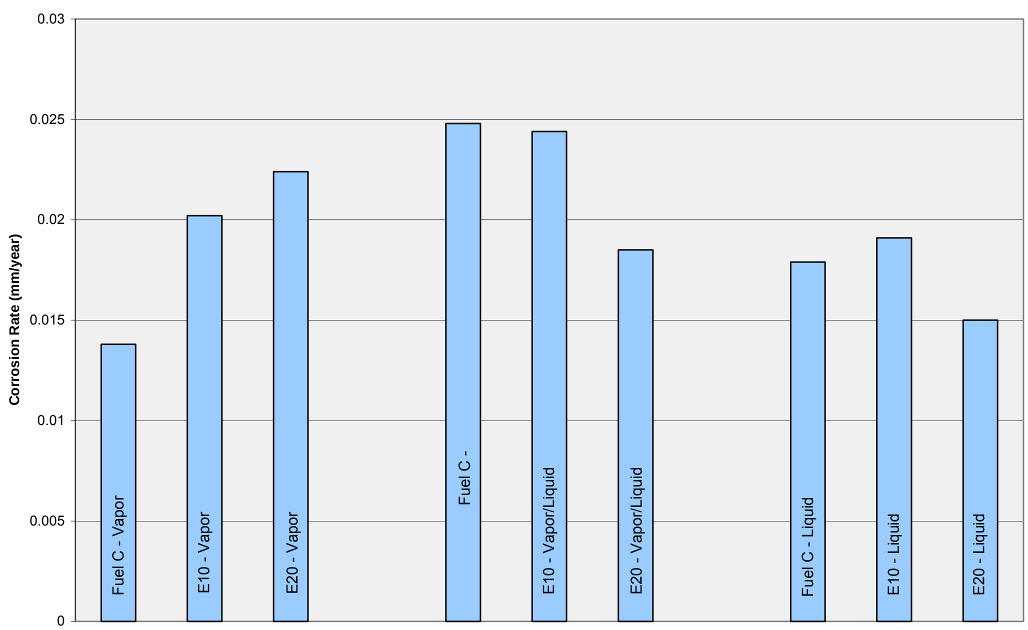


Figure 8.3.1: Magnesium AZ91D Corrosion Rates

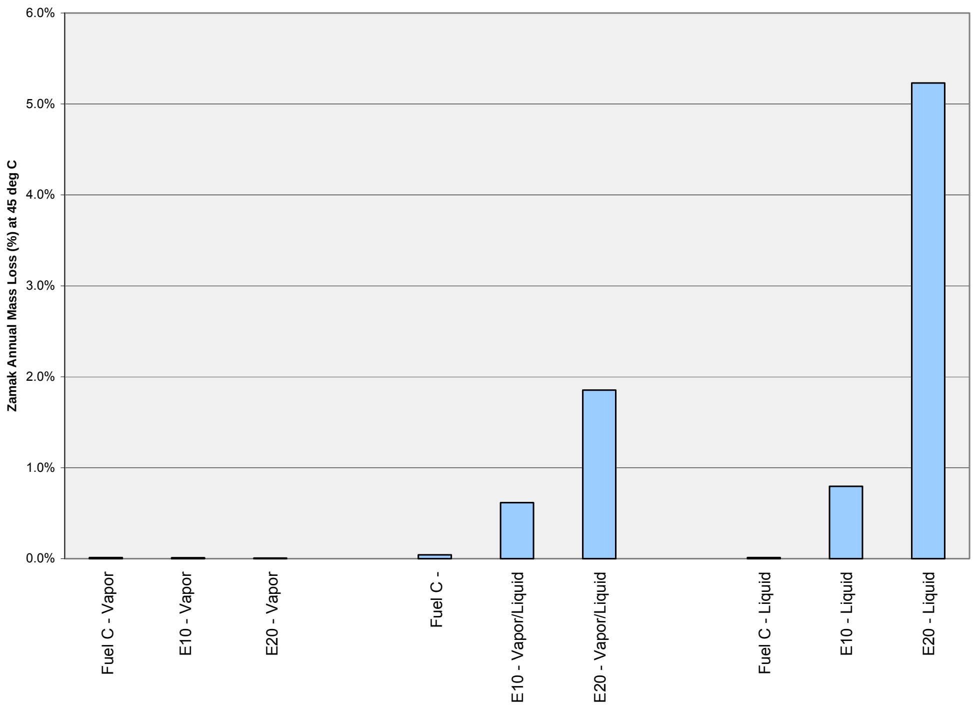


Figure 8.3.2: Zamak 5 Mass Loss Rates

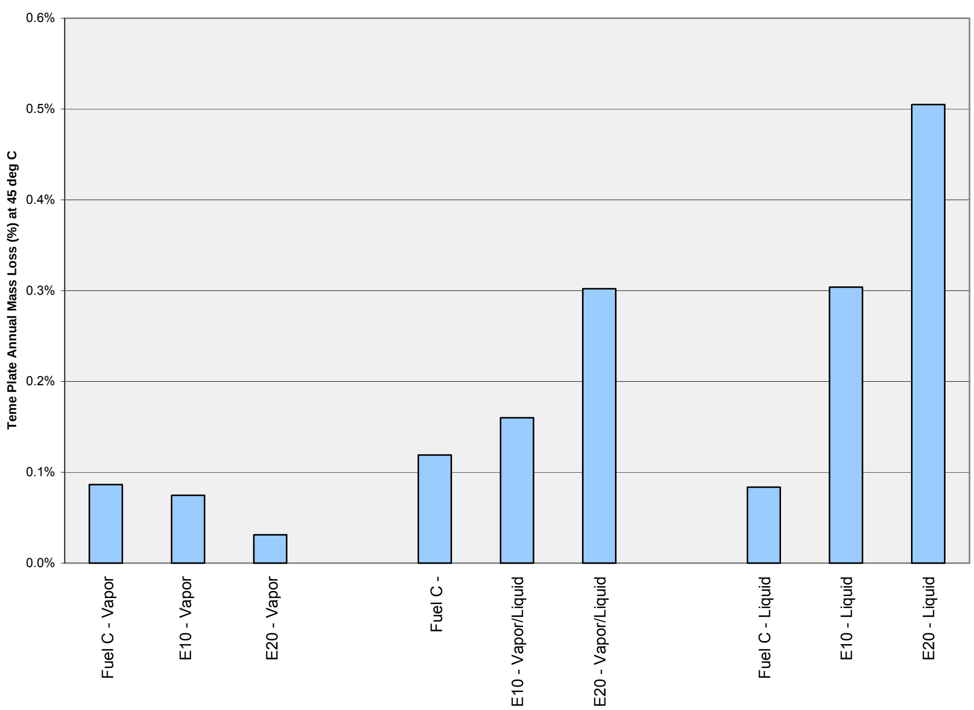


Figure 8.3.3: Terne Plate Mass Loss Rate

8.4 Electrical Conductivity

According to Delgado, *et al*. (2007), at 80 micro Siemens per meter (μS/m) the conductivity of E20 is about eight times the conductivity of E0, 10 μS/m. The study did not report any intermediate values of conductivity. Conductivity is associated with galvanic corrosion, which implies that higher ethanol concentrations could produce higher rates of corrosion under some conditions. The literature search did not reveal conductivity data for E10 or E15, so it is not possible to predict how E15 might increase rates of corrosion because of enhanced electrical conductivity. Based on a Minnesota State University test evaluating fuel pump durability in E0, E10, and E20 galvanic corrosion does not appear to be a significant factor for current fuel systems. Combining this observation with the hardware observations in Section 9, it does not appear that fuel systems from the study period of this analysis are negatively affected in terms of corrosion by E10, therefore it is not expected that exposure to E15 will cause further problems with corrosion.

9. HARDWARE OBSERVATIONS

Vehicles elected for the physical component review were representative of the top 25 platforms from 1994 through 2000 (see Section 2.4 – Vehicle Platforms). Fuel system components reviewed in this study were selected from out of service high mileage vehicles. This reclaimed hardware was used to provide a representative assessment of the current, or potential, service condition of fuel systems for vehicles in the 1994 MY to 2000 MY time period covered in this study. The high mileage criteria considered vehicles beyond their useful life of 10 years and 100,000 miles.

Fuel systems sampled in this study were procured from a reclamation service from a single geographic region – South East Michigan, U.S. No vehicle history records were available, therefore no indications of operator care or fuel use history can be ascertained. The high percentage availability of E10 fuel in the S.E. MI area indicates anecdotally that the vehicles were most likely exposed to E10 for at least a portion of their service life.

Table 9.1 lists the vehicle, mileage, and physical components that were acquired for observation. An example of some of the fuel system components, along with a description of the observed state of the components, can be found in Figures 9.1 to 9.4. The remainder of the components reviewed can be found in Appendix C.

