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AAA FUEL QUALITY RESEARCH:
Proprietary research into the effectiveness of fuel additive packages in commercially-available gasoline

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Abstract

AAA conducted primary research in the area of fuel quality to better understand the impact of detergent additive packages on engine cleanliness. These additives have been used in commercially available gasoline for more than 20 years to help keep fuel system components clean and prevent the buildup of carbon deposits on critical engine components such as fuel injectors, intake valves and combustion chamber surfaces. Such deposits disturb airflow and affect air/fuel ratios, which can lead to detonation, pre-ignition, incomplete combustion, reduced fuel economy and increased exhaust emissions. [1]

In 1996 the Environmental Protection Agency (EPA) [2]established a standard that specified the lowest additive concentration (LAC) permissible for detergent additives used in gasoline sold in the United States. Those standards remain in place today. While this level of additives helped minimize certain deposits, some automakers felt the standards did not go far enough in reducing intake valve deposits.

In 2004, a group of vehicle manufacturers created the TOP TIER™ [3] Detergent Gasoline program to develop a higher standard for gasoline detergent additives that better protects against intake valve deposits and general carbon buildup.

Aside from the EPA's lowest additive concentration mandate, the TOP TIER™ Detergent Gasoline program is the only performance standard for gasoline deposit control performance, and is the focus of this report.

Research Questions:

1. Are there differences in the quantity of intake valve and combustion-chamber deposits between engines operated on TOP TIER and non-TOP TIER gasoline?
2. What issues might be experienced by motorists who operate their vehicles' engines on non-TOP TIER gasoline?
3. Can existing engine carbon deposits be reduced or removed by switching to a gasoline that meets TOP TIER standards?
4. What are the current consumer trends in purchasing gasoline?
5. Is there a retail price difference between TOP TIER and non-TOP TIER gasoline?

Key Findings:

1. The test engine operated on a TOP TIER gasoline averaged 19 times fewer intake valve deposits than when it was operated on non- TOP TIER gasoline. (based on the ASTM D6201 test - TOP TIER gasoline averaged 34.1mg of deposits per intake valve versus non- TOP TIER average of 660.6mg)
2. Based upon secondary research findings, long-term use of a gasoline without an enhanced additive package can lead to reductions in fuel economy of 2-4%, drivability issues, and increased emissions.

3. In most cases, carbon deposits can be reduced or removed from critical engine components[1] by switching to a gasoline that meets TOP TIER standards.
4. Approximately six in ten drivers (63%) believe there is a difference in the quality of gasoline sold by retailers, yet only (12%) of drivers purchase gasoline based upon its detergent additive package. The primary motivation for choosing a particular gas station is location / convenience (75%), followed closely by the price of the fuel (73%).
5. Most TOP TIER gasolines do not cost significantly more than non-TOP TIER gasoline. The average price difference between the TOP TIER and non-TOP TIER brands surveyed was three cents per gallon over a 12-month period.

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[1] Back side of intake valves, roof of combustion chamber, top of piston, and piston crown in the emissions-critical area above the top compression ring

Contents

1 Introduction

Extracting crude oil from the ground and transforming it into a product that motorists can use is a major undertaking that requires billions of dollars' of infrastructure in the form of drilling rigs, pipelines, tanker ships and refineries.

Crude oil is extracted from the ground through multiple techniques such as on-land and deep-water well drilling, oil sands extraction, hydraulic fracturing and more. Once obtained, the heavy crude oil is held in temporary storage tanks.

The crude oil is then distributed to a network of 142 [4] refineries in the U.S. primarily through pipelines, although some is transported via tanker ships. The oil is then refined into various products such as gasoline, diesel, kerosene and jet fuel through the process of distillation.

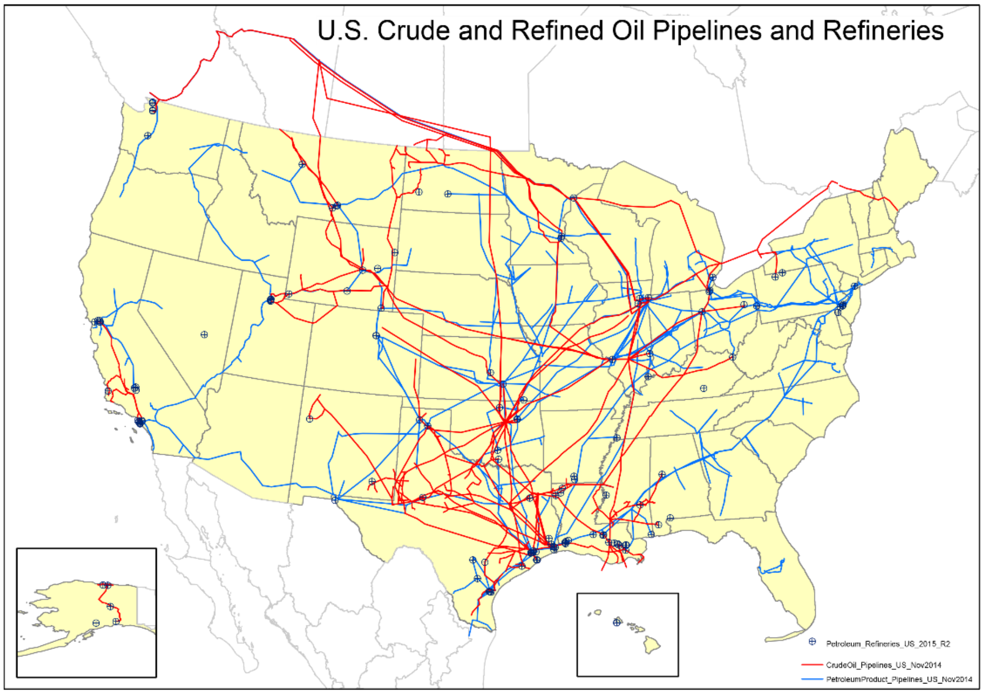


Figure 1: U.S. Crude Oil and Refined Petroleum Pipelines Image Source: AAA, U.S. Energy Information Administration dataset

Refined gasoline is transported via trucks, tanker ships and barges, or pipelines to various distribution terminals across the country. However, the refined gasoline is still not ready for use by retailers because a detergent additive packages has not yet been blended into the fuel.