Model Year	OEM / Make	Model	Mileage	Stock / ID#	Component(s) Reviewed
1994	Honda	Accord	Unknown	732K94	Fuel tank; fuel lines
1994	Toyota	Camry	Unknown	077H94	Fuel tank; fuel lines
1995	Ford	Escort	127781	6114C	Fuel tank
1996	Dodge	Ram Truck	200013	5946C	Fuel tank
1997	Dodge	Caravan	Unknown	N/A	Fuel tank; fuel lines; fuel rail; injectors
1997	Pontiac	Grand Prix	221487	6032C	Fuel tank; fuel lines; fuel rail; injectors
1998	Ford	Explorer	153196	5834C	Fuel tank; fuel lines; fuel filter section
1998	Ford	Taurus	138823	6220C	Fuel lines; fuel rail; injectors; fuel filter section
1998	Chevrolet	Malibu	102709	6255C	Fuel tank ; fuel lines; fuel rail; injectors
1998	Toyota	Camry	Unknown	033K98	Fuel tank; fuel lines
1999	Honda	Civic	Unknown	561K99	Fuel tank; fuel lines

Table 9.1: Legacy Vehicle Information and Reviewed Components

Figure 9.1: Fuel Tank Assembly, 1994 Honda Accord (ID# 732K94)

Figure 9.1 shows a fuel tank assembly from a 1994 Honda Accord. This is a steel tank with polymer coating (similar to that used on Honda fuel lines). No internal corrosion was observed, most likely as a result of the internal plating material used. Minor external corrosion was present, but there were no perforations into the tank. The fuel level sensor was mounted separate from the fuel pump. There was a gasket interface to the fuel pump and sensor mounts. No corrosion was seen on any internal components.

Observations of the acquired fuel tank assemblies showed that many different types of tanks were used on vehicles manufactured during the study period, even by the same manufacturer. Tanks made of plastic did not show any external or internal corrosion, except when the fuel pump and fuel lever sensor assembly was hard mounted to the tank (ie. no seal). Some of the steel tanks had an external coating, which reduced the amount of corrosion that occurred. The steel tanks that did not have an external coating had high levels of corrosion on the outside surface of the tank. The steel tanks that had internal coatings showed no signs of corrosion. Steel tanks that did not have internal coatings resulted in minor corrosion on some of the internal components. Many of the tanks used different types of sealing materials at the interface of the tank and the fuel pump assembly. None of these seals appeared to be damaged.

Photos of fuel tanks from the other end of life vehicles can be found in Appendix D.

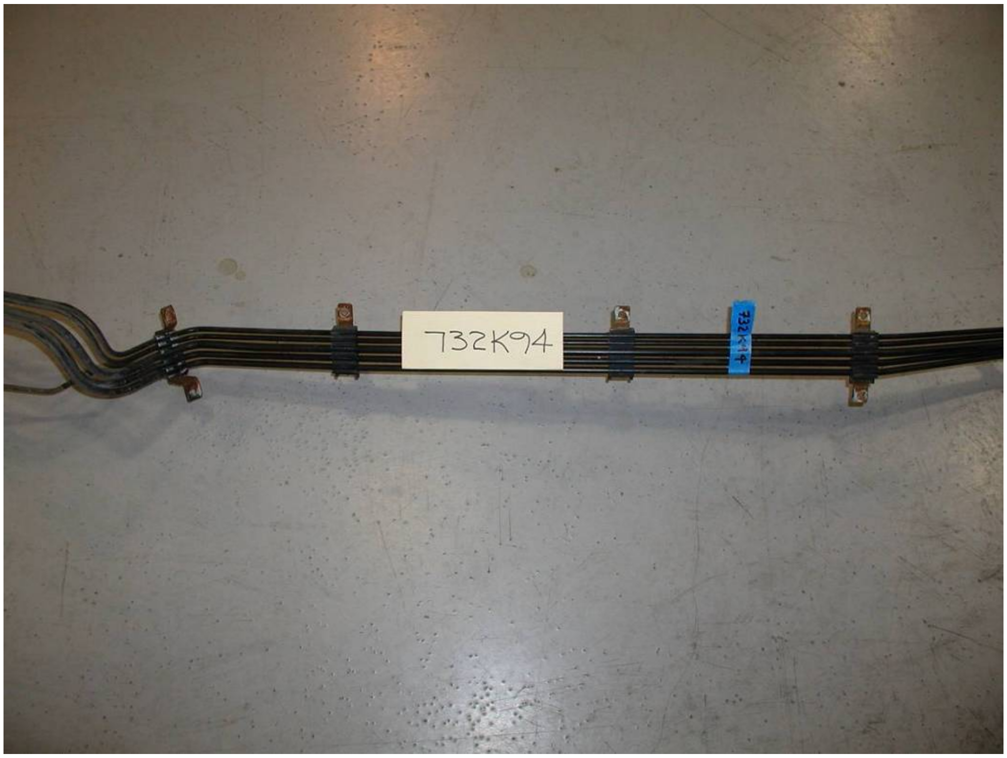


Figure 9.2: Fuel Line Bundle, 1994 Honda Accord (ID# 732K94)

Figure 9.2 shows fuel lines from a 1994 Honda Accord. The fuel lines are made of steel and have a nylon coating. It was observed that there is some loss of coating adhesion and minor corrosion originating at the fittings.

Most of the fuel lines acquired were made of steel. Some were coated, some were plated, and some were bare metal. Varying levels of corrosion were present on all the steel lines. For the nylon coated lines, very little corrosion was present, and it originated at the fittings. For the other coated lines, most of the corrosion was observed under the coating, causing the coating to peel away. For the plated steel lines, there was corrosion in select areas. The steel fuel lines that were not coated or plated were highly corroded and significant flaking was present. Two of the fuel lines acquired were made of stainless steel. These lines showed no sign of corrosion. Overall the degradation of the metallic fuel lines appeared to have been primarily caused by external influences (outside-in). Internal corrosion (inside-out) caused by fuel composition did not appear to be an important factor in the overall condition of the fuel lines.

Figure 9.3: Fuel Rail and Injectors, 1997 Dodge Caravan (ID# Caravan)

Figure 9.3 shows a fuel rail and injector assembly from a 1997 Dodge Caravan. The fuel rail is made of steel and is coated. Although corrosion was not observed on the rail, it was highly oxidized.

There were steel, plastic, and aluminum fuel rails from the legacy vehicles. Only the plated steel fuel rail showed minor signs of corrosion. This corrosion was present on the exterior surface of the rail.

Figure 9.4: Fuel Filter Sectioned, 1998 Ford Explorer (ID# 5834C)

Figure 9.4 shows a fuel filter from a 1998 Ford Explorer that has been sectioned. The filter is made of steel and is plated. Minor corrosion is present on the exterior surface.

Two fuel filters were acquired. Both were made of plated steel. Minor corrosion was present on the exterior surface of both filters, but no interior corrosion was present.

Many different materials were used for the fuel system components of the legacy vehicles. Where present, corrosion was observed on the outside surfaces of the components, not the internal surfaces. Since most of these vehicles were probably exposed to E10, it is likely that the use of E15 in these vehicles would not be a source of material degradation.

It is also interesting to note that none of the hardware in the fuel systems that were inspected from the legacy vehicles appeared to be fully compliant with enhanced evaporative emissions legislation. This was evidenced by the presence of hose clamps and spring clamps on many of the connections around the fuel tank and vapor lines. Therefore, this sample of vehicle hardware represents the vehicles that are potentially less likely to be tolerant to ethanol blends as discussed earlier in this report. These potentially less robust systems in fact show no ill effects from exposure to E10 and are not expected to experience further degradation when exposed to E15, again based on the discussion earlier in this study.

10. CONCLUSION

While performing an engineering assessment on a fleet of such magnitude as the current U.S. motor vehicle fleet, it was necessary to make certain assumptions and approximations to allow an overall assessment to be made. Due to this unavoidable circumstance, there are certain exceptions to the overall findings of this study which may occur in the field due to unpredictable conditions outside the scope of normal operation. Without investigating each and every vehicle in the fleet individually for its reaction to an E15 fuel blend, there cannot be 100% certainty that some vehicles will not observe adverse effects from the use of E15. However, using statistical analysis, the fleet was reduced to a more manageable and representative collection of platforms and manufacturers. The vehicles arising from this methodology were evaluated and served as representative vehicles for the time period.

The effect of E15 on various vehicle systems was assessed for vehicles in the 1994 to 2000 MY time period. Overall, moving from the use of E10 to E15 in the current U.S. light vehicle fleet is seen as a low risk from an engineering analysis perspective. While certain risks do remain, they are manageable and exist in vehicles that are outside the normal bounds of “standard” vehicles in the 1994 to 2000 MY timeframe.

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12. APPENDIX A – VEHICLE SALES BY MANUFACTURER

The following Figures (Figure A.1 – A.6) show the vehicle sales by manufacturer from 1995 to 2000.

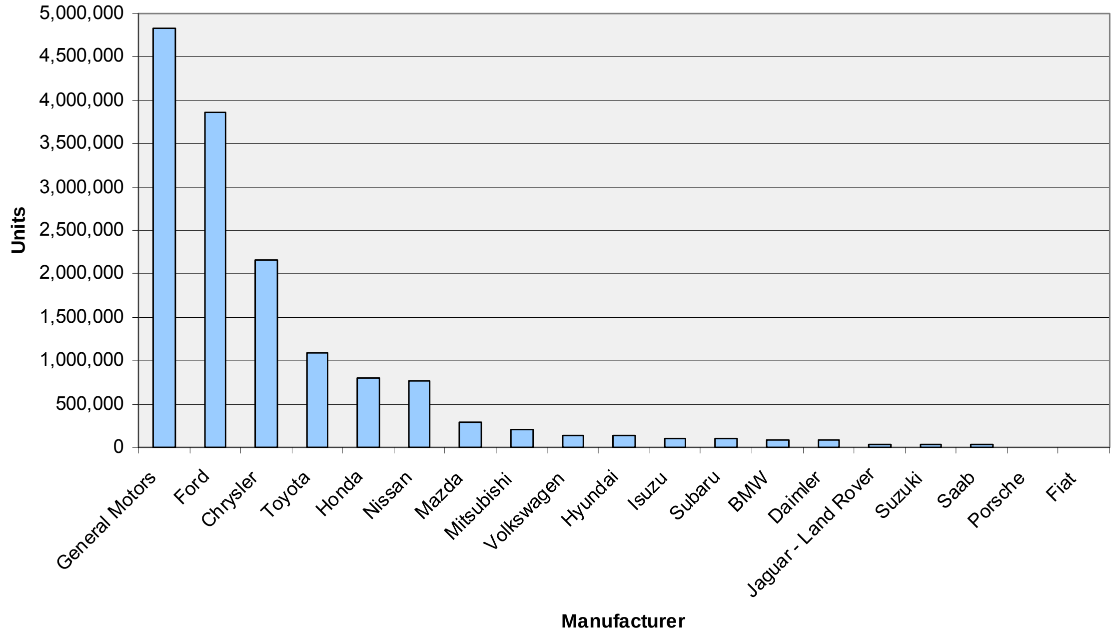

Figure A.1: 1995 New U.S. Vehicle Registrations by Manufacturer

Sales of the Big 6 automakers represented 91.7% of all vehicles sold in 1995. The Big 6 manufacturers had similar sales in 1995 as they did in 1994, with very little change in volume.

Vehicle Manufacturer	1995 Sales	% Change 1994 to 1995
General Motors	4,829,464	-3.5%
Ford	3,856,235	-0.4%
Chrysler	2,164,343	-1.8%
Toyota	1,083,351	-0.4%
Honda	794,579	0.8%
Nissan	770,904	-0.5%
Mazda	283,745	-24.4%
Mitsubishi	198,059	-14.0%
Volkswagen	133,238	-3.6%
Hyundai	132,118	6.7%
Isuzu	106,466	-2.9%

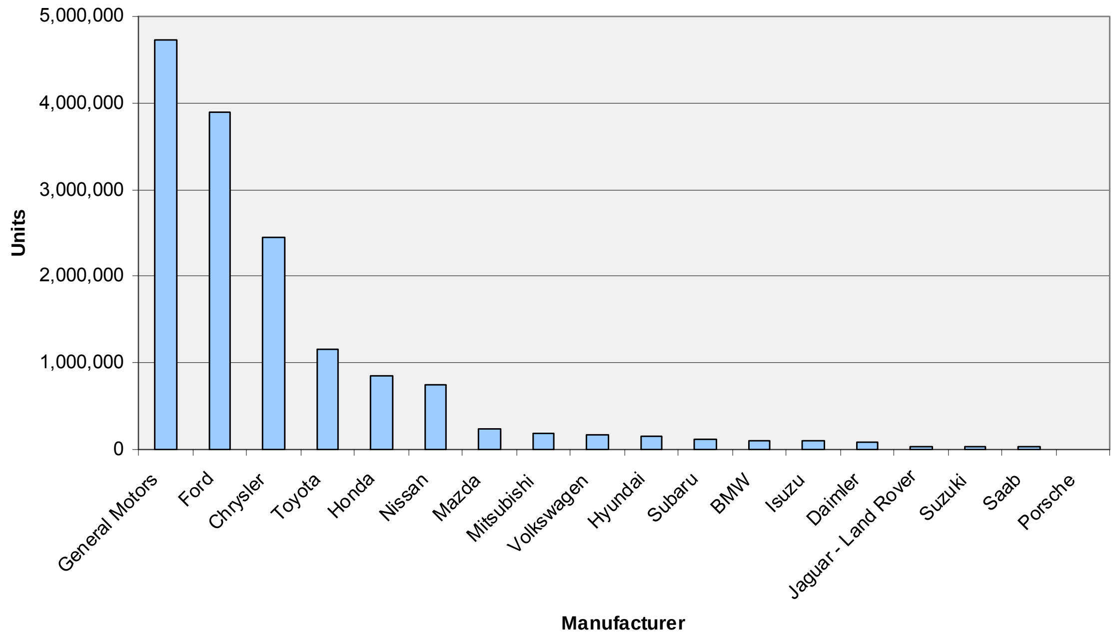

Figure A.2: 1996 New U.S. Vehicle Registrations by Manufacturer

Manufacturer sales in 1996 were quite different compared to 1995 sales. The Big 6 manufacturers represented 91.6% of total sales in the U.S. GM sales were down 2%, Nissan was down 2.7%, Ford was up 1%, Chrysler was up 13.2%, Toyota was up 7%, and Honda was up 6.2%. Volkswagen rose quickly into the top 10, showing a 22.6% increase over their 1995 sales. Nissan (#6) sold 3 times as many vehicles as Mazda (#7).

Vehicle Manufacturer	1996 Sales	% Change 1995 to 1996
General Motors	4,732,351	-2.0%
Ford	3,895,370	1.0%
Chrysler	2,450,826	13.2%
Toyota	1,159,718	7.0%
Honda	843,928	6.2%
Nissan	749,763	-2.7%
Mazda	238,285	-16.0%
Mitsubishi	187,126	-5.5%
Volkswagen	163,286	22.6%
Hyundai	144,742	9.6%

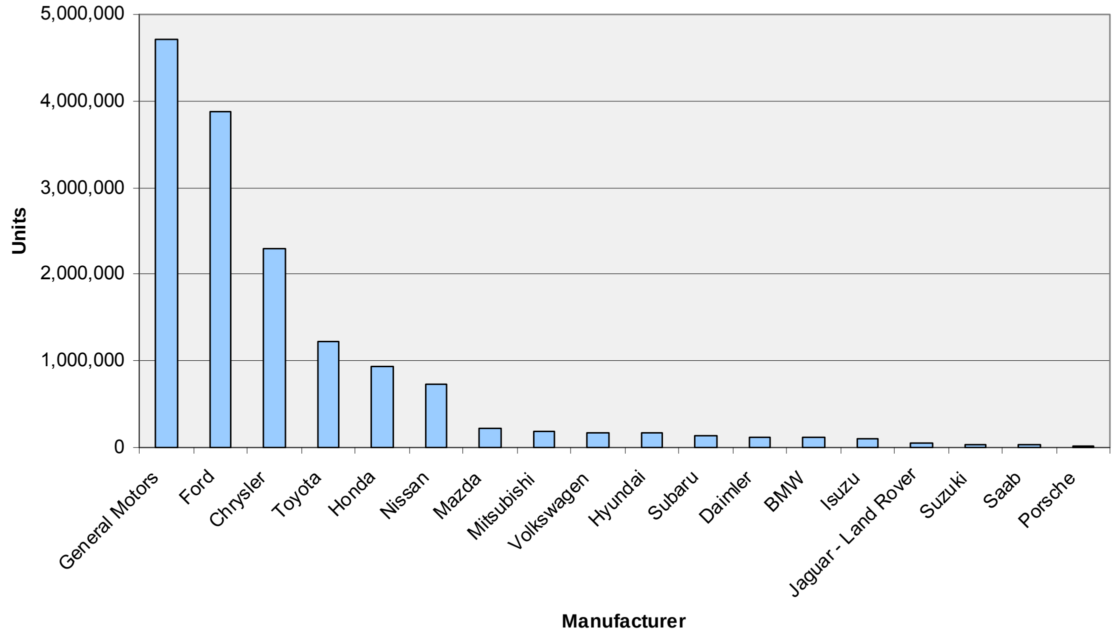

Figure A.3: 1997 New U.S. Vehicle Registrations by Manufacturer

Although the total number of vehicles sold in 1997 did not change from 1996, the distribution across manufacturers differed greatly. The Big 6 manufacturers continued to make up a large percentage of the total U.S. sales (91.1%). General Motors, Ford, and Chrysler saw a decrease in sales in 1997 compared to 1996 sales, whereas Toyota and Honda had a significant increase in sales in 1997.

Vehicle Manufacturer	1997 Sales	% Change 1996 to 1997
General Motors	4,703,549	-0.6%
Ford	3,871,621	-0.6%
Chrysler	2,303,788	-6.0%
Toyota	1,230,112	6.1%
Honda	940,386	11.4%
Nissan	728,377	-2.9%
Mazda	221,840	-6.9%
Mitsubishi	189,163	1.1%
Volkswagen	172,045	5.4%
Hyundai	168,511	16.4%