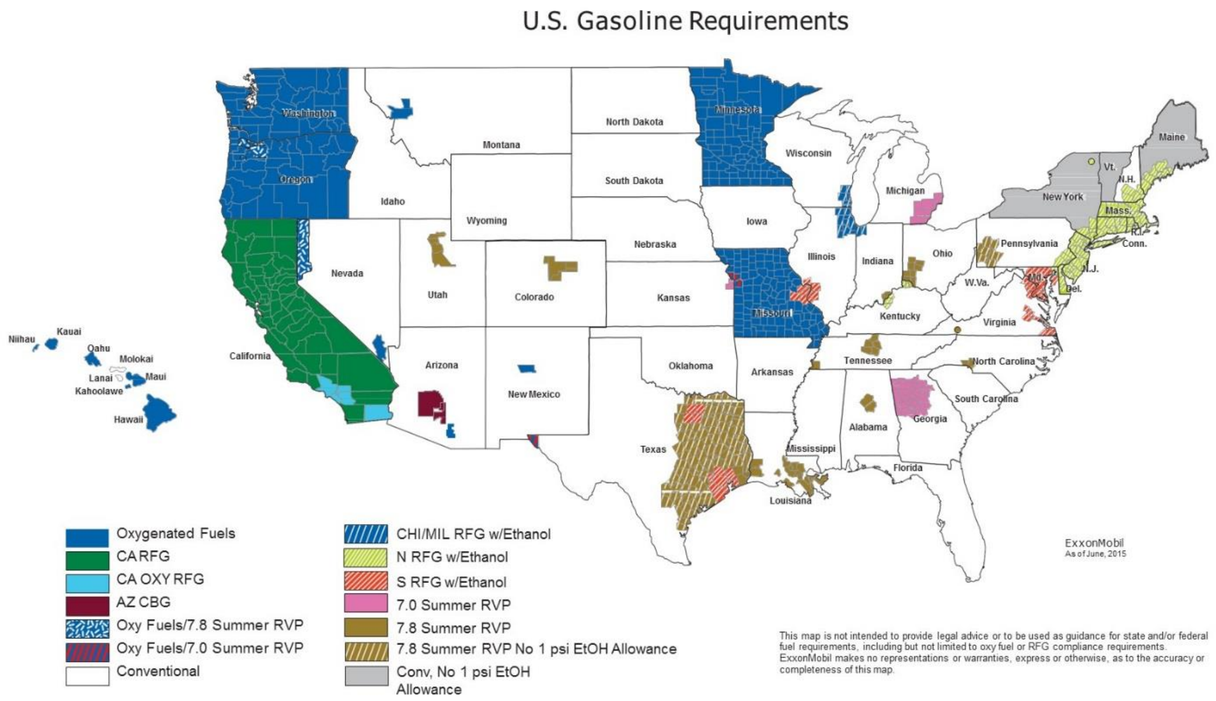
Base gasoline (fuel without additives) from various refineries is usually stored in common tanks at the distribution terminal until a retail gas station places an order for the product. This is when the individual brands are created through the addition of proprietary additive packages. As a tanker truck is being filled at the terminal, base gasoline is blended with a detergent additive package specific to that retailer.

Figure 2: Fuel distribution terminal and tanker truck Image Source: AAA

In addition to different additive packages, the makeup of base gasoline can also change based on season of the year, geographic region and local statutes. For example, many areas of the country undergo spring and fall switchovers between summer and winter base gasoline. Winter fuel has higher volatility for better cold-weather starting and running, while summer fuels have lower volatility for reduced evaporative emissions.

As shown on the chart below (fig. 3), several regions of the United States have “boutique” fuels with unique properties that are intended to reduce evaporative and exhaust emissions for vehicles in their region. These specially-refined base fuels, such as California’s Reformulated Gasoline (RFG3), are inherently cleaner due to stringent requirements on olefins, aromatics, heavy ends (high boiling point molecules) and sulfur content [5]. While RFG3 and other boutique base fuels are cleaner than most other gasolines, they will still form engine carbon deposits without proper level of detergent additives.

At the time of this report, there were fourteen different boutique fuel blends in the United States, which adds complexity to the distribution network and creates potential challenges for vehicle manufacturers when they have to track engine performance issues related to fuel type and quality.



This map is not intended to provide legal advice or to be used as guidance for state and/or federal fuel requirements, including but not limited to oxy fuel or RFG compliance requirements. ExxonMobil makes no representations or warranties, express or otherwise, as to the accuracy or completeness of this map.

Figure 3: U.S. fuel map showing custom fuel blends per region Image Source: Exxon Mobile

2 Background of Fuel Additives

Additives have been used in automotive fuels since the early 1900s to help prevent knocking and detonation.[2] Over time, additional additives were developed to address various issues such as deposit formation in carburetor venturi around the throttle plates which could cause throttle sticking. Deposit control additives were first added to gasoline in the 1970s [5] to prevent carbon deposit formation on the intake valves.

As electronic fuel injection systems began to arrive on the market in the 1980s automakers began experiencing issues with injectors sticking or becoming clogged due to contamination in the base fuel. These port-fuel injected engines sprayed fuel directly above the intake valves, which resulted in carbon build-up on the injector nozzle and backside of the intake valve. Some of these early electronic fuel injector designs were susceptible to internal deposit formation due to fuel varnishing near the injector

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[2] Knocking and detonation can be very harmful to your engine and left un-treated, can result in very costly engine repairs.

tip. When an engine is shut off, fuel trapped inside of the injector is subjected to intense heat that can promote deposit formation in the absence of an effective detergent additive.