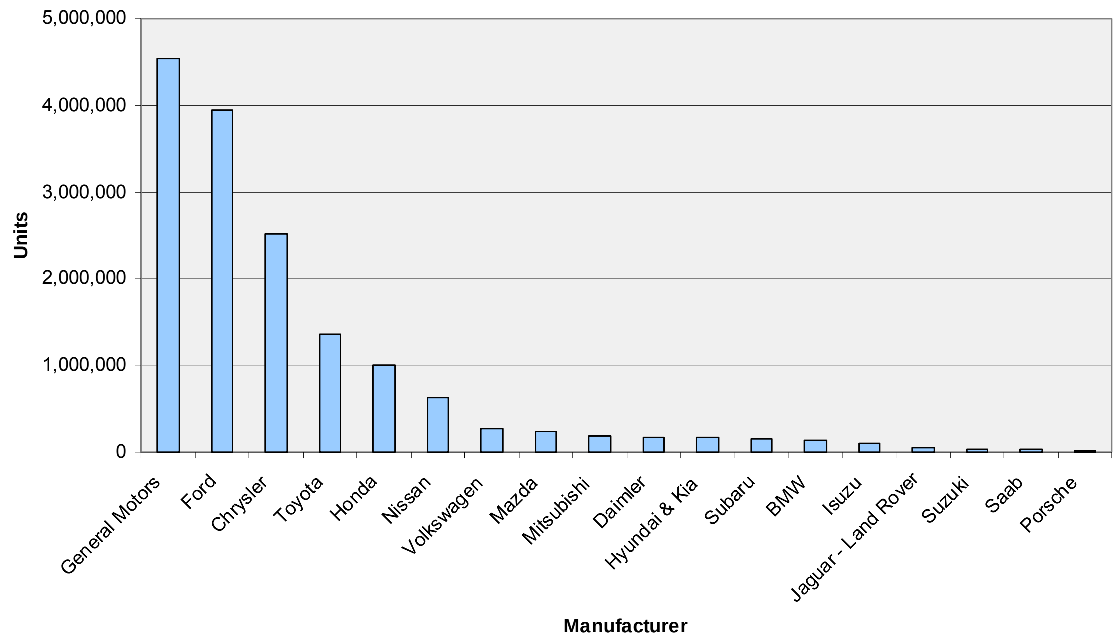

Figure A.4: 1998 New U.S. Vehicle Registrations by Manufacturer

Total U.S. vehicle sales in 1998 increased from 1997. The Big 6 maintained total sales at 90.0%. Volkswagen experienced a huge increase in sales, moving them from position #9 to #7. Hyundai fell out of the top 10, and was replaced by Daimler. Toyota and Honda continued to have strong sales increase in 1998.

Vehicle Manufacturer	1998 Sales	% Change 1997 to 1998
General Motors	4,540,870	-3.5%
Ford	3,937,946	1.7%
Chrysler	2,510,011	9.0%
Toyota	1,361,025	10.6%
Honda	1,009,600	7.4%
Nissan	621,528	-14.7%
Volkswagen	267,196	20.4%
Mazda	240,546	27.2%
Mitsubishi	190,515	10.7%
Daimler	173,185	2.8%

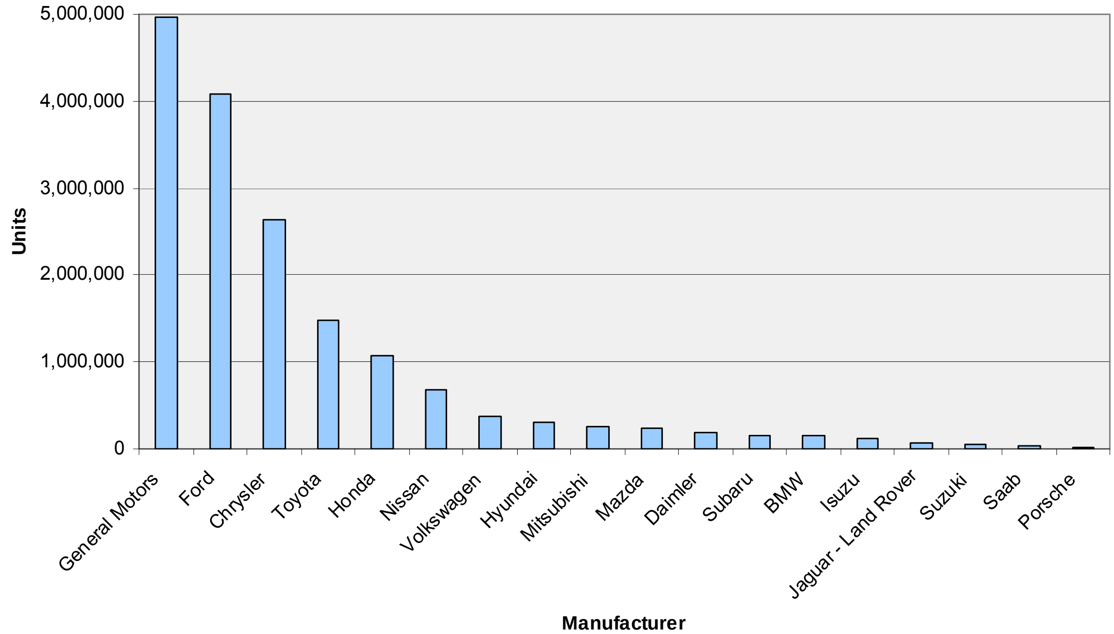

Figure A.5: 1999 New U.S. Vehicle Registrations by Manufacturer

1999 was a unique year for the top ten manufacturers, with each showing an increase in sales compared to 1998. The overall total vehicle sales in the U.S. also increased. The Big 6 continued to make up a majority of the total vehicle sales, at 88.3%. Double digit sales increases were seen for #7 to #10 manufacturers. Hyundai moved back up to #8, taking Daimler off the top 10 list.

Vehicle Manufacturer	1999 Sales	% Change 1998 to 1999
General Motors	4,965,822	9.4%
Ford	4,082,932	3.7%
Chrysler	2,638,561	5.1%
Toyota	1,475,441	8.4%
Honda	1,076,893	6.7%
Nissan	677,212	9.0%
Volkswagen	381,522	42.8%
Hyundai	298,784	24.2%
Mitsubishi	261,254	37.1%
Mazda	243,708	40.7%

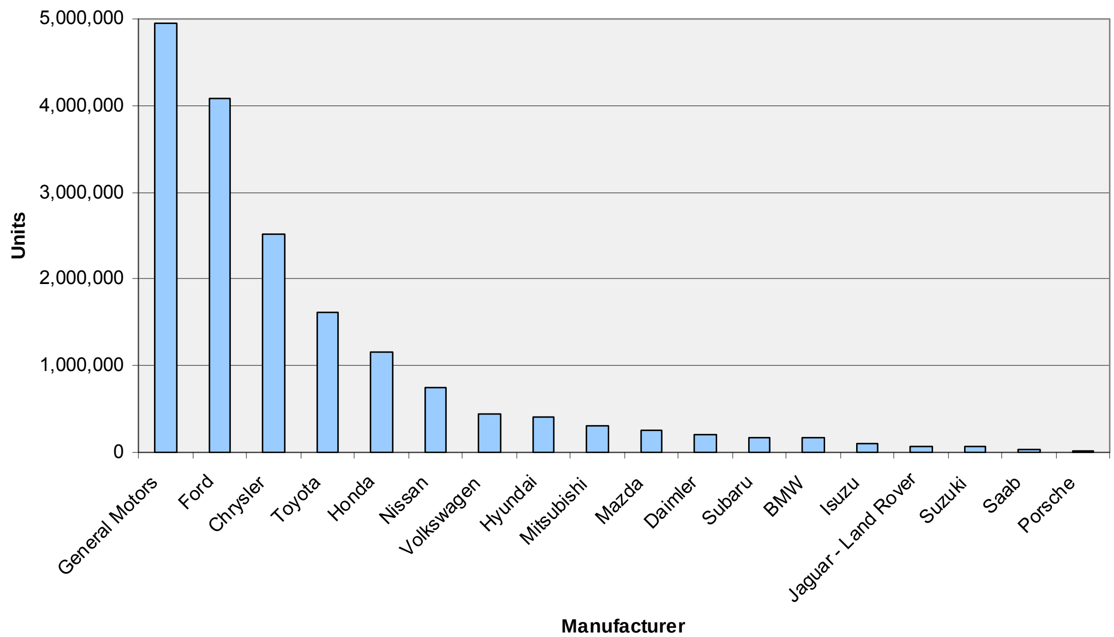

Figure A.6: 2000 New U.S. Vehicle Registrations by Manufacturer

2000 had record-high total vehicle sales in the U.S, with over 17 million units sold. The Big 6 made up 87.0% of the total sales and the top ten manufacturers remained the same as in 1999. Hyundai had another strong year, with a 35.5% increase in sales.

Vehicle Manufacturer	2000 Sales	% Change 1999 to 2000
General Motors	4,940,554	-0.5%
Ford	4,076,859	-0.1%
Chrysler	2,522,695	-4.4%
Toyota	1,619,206	9.7%
Honda	1,158,860	7.6%
Nissan	752,088	11.1%
Volkswagen	435,851	14.2%
Hyundai	404,997	35.5%
Mitsubishi	314,417	20.3%
Mazda	255,526	4.8%

13. APPENDIX B - MODEL YEAR SALES BY MANUFACTURER

The following Figures (Figure B.1 – B.6) show the model year vehicle sales by manufacturer for 1995 to 2000 MY.