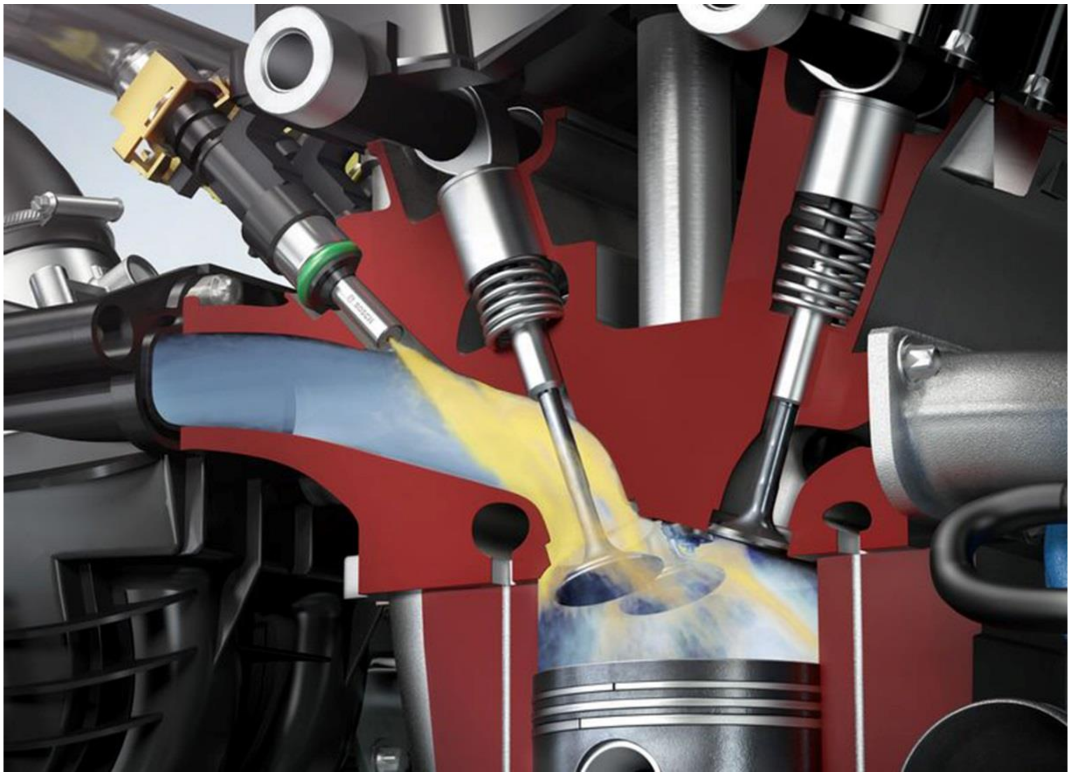

Figure 4: Port fuel injected engine illustrating fuel spray over intake valve. Image Source: Bosch

The gasoline industry responded to this issue with an aggressive detergent additive package that was very effective at removing fuel injector and intake valve deposits, but ultimately resulted in excessive combustion chamber deposits [5]. The deposits became so bad on some engines that the carbon build up resulted in mechanical interference between the pistons, valves, and cylinder heads which resulted in engine failures. The automotive and fuel industry responded with different detergent chemistry compositions that still removed fuel injector and intake valve deposits, yet limited the buildup of deposits in the combustion chamber.

Detergent additive packages are needed to promote cleaning and prevent buildup of carbon deposits on critical engine components[3]. Without detergent additive packages, the carbon deposits can readily form on the intake valves, in the combustion chamber and on the injector tip of gasoline direct injection (GDI) engines.

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[3] Back side of intake valves, roof of combustion chamber, top of piston, and piston crown in the emissions-critical area above the top compression ring.

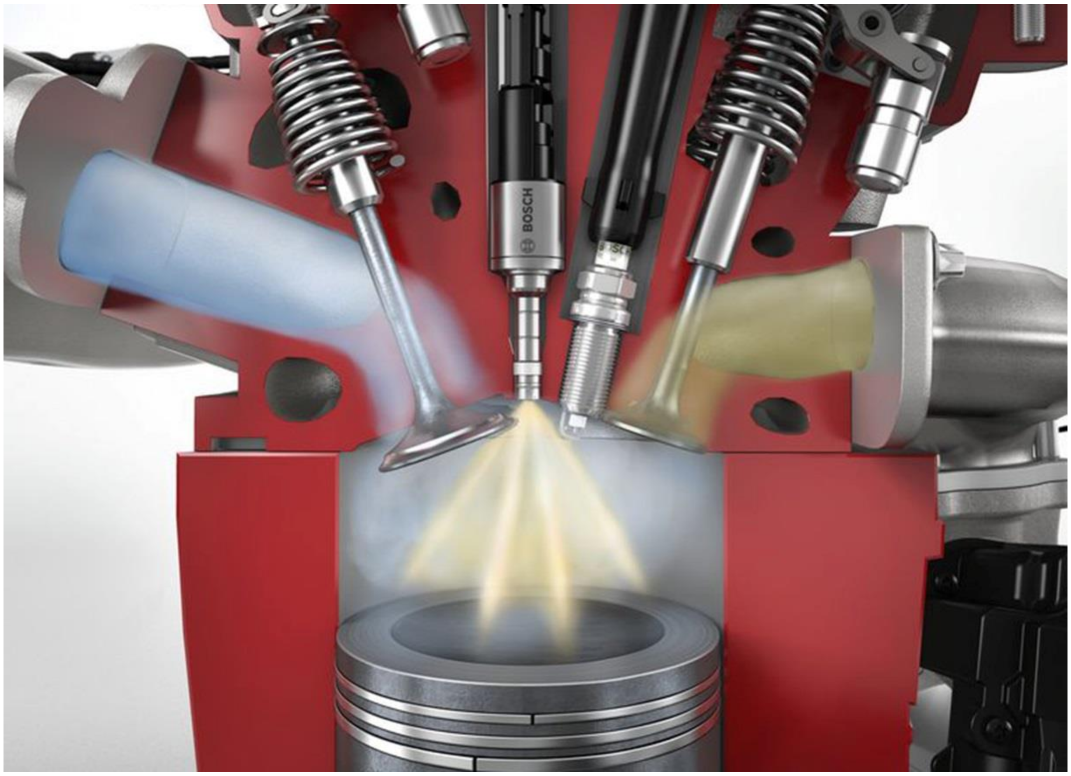

Figure 5: Gasoline direct injection engine illustration fuel spray directly into combustion chamber. Image Source: Bosch

When the EPA established the lowest additive concentration (LAC) requirements in 1996, the engine technology was relatively simple in comparison to today's modern engines. At that time, most engines featured port-fuel injection, non-adjustable cam timing and turbo-charging was not a widely used method of boosting engine performance. As a result, engines were not pushed as hard in terms of brake mean effective pressure (BMEP), engines as a whole were less efficient and the emissions regulations were far less stringent as their modern day counterparts.

Fast forward twenty years to 2016 and the engine technology has changed dramatically. Modern engines now feature high compression ratios, variable valve timing, turbocharging and gasoline direct injection. These newer engines operate very efficiently with higher effective BMEP which results in greater power output, fuel efficiency and reduced emissions.

To prevent carbon build-up, many experts have concluded that the fuel used in modern engines should contain an enhanced additive package. At least eight automakers currently recommend the use of TOP TIER [3] fuels in their owner's manual. In addition, the EPA Tier3 emissions standards [6] recognizes the need for a higher quality fuel used in current vehicle technology.

The TOP TIER fuel program is a performance standard for gasoline that enables vehicle manufacturers to ensure that engines they design and produce will continue to meet their original emissions and performance criteria over time. Fuels that are part of the TOP TIER program must undergo testing to ensure that engines do not develop excessive carbon deposits on intake valves and the combustion chamber that can impact emissions and drivability. A fuel that passes the TOP TIER certification test must have less than a 50mg carbon deposit average per intake valve once the ASTM D6201 test is complete. [3]

3 Gasoline and Detergent Additive Chemistry

Additive companies and gasoline retailers invest heavily in research and development in an effort improve additive packages for use in retail fuel. Custom additives are developed by chemists in labs where initial tests on detergent performance are carried out in a controlled environment. Additives that work well in the lab tests might then be tested in a real-world scenarios either through testing with a fleet of identical vehicles or in a controlled engine dynamometer test. Fuel companies must not only balance the chemical composition of the detergent additive packages, but also the concentration. A detergent package must be able to remove/prevent injector, intake valve and combustion chamber deposits, and it must not cause any adverse effects on engine performance and long-term reliability.

Gasoline is composed of hydrocarbons containing 4-12 carbon atoms per molecule. Specifically, five main types of hydrocarbons are present; including paraffins (alkanes), aromatics, oxygenates, naphthenes (cycloalkanes), and olefins (alkenes). In regards to paraffins and olefins, both straight-chain and branched isomers are present. For example, n-Octane is represented by the chemical formula C_8H_{18}; however, many structural isomers of n-Octane exist and are present in gasoline. Structural isomers share the same chemical formula but vary in the connectivity of atoms in the molecule. Base gasoline contains other organic compounds such as aromatic hydrocarbons, oxygenates, and small amounts of organosulfur contaminants which are typically removed at the refinery.

Various additives such as metal deactivators, corrosion inhibitors, oxygenates, and anti-oxidants are also included in gasoline. Of specific interest are detergents that reduce or prevent fuel injector and intake valve deposits. Examples include polyether amines and polyisobutylene-based (PIB) compounds such as (PIB)-Mannichs, (PIB)-amines, and (PIB)-succinimides.

The effectiveness of each detergent is different depending on the type of deposit. Polyether amines in general are effective at controlling combustion chamber deposits, but less effective with intake valve and fuel injector deposits. Both PIB-amines and PIB-Mannichs are effective at controlling intake valve deposits and slightly less effective at preventing fuel injector deposits. PIB-succinimides are moderately effective against port fuel injector deposits, but relatively ineffective at controlling intake valve deposits [7].

Each detergent listed shares a common general structure; consisting of a long hydrophobic tail comprised of a varying number of monomers, and a hydrophilic nitrogen-containing head. The purpose of the hydrophobic region of the compound is to increase solubility in a carrier fluid. The nitrogen-containing head varies depending on the specific nitrogen-containing functional group. Common functional groups are amines, Mannich (aromatic amine), and succinimides.

It is generally believed that the hydrophilic nitrogen-containing region of the detergent is responsible for preventing deposit formation by adhering to the metal surface and forming a thin hydrocarbon film. It is also believed that, at higher concentrations, detergents can remove deposits by dissolving the soluble part of the deposit, which binds to the surface of the metal [7].

4 Inquiry #1: Are there differences in the quantity of intake valve and combustion-chamber deposits between engines operated on TOP TIER gasoline and those operated on non-TOP TIER gasoline?

4.1 Objective

To better understand how detergent additive packages impact carbon deposits on engine intake valves and combustion chambers.

4.2 Methodology

AAA engaged the services of an independent (International Standards Organization) ISO 17025 certified engine testing lab to perform an ASTM standard test on a variety of fuels and provide the results. The lab routinely performs this test hundreds of times per year for fuel companies and engine manufacturers. This capability allowed AAA to compare the effects of fuel quality on the same test engine using back-to-back testing to minimize variability.

At the time of this report, the preferred method for evaluating fuel deposits is the ASTM D6201 test [8], which involves running the test fuel in a Ford 2.3L port fuel injected engine in a dynamometer test cell. This particular engine test has been an industry standard for more than 15 fifteen years because the orientation and temperature of the intake valves during the dynamometer test cycle accelerate intake valve deposit formation. This allows fuel marketers and vehicle manufacturers to screen different gasoline detergent additive packages in only 100 hours of testing.

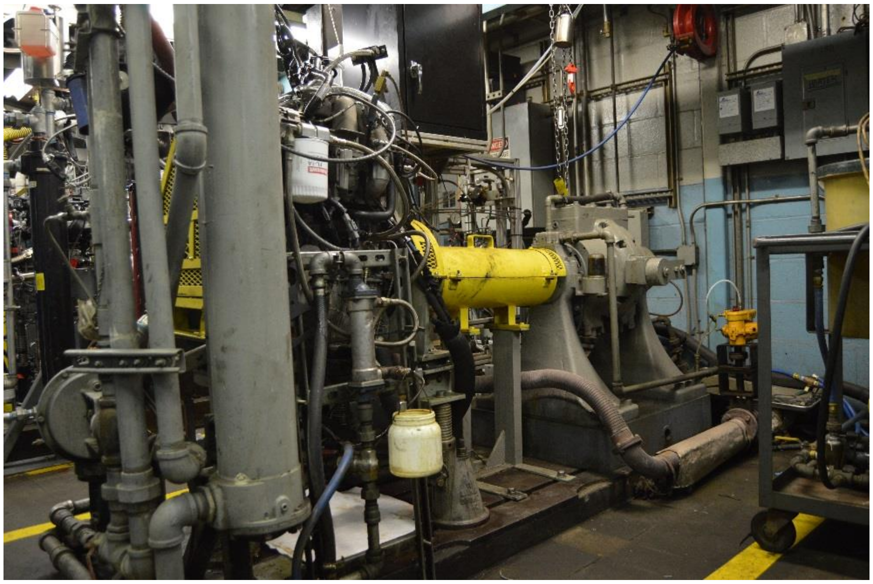

Figure 6: Ford 2.3L fuel quality research engine on dynamometer **Image Source: AAA**

Prior to testing, the engine's cylinder head is cleaned, critical clearances measured, and new intake valves are installed. All operating parameters (e.g., ignition timing, coolant temperature, intake air temperature) are tightly controlled by the test cell. The engine is operated on a specific test cycle that involves engine speeds that would typically be encountered during highway driving. The test engine is operated continuously for 100 hours which simulates roughly 4,000 miles of real-world driving.