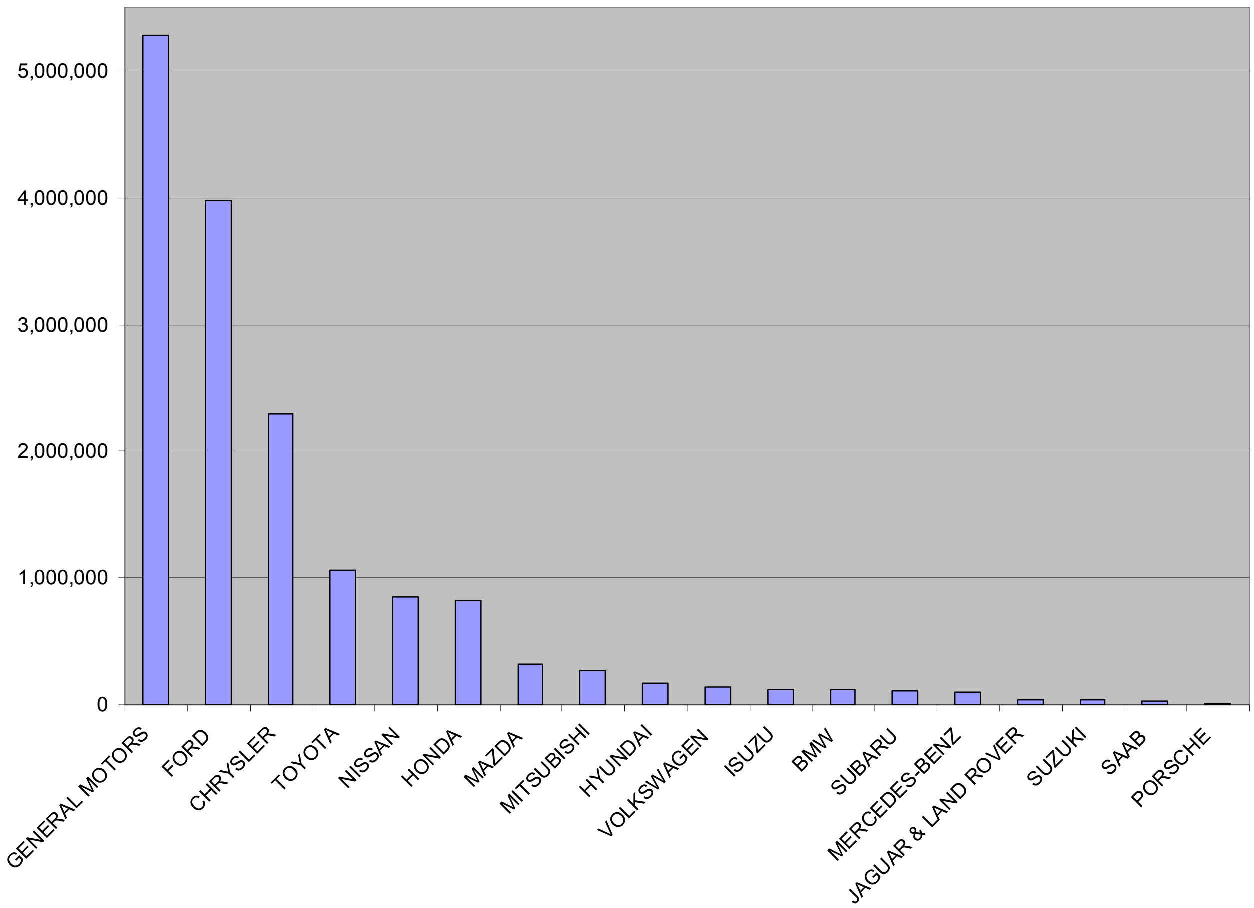

Figure B.1: 1995 Model Year Sales by Manufacturer

Vehicle Manufacturer	1995 MY Sales
General Motors	5,280,864
Ford	3,975,615
Chrysler	2,295,574
Toyota	1,065,756
Nissan	852,052
Honda	819,034
Mazda	320,319
Mitsubishi	273,206
Hyundai	173,597
Volkswagen	139,618

Sales by the Big 6 manufacturers represented 90.6% of all 1995 model year vehicles.

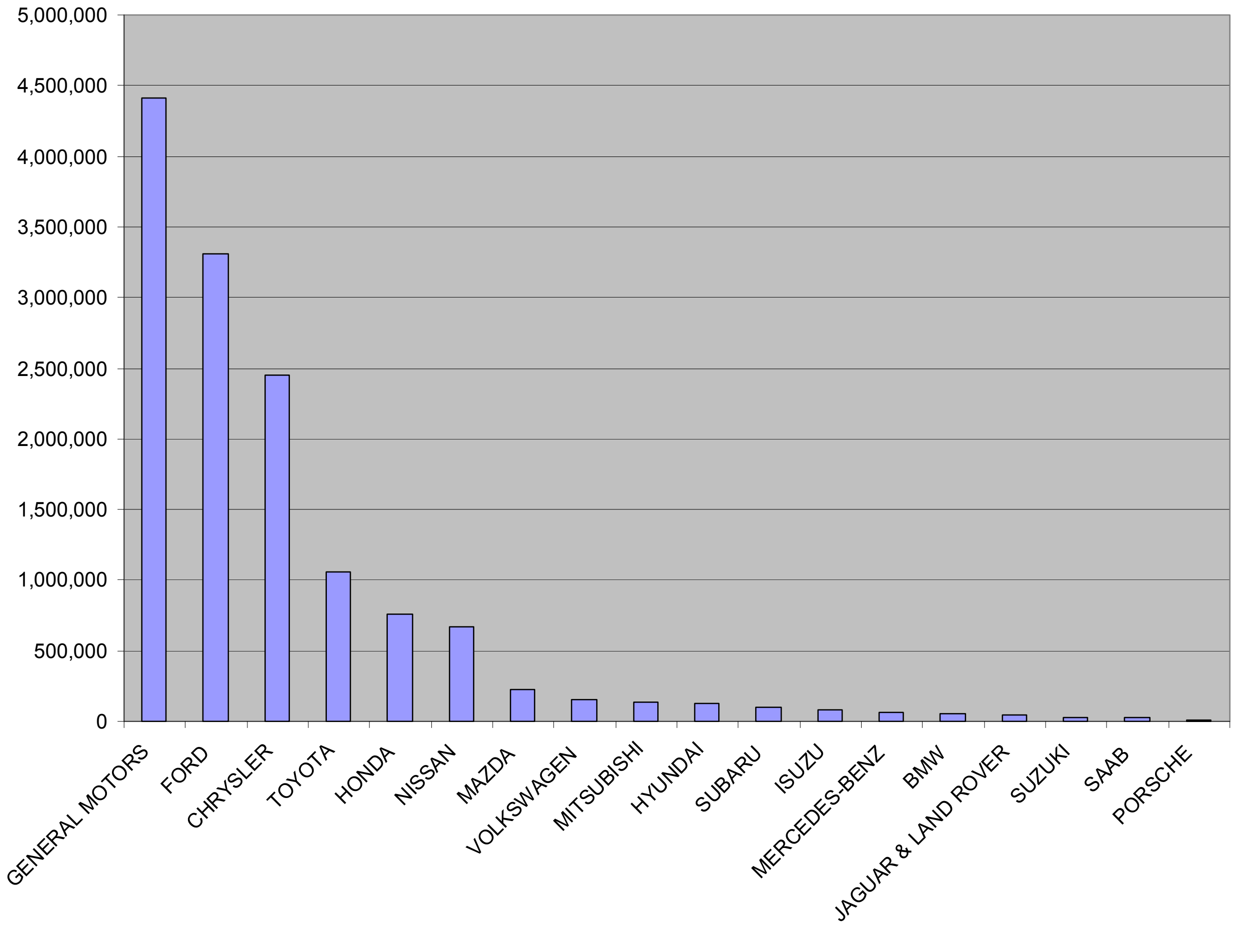

Figure B.2: 1996 Model Year Sales by Manufacturer

Vehicle Manufacturer	1996 MY Sales
General Motors	4,412,392
Ford	3,310,605
Chrysler	2,448,349
Toyota	1,054,871
Honda	757,088
Nissan	669,996
Mazda	230,031
Volkswagen	155,275
Mitsubishi	136,442
Hyundai	125,609

Sales by the Big 6 manufacturers represented 92.4% of all 1996 model year vehicles.