Once the engine reaches the end of test, the cylinder head is removed, inspected and engine components are measured using precision equipment in a clean room. Engine components are visually inspected and weighed by an ASTM certified rating professional to identify the level of deposits compared to a well-established baseline. All components are also photographed to show the build of carbon deposits post-test.

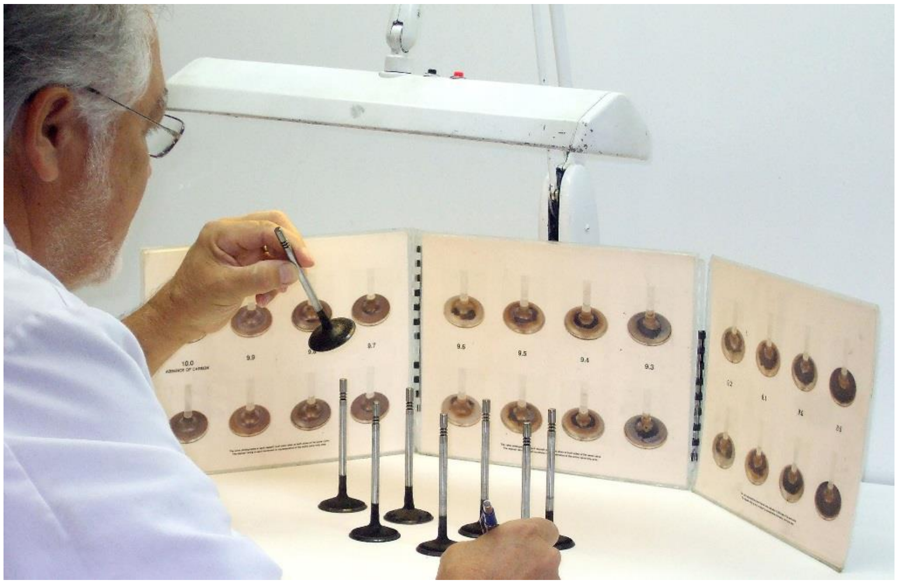

Figure 7: Intake valve visual inspection and rating. Image Source: AAA

Test Measurement Parameters (Individual Cylinder Measurements):

1) Intake Valve Deposit Weights (mg)
2) Piston Top Deposit Weights (mg)
3) Cylinder Head Deposit Weights (mg)
4) Piston Top Deposit Thickness (mil)
5) Cylinder Head Deposit Thickness (mil)
6) Visual Rating of Parts – ASTM Rating Scale

4.2.1 Test Fuel Selection

For this test, AAA selected six fuel brands from the southern Texas market by first defining all major brands in the geographic region (city). Recognizing TOP TIER is the only industry standard for gasoline detergents other than the EPA's LAC, those brands were divided into two groups: TOP TIER and non-TOP TIER gasoline. A random number generator program was then used to randomly select the actual fuel brands for evaluation. Once the brands were identified, the test lab sourced the fuels by selecting a retailer in the test area without any input or direction from AAA. The fuel samples collected were not boutique fuels so the test results should be representative for the majority of the United States.

Premium fuel (93 octane) was selected as the octane grade for this evaluation due to the trend of some brands to put a slightly higher concentration of detergent in their premium grades of fuel. Even non-TOP TIER gasolines may include additional additives in their premium grades, so this choice in octane was intended to eliminate that variable. Retailers that sell TOP TIER gasoline are required to meet TOP TIER standards in all grades of fuel, not just premium. For TOP TIER gasoline, the test results (fig. 8) should be consistent if the test was conducted with regular grade gasoline. Testing non-TOP TIER brands of regular grade gasoline would likely result in similar or higher levels of carbon deposits on critical engine components.

The fuels were transported directly from the retail gas stations to the test facility where they were placed in stainless steel tanks that connected directly to the engine test cell fuel system. Prior to testing, all fuel lines were purged with test fuel to eliminate any potential of cross contamination.

4.3 Test Results

The weight of the intake valve deposits was measured with a high accuracy lab scale. The weight of the deposits on all four intake valves were averaged into the values shown below (fig. 8) to represent each brand of fuel. The non-TOP TIER gasolines resulted in a group average 660.6mg of deposits per intake valve. The TOP TIER gasolines had a group average of 34.1mg per valve or roughly nineteen times fewer deposits than the non-TOP TIER gasolines.

		Intake Valve Deposits (mg)							
Fuel Source	**TEST NUMBER**	**Cyl 1**	**Cyl 2**	**Cyl 3**	**Cyl 4**	**Avg (mg)**	**Min (mg)**	**Max (mg)**	**Std. Dev.**
Non-TOP TIER Fuels									
Fuel #1	IVD9-147	751.5	868.5	1005.8	682.8	**827.2**	682.8	1005.8	141.6
Fuel #2	IVD9-149	624.5	540.7	858.1	378.8	**600.5**	378.8	858.1	199.7
Fuel #3	IVD9-151	563.6	549.1	783.9	319.6	**554.0**	319.6	783.9	189.7
TOP TIER Fuels									
Fuel #4	IVD9-148	21.1	3.7	44.1	26.2	**23.8**	3.7	44.1	16.6
Fuel #5	IVD9-150	52.5	94.5	86.1	42.2	**68.8**	42.2	94.5	25.4
Fuel #6	IVD9-152	20.4	3.4	11.2	3.6	**9.6**	3.4	20.4	8.0

		Piston Top Deposits (mg)							
Fuel Source	**TEST NUMBER**	**Cyl 1**	**Cyl 2**	**Cyl 3**	**Cyl 4**	**Avg (mg)**	**Min (mg)**	**Max (mg)**	**Std. Dev.**
Non-TOP TIER Fuels									
Fuel #1	IVD9-147	867.6	814.8	796.4	640.0	**779.7**	640.0	867.6	97.9
Fuel #2	IVD9-149	429.3	637.4	373.0	534.5	**493.6**	373.0	637.4	116.9
Fuel #3	IVD9-151	350.0	520.8	334.6	537.7	**435.8**	334.6	537.7	108.3
TOP TIER Fuels									
Fuel #4	IVD9-148	389.4	511.7	426.2	513.7	**460.2**	389.4	513.7	62.4
Fuel #5	IVD9-150	522.6	521.0	393.2	553.7	**497.6**	393.2	553.7	71.2
Fuel #6	IVD9-152	605.5	751.6	381.8	745.8	**621.2**	381.8	751.6	173.3

		Cylinder Head Deposits (mg)							
Fuel Source	**TEST NUMBER**	**Cyl 1**	**Cyl 2**	**Cyl 3**	**Cyl 4**	**Avg (mg)**	**Min (mg)**	**Max (mg)**	**Std. Dev.**
Non-TOP TIER Fuels									
Fuel #1	IVD9-147	889.2	829.0	667.3	792.1	**794.4**	667.3	889.2	93.7
Fuel #2	IVD9-149	762.7	862.3	830.2	595.4	**762.6**	595.4	862.3	119.0
Fuel #3	IVD9-151	628.5	786.8	715.8	802.5	**733.4**	628.5	802.5	79.5
TOP TIER Fuels									
Fuel #4	IVD9-148	1137.7	969.5	1015.1	950.4	**1018.2**	950.4	1137.7	84.2
Fuel #5	IVD9-150	799.9	835.3	787.8	807.0	**807.5**	787.8	835.3	20.2
Fuel #6	IVD9-152	726.3	961.5	748.0	986.9	**855.7**	726.3	986.9	137.5

Figure 8: ASTM D6201 Post Test Carbon Deposits

It was observed that one TOP TIER test fuel (Fuel #5) exceeded the TOP TIER standard of 50mg maximum for intake valve deposits. However, the relative magnitude of the deposits for test fuel number five was still significantly less than the average intake valve deposits for the non-TOP TIER fuels. A visual comparison of the intake valve deposits for all test fuels can be found in the appendices of this report.

Figure 9: Intake valve comparison before and after 100hr engine test. The results shown above are consistent among TOP TIER and non-TOP TIER gasolines tested. **Image Source: AAA**

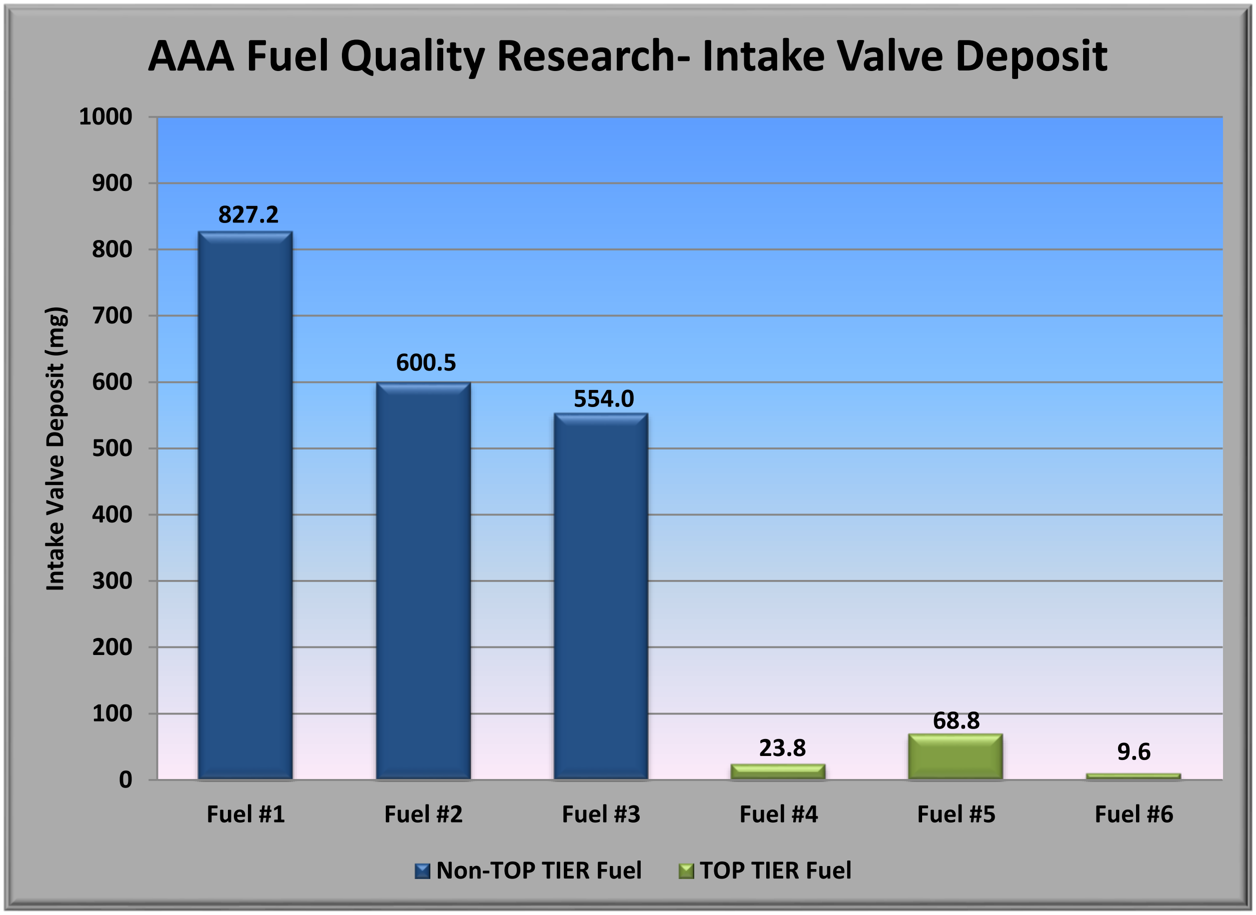

Figure 10: Intake valve deposit weights (avg. weight per valve)

Managing intake valve and combustion chamber deposits is a difficult balance of quantity of detergent and the appropriate chemical composition of the polymers that remove carbon deposits on the desired engine components. If the chemical composition is incorrect, deposits can form on the injector, back of intake valves, and in the combustion chamber. The concentration of detergent within the fuel must also be balanced since a low detergent concentration could result in higher intake valve deposits. A high concentration of detergent could potentially cause deposits to form within the combustion chamber and/or lead to intake valve sticking.