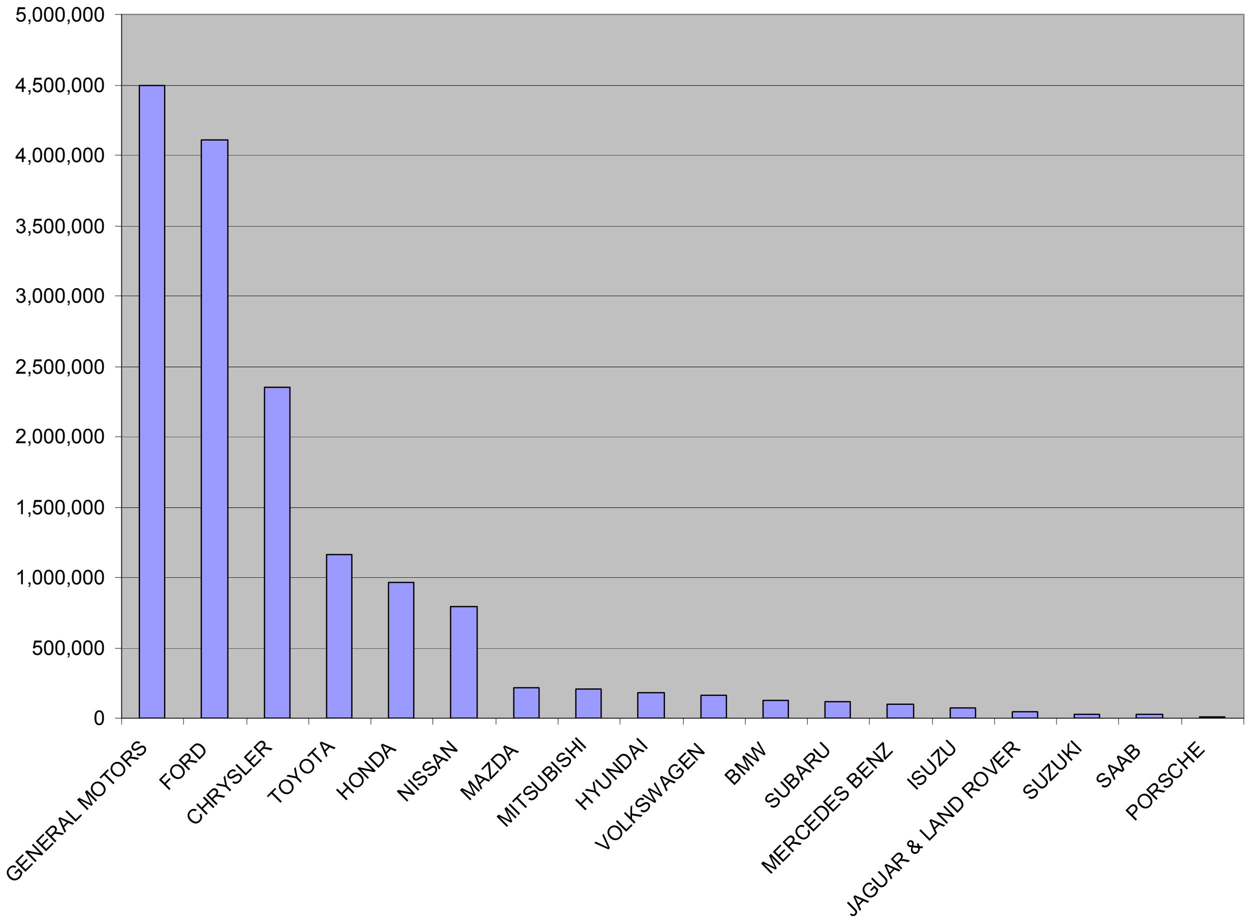

Figure B.3: 1997 Model Year Sales by Manufacturer

Vehicle Manufacturer	1997 MY Sales
General Motors	4,491,637
Ford	4,104,010
Chrysler	2,355,083
Toyota	1,158,849
Honda	960,001
Nissan	791,168
Mazda	213,110
Mitsubishi	203,237
Hyundai	176,412
Volkswagen	164,894

Sales by the Big 6 manufacturers represented 91.4% of all 1997 model year vehicles.

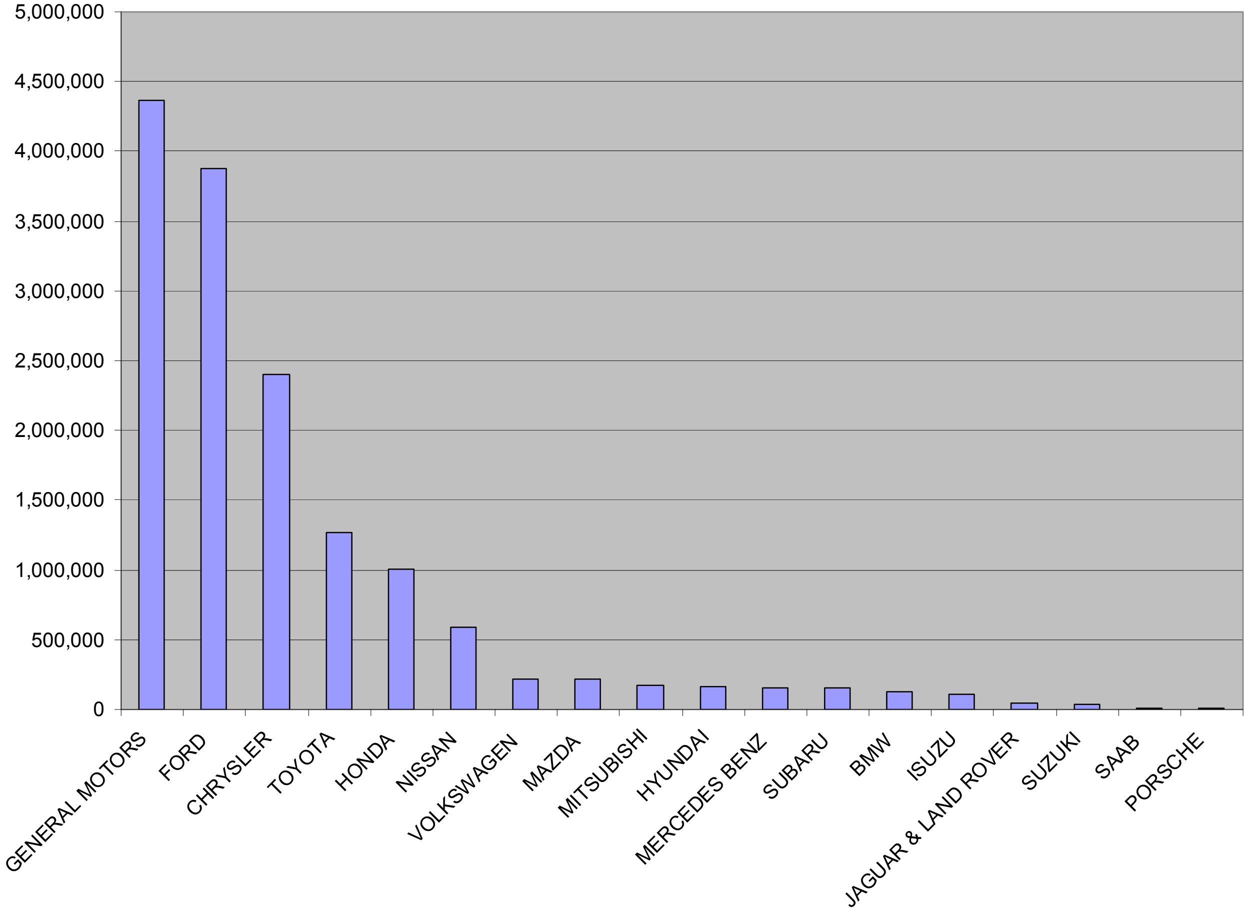

Figure B.4: 1998 Model Year Sales by Manufacturer

Vehicle Manufacturer	1998 MY Sales
General Motors	4,367,193
Ford	3,877,530
Chrysler	2,398,994
Toyota	1,269,250
Honda	1,009,144
Nissan	591,879
Volkswagen	218,857
Mazda	218,501
Mitsubishi	172,766
Hyundai	161,052

Sales by the Big 6 manufacturers represented 90.5% of all 1998 model year vehicles.

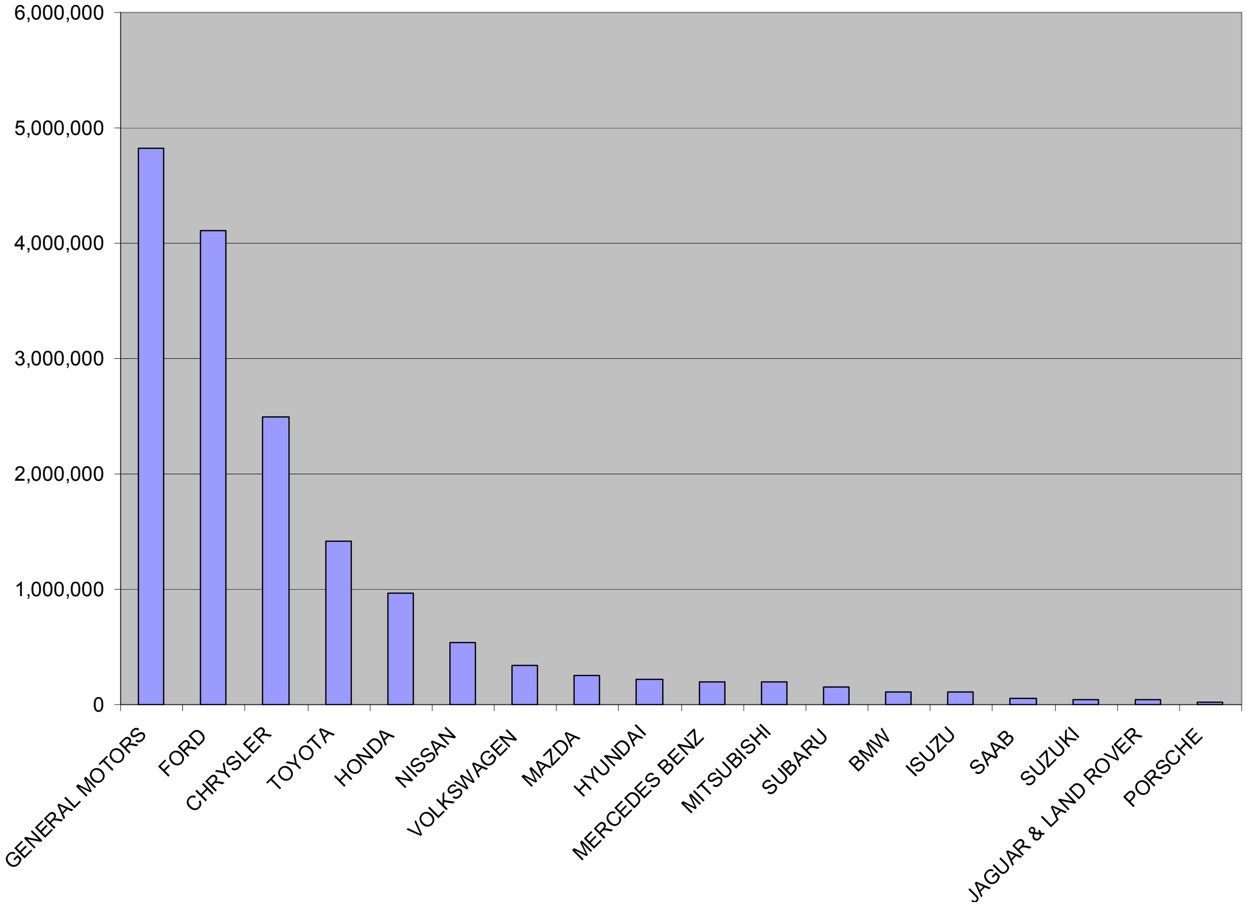

Figure B.5: 1999 Model Year Sales by Manufacturer

Vehicle Manufacturer	1999 MY Sales
General Motors	4,825,624
Ford	4,113,072
Chrysler	2,499,051
Toyota	1,418,273
Honda	962,366
Nissan	541,543
Volkswagen	340,363
Mazda	251,245
Hyundai	220,542
Mercedes Benz	197,856

Sales by the Big 6 manufacturers represented 89.0% of all 1999 model year vehicles.