Part of the ASTM D6201 test protocol is to measure the deposit thickness and weight of the carbon deposits in the combustion chamber to verify that excessive buildup has not occurred as a result of adding more detergent. It is noted that in the TOP TIER acceptance testing, fuels are also screened against test scenarios for excessive detergent build up that could cause intake valve sticking and/or excessive increase of combustion chamber deposits.

The graph shown below (fig. 11) illustrates the total carbon deposit accumulated at the end of the 100-hour dynamometer test. This data includes the intake valve, piston top and cylinder head deposits as measured post-test per cylinder.

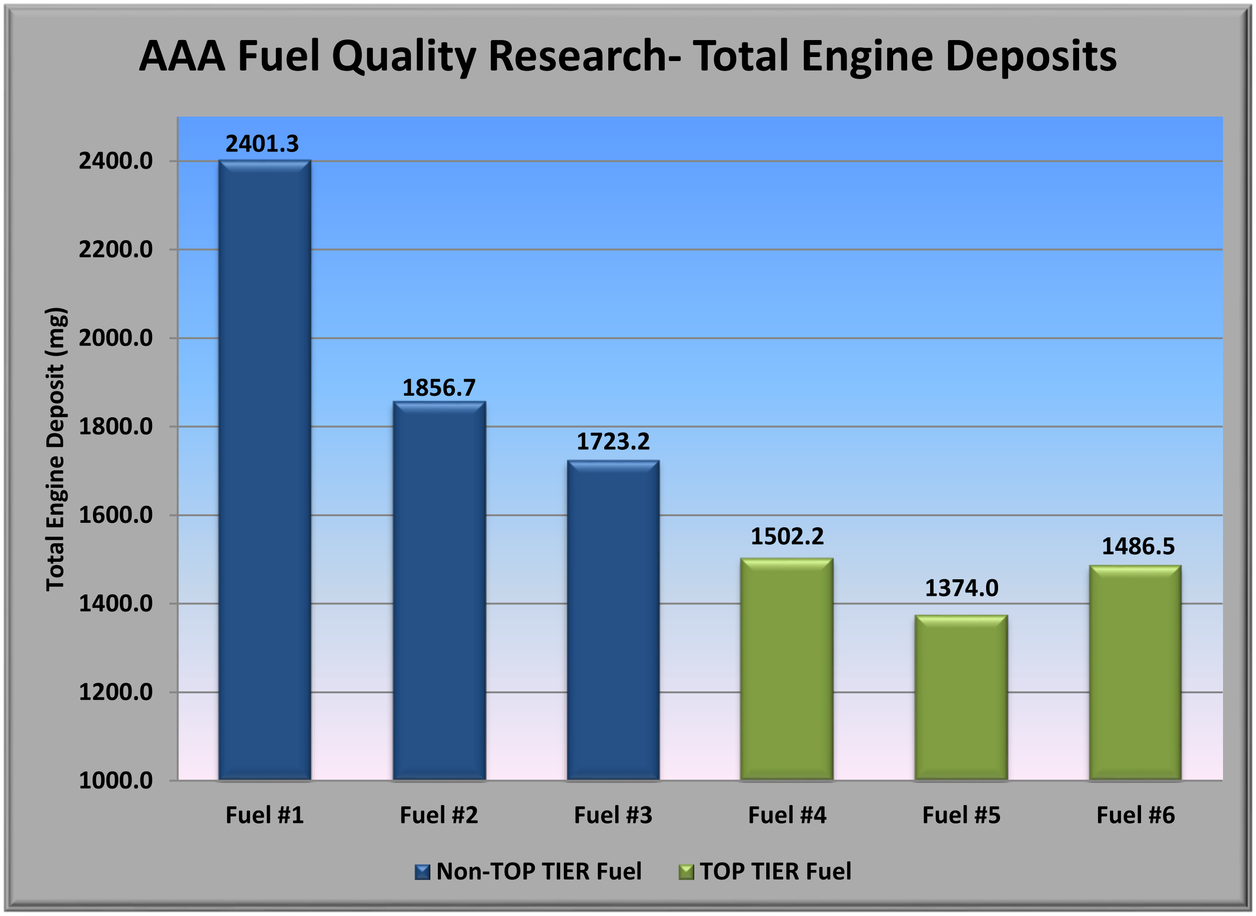

Figure 11: Total engine carbon deposit comparison

5 Inquiry #2: What issues might be experienced by motorists who operate their vehicles' engines on a non-TOP TIER gasoline?

When an engine is run on a non-TOP TIER gasoline for an extended period, carbon deposits can build up on injectors, the back sides of the intake valves and in the combustion chamber. These deposits can have numerous effects on the engine.

5.1 Objective

Identify potential issues that might be experienced by motorists after operating vehicle engines for extended periods on non-TOP TIER gasoline.

5.2 Methodology

Data was collected through a review of existing literature on the effects of intake valve and injector deposits on engine performance and emissions.

5.3 Findings

When engines run for extended periods on Non-TOP TIER gasolines, some or all of the following issues may become evident:

Rough Idle: Intake valve deposits can result in a noticeable difference in engine idle quality. This will often be most noticeable with a cold engine as the valve deposits tend to absorb some of the additional fuel required for starting and initial running. Under all conditions, the deposits disrupt air [9] and fuel flow into the engine, negatively impacting combustion efficiency, engine smoothness and fuel economy.

Hesitation: Intake valve and injector deposits can result in hesitation when the engine rpm is increased such as accelerating from a stop. Some of this is due to airflow disruption and fuel absorption by intake valve deposits, while poor fuel spray patterns from fuel injector deposits can contribute as well. When hesitation occurs, a driver's natural response is to apply more throttle (step on the gas), which reduces fuel economy.

Knocking / Pinging: For greater efficiency, modern engines are often designed to run at lower rpms, larger throttle openings and higher loads that require precisely controlled air/fuel ratios. Under these conditions two similar, but different, conditions can occur if there are carbon deposits on piston tops and cylinder head combustion chambers. These deposits effectively raise the compression ratio which makes the engine more sensitive to the octane of fuel being used.

The first problem is detonation, which occurs when the expanding flame front initiated by the spark plug compresses the air/fuel mixture in another part of the combustion chamber to the point where it self-combusts. The second problem is pre-ignition, which occurs when carbon deposits in the combustion chamber get hot and begin to glow during the compression stroke, igniting the air-fuel mixture before the spark plug fires.