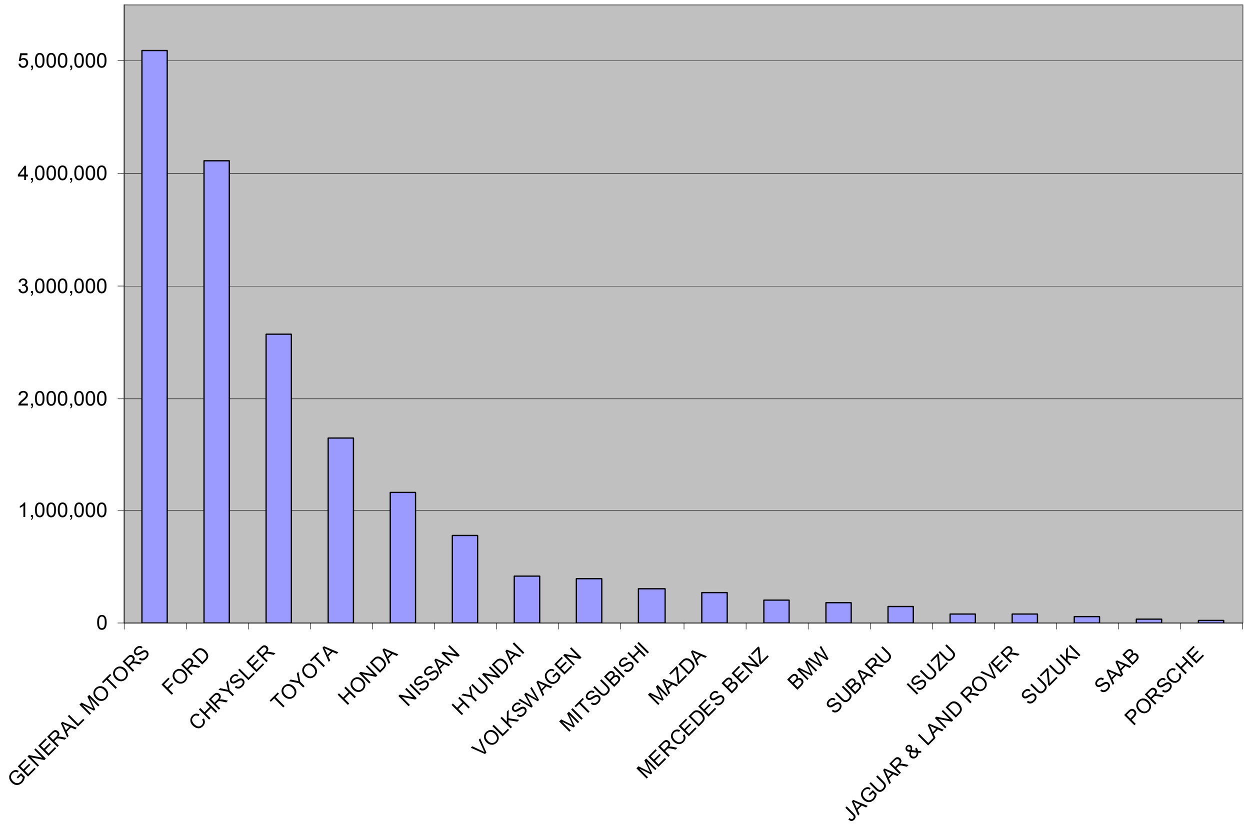

Figure B.6: 2000 Model Year Sales by Manufacturer

Vehicle Manufacturer	2000 MY Sales
General Motors	5,099,437
Ford	4,118,239
Chrysler	2,574,220
Toyota	1,643,363
Honda	1,165,470
Nissan	774,137
Hyundai	411,875
Volkswagen	398,575
Mitsubishi	301,332
Mazda	266,084

Sales by the Big 6 manufacturers represented 87.5% of all 2000 model year vehicles.

14. APPENDIX C – TIMELINE OF EPA EMISSIONS REGULATIONS

	Veh. Type	Test Proce-dure	Emission Cat.	Emission Standards	Model Year									
					1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Federal (non-NLEV)	LDV LDT1 & LDT2	FTP	Tier 0	Cert & In-use	60% max	20% max	0%	-	-	-	-	-	-	-
			Tier 1[b]	Cert[a]	40% min	80% min	100%	100%	100%	100%	100%	100%	100%	100%
				Interim In-Use	40% min	80% min	60% max	20% max	0%	-	-	-	-	-
				Final In-Use[a]	-	-	40%	80%	100%	100%	100%	100%	100%	100%
		SFTP[a]	Tier 1	Cert & In-Use[a]	-	-	-	-	-	-	40%	80%	100%	100%
	LDT3 & LDT4	FTP	Tier 0	Cert & In-use	100%	100%	50% max	0%	-	-	-	-	-	-
			Tier 1	Cert [a]	-	-	50% min	100%	100%	100%	100%	100%	100%	100%
				Interim In-Use	-	-	50% min	100%	50% max	-	-	-	-	-
				Final In-Use[a]	-	-	-	-	50% min	100%	100%	100%	100%	100%
		SFTP[a]	Tier 1	Cert & In-Use	-	-	-	-	-	-	-	-	40% min	80% min
	LDV&LDT1	FTP	CARB LEV I	Cert.	-	-	-	-	-	0.148 NMOG fleet avg[f,g]	0.095 NMOG fleet avg[f]	0.075 NMOG fleet avg.[g]	0.075 NMOG fleet avg.	0.075 NMOG fleet avg.
	LDT2			Cert.	-	-	-	-	-	0.19 NMOG fleet avg.[f,g]	0.124 NMOG fleet avg.[f]	0.1 NMOG fleet avg.[g]	0.1 NMOG fleet avg.	0.1 NMOG fleet avg.

Notes:
a Small volume manufacturer exempt until last year of phase-in.
b Light-duty vehicle (LDV) may be combined with light-duty truck 1 (LDT1) and LDT2 for Tier 1 phase-in.
c LDV and LDT1 combined with LDT2 for Supplemental Federal Test Procedure phase-in.
d Other equivalent schedules allowed.
e Fleet average derived from 50,000 mile standards.
f Not applicable to small volume manufacturers.
g Early credits available.

15. APPENDIX D – HARDWARE OBSERVATIONS

Figure D.1: Fuel Tank Assembly, 1994 Toyota Camry (ID# 077H94)

Figure D.1 shows a fuel tank assembly from a 1994 Toyota Camry. This is a steel tank with an aluminum based coating. Minor internal corrosion was observed. There was also corrosion on the fuel pump exterior casing. A polymer gasket is present at the interface of the integrated fuel pump and level sensor assembly.

Figure D.2: Fuel Tank Assembly, 1995 Ford Escort (ID# 6114C)

Figure D.2 shows a plastic molded tank from a 1995 Ford Escort. Advanced corrosion was detected on the pump assembly retainer. The fuel pump and level sensor assembly was hard interfaced to the tank. No corrosion was seen on internal components or on the outside of the tank.

Figure D.3: Fuel Tank Assembly, 1996 Dodge Ram Truck (ID# 5946C)

Figure D.3 shows the fuel tank assembly for a 1996 Dodge Ram Truck. This was a plastic molded tank with a plastic retaining ring interface to the integrated fuel pump and level sensor assembly. Corrosion was not seen on any internal components.

Figure D.4: Fuel Tank Assembly, 1997 Dodge Caravan (ID# Caravan)

Figure D.4 shows a plastic molded tank from a 1997 Dodge Caravan. This tank had a plastic retaining ring interface to the integrated fuel pump and level sensor assembly. The internal components were not observed to have corrosion.

Figure D.5: Fuel Tank Assembly, 1997 Pontiac Grand Prix (ID# 6032C)

Figure D.5 shows a steel tank from a 1997 Pontiac Grand Prix. This tank had an interior coating and did not show internal tank corrosion. None of the internal components were observed to have corrosion. The external surface of the tank was corroded. The tank had a blue o-ring interface to the integrated fuel pump and level sensor assembly.

Figure D.6: Fuel Tank Assembly, 1998 Ford Explorer (ID# 5834C)

Figure D.6 shows a steel tank from a 1998 Ford Explorer. This tank had an interior coating. No corrosion was detected on the interior of the tank or on the internal components. However, the external surface of the tank was corroded. There was a gasket at the interface to the integrate fuel pump and level sensor assembly.

Figure D.7: Fuel Tank Assembly, 1998 Ford Taurus (ID# 6220C)

Figure D.7 shows a fuel tank assembly from a 1998 Ford Taurus. This fuel tank is made of steel and has a coated interior. There is an o-ring interface to the integrated fuel pump and level sensor assembly. No corrosion was seen on internal components or on the fuel tank interior, but some external corrosion was observed on the tank.

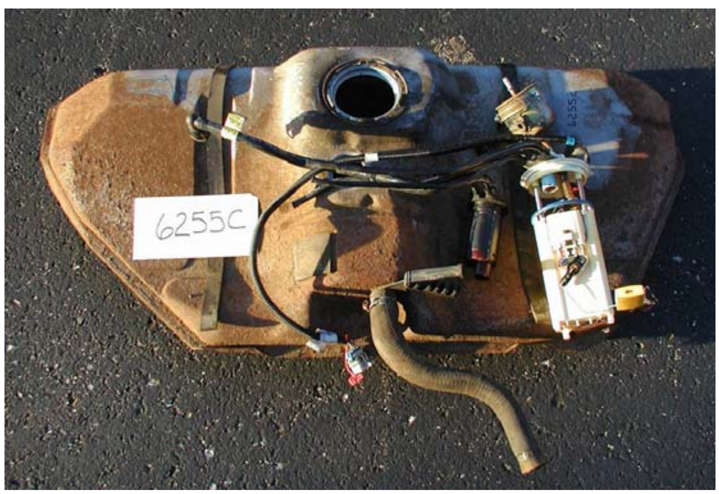

Figure D.8: Fuel Tank Assembly, 1998 Chevrolet Malibu (ID# 6255C)

Figure D.8 shows a steel fuel tank assembly from a 1998 Chevrolet Malibu. The tank interior was coated and corrosion was not detected, but the external surface was corroded. There was a blue o-ring interface to the integrated fuel pump and level sensor assembly. The internal components of the fuel tank were not corroded.

Figure D.9: Fuel Tank Assembly, 1998 Toyota Camry (ID# 033K98)

Figure D.9 shows a fuel tank assembly for a 1998 Toyota Camry. The fuel tank is made from steel and has an external polymer coating. The interior of the tank is zinc plated. There is a black o-ring at the interface of the integrated fuel pump and level sensor assembly. No corrosion was seen on the internal components or the tank interior. Very little corrosion was observed on the outside surface of the tank, mainly on the tank seams.

Figure D.10: Fuel Tank Assembly, 1999 Honda Civic (ID# 561K99)

Figure D.10 shows a steel fuel tank with polymer exterior coating from a 1999 Honda Civic. The interior of the tank is zinc plated. The fuel level sensor is mounted separate from the fuel pump. There is a gasket interface to the fuel pump and sensor mounts. Corrosion was not observed in the tank interior or on internal components. Very little corrosion was seen on the outside surface of the tank, and was mainly present on the tank seams.

Figure D.11: Fuel Line Bundle, 1994 Toyota Camry (ID# 077H94)

Figure D.11 shows steel fuel lines from a 1994 Toyota Camry. These fuel lines are coated, but corrosion was observed under the coating, which caused substantial peeling. The corrosion was not seen to go through the lines.

Figure D.12: Fuel Line Bundle, 1997 Dodge Caravan (ID# Caravan)

Figure D.12 shows fuel lines from a 1997 Dodge Caravan. These steel lines have a plated coating. There is minor corrosion in select areas, but it does not go through the lines.

Figure D.13: Fuel Line Bundle, 1997 Pontiac Grand Prix (ID# 6032C)

Figure D.13 shows steel fuel lines from a 1997 Pontiac Grand Prix. These lines are not coated or plated. Significant corrosion was observed with some flaking, causing a reduction in the outer line diameter. The corrosion did not go through the lines.

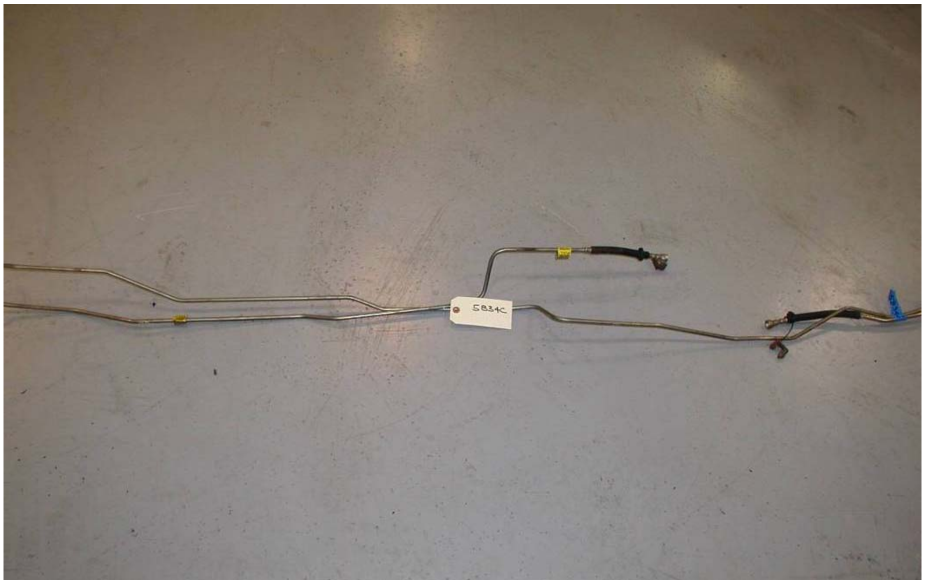

Figure D.14: Fuel Line Bundle, 1998 Ford Explorer (ID# 5834C)

Figure D.14 shows stainless steel fuel lines from a 1998 Ford Explorer. No corrosion was observed on the external or internal surfaces.

Figure D.15: Fuel Line Bundle, 1998 Ford Taurus (ID# 6220C)

Figure D.15 shows fuel lines from a 1998 Ford Taurus. These stainless steel lines did not show signs of internal or external corrosion.

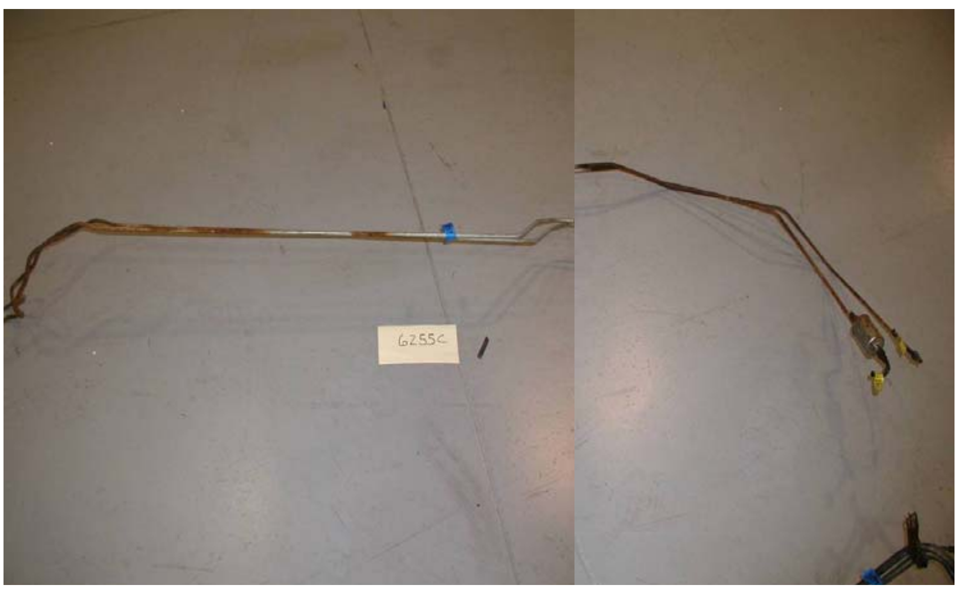

Figure D.16: Fuel Line Bundle, 1998 Chevrolet Malibu (ID# 6255C)

Figure D.16 shows plated steel fuel lines from a 1998 Chevrolet Malibu. These lines exhibited significant corrosion with some flaking, causing a reduction in the outside line diameter. The corrosion did not go through to the internal area.

Figure D.17: Fuel Line Bundle, 1998 Toyota Camry (ID# 033K98)

Figure D.17 shows fuel lines from a 1998 Toyota Camry. These steel lines had a nylon coating and did not show signs of degradation or de-lamination.

Figure D.18: Fuel Line Bundle, 1999 Honda Civic (ID# 561K99)

Figure D.18 shows coated steel fuel lines from a 1999 Honda Civic. Corrosion was present under the coating, causing substantial peeling. No corrosion went through the lines.

Figure D.19: Fuel Rail and Injectors, 1997 Pontiac Grand Prix (ID# 6032C)

Figure D.19 shows the fuel rail and injectors from a 1997 Pontiac Grand Prix. The steel fuel rail is plated and minor corrosion is present.

Figure D.20: Fuel Rail and Injectors, 1998 Ford Taurus (ID# 6220C)

Figure D.20 shows the fuel rail from a 1998 Ford Taurus. This polymer fuel rail displays no signs of corrosion.

Figure D.21: Fuel Rail and Injectors, 1998 Chevrolet Malibu (ID# 6255C)

Figure D.21 shows an aluminum fuel rail from a 1998 Chevrolet Malibu. Corrosion was not present on this component.

Figure D.22: Fuel Filter Sectioned, 1998 Ford Taurus (ID# 6220C)

Figure D.22 shows a sectioned fuel filter from a 1998 Ford Taurus. The plated steel filter has minor exterior corrosion.

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