Both of these conditions result in a knocking or pinging noise, and most newer cars have knock sensors that their engine control systems use to retard the ignition timing and/or add additional fuel to prevent detonation and, to a lesser degree, pre-ignition. However, whenever this occurs both engine power and fuel economy are reduced. To make things worse, there is normally no way for a driver to know when this process occurs because knocking is eliminated and no diagnostic trouble codes are set in the engine control computer memory.

Fuel Economy Reduction: Depending on the nature of the problems created, carbon deposits can reduce fuel economy by approximately 2 to 4 percent [1] [10] depending on engine type and driving conditions. Considering there is often minimal financial impact in switching to a TOP TIER gasoline (see Section 8 below), the additional cost for the gasoline could be offset by fuel economy gains if the fuel helps remove existing carbon deposits (see Section 6 below).

Engine Emissions: Today's engines are precisely tuned and calibrated to meet very stringent exhaust emissions with the aid of catalytic converters. Their electronic control systems use extensive networks of sensors, computers and actuators to regularly monitor emission control systems and optimize engine efficiency. A key component in that work is oxygen sensors, which monitor the oxygen content of the vehicle's exhaust and generate data that is used to continually fine-tune the air/fuel ratio.

Carbon deposits from lower-quality fuel can disrupt the flow of air entering the combustion chamber past the intake valves, and also the flow and pattern of fuel being sprayed by the injectors. These issues can cause delayed or incomplete combustion, which will dramatically increase exhaust emissions. This increase in exhaust emissions is intensified during initial cold start conditions when the exhaust catalyst is not fully up to operating temperature.

Modern engines with gasoline direct injection (GDI), which inject fuel directly into the combustion chambers rather than upstream of the intake valves, are particularly susceptible to carbon deposits on the fuel injector tips. Carbon deposits can impact the fuel spray pattern of the injector which can lead to localized detonation, incomplete combustion and drastically increased CO emissions. Elevated carbon monoxide measurements (CO) are an indication of incomplete combustion in the engine.

Testing has shown that running an engine on a non-enhanced additive package fuel can roughly double carbon monoxide emissions (180-200 percent rise) and cause a 20-30 percent increase in hydrocarbon emissions [10]. These emission increases were measured ahead of the catalyst over the course of 55 hours of dynamometer testing that equated to approximately 2,000 miles of real-world driving. The engine was then switched to a fuel with an enhanced additive package and the emissions returned to normal levels after about 1,000 miles of real-world driving as simulated on a dynamometer [10].

6 Inquiry #3: Can existing engine carbon deposits be reduced or removed by switching to a TOP TIER gasoline?

Marketers of TOP TIER gasolines claim those fuels are able to remove preexisting carbon deposits from engines. If this statement is accurate, there would be a definite benefit for consumers who switch over from a non-TOP TIER gasoline.

6.1 Objective

Assess the impact of gasoline detergent additives on existing carbon deposits in an engine that has been operated for an extended period of time on LAC gasoline.

6.2 Methodology

Fuel and additive companies have demonstrated this clean-up performance by running test vehicles in a controlled real-world scenario to validate the effectiveness of their additive packages. AAA reviewed existing research in this area for the purpose of understanding the cleaning properies of fuel additives [11]. This test utilized multiple vehicles in on-road testing for 15,000 miles.

During the initial part of the test, which is known as the "dirty-up" phase, vehicles were driven on LAC fuel for 10,000 miles to promote carbon deposit formation in their engines. The engines were then disassembled and the deposits were weighed and measured using industry standard procedures. The engines were then re-assembled with the carbon deposits intact, and driven for an additional 5,000 miles on the additized fuel to evaluate its "clean-up" performance. At the end of testing, the engines were disassembled once again, the carbon deposits were measured and weighed, and the findings compared to the first set of results to assess the clean-up performance of the additized fuel.

Gasolines with an enhanced additive package demonstrated a clean-up performance (reduction of intake valve deposits) ranging from 45 percent to as much as 72 percent [11] in the 5,000-mile test. The variation in cleaning performance was primarily based on the concentration of the additive package in the fuel.

Performing a multi-vehicle test to replicate the clean-up results discussed above was outside the scope of AAA's research. However, a borescope was used to evaluate the clean-up performance of a TOP TIER gasoline on one subject vehicle for verification purposes.

AAA used a borescope to visually inspect for carbon deposits in one cylinder of a common, high-mileage V-8 engine that was operated on non-TOP TIER gasoline for the majority of its service life. The initial inspection revealed that deposits had formed on the backside of the intake valve and there was black residue in the intake ports of the cylinder head.

Once the inspection was complete, the engine was run on TOP TIER gasoline for approximately 1,000 miles, during which it consumed 74.8 gallons of fuel. Afterward, the engine was re-inspected to assess the nature and extent of any changes in the carbon deposits.

Figure 12: AAA engine borescope inspection, pre-test (left) and post-test (right).

6.3 Test Results

Gasoline with enhanced additive packages, such as those in the TOP TIER program, will not only help prevent carbon deposit formation on critical engine components, they will also reduce existing deposits that have accumulated over time [11].

The before and after photos above illustrate the cleaning performance of TOP TIER gasoline in a real-world application. In this case, the deposits were noticeably reduced and the intake ports were visually cleaner after only 1,000 miles when using TOP TIER gasoline. Given the research findings discussed above [11], it is likely that the cleaning effects of this fuel would become even more pronounced with extended use.

Given the general similarity of internal combustion engines, one can assume that engine carbon deposits formed when using LAC gasoline can, in most cases, be largely removed by switching to a gasoline that meets TOP TIER standards. While the effects may vary with the specific engine, and will not be instantaneous, using fuel with an enhanced additive package does tend to reduce carbon deposits over the course of a few thousand miles.

7 Inquiry #4: What are the current consumer trends in purchasing gasoline?

Identify consumer trends related to purchasing gasoline to establish relevance and value to other findings in this report.

7.1 Objective

Obtain statistically valid information on the current gasoline buying habits of United States motorists.

7.2 Methodology

AAA contracted with a national research company to perform a telephone survey of 1,002 adults (18 years of age and older) living in the continental United States. Half of the respondents were contacted via landline phone; the other half were contacted via cellphone. Survey responses were weighted by six variables (age, gender, geographic region, race/ethnicity, education, and landline vs. cell phone only) to ensure reliable and accurate representation of the total continental U.S. population, 18 years of age and older. The margin of error for the results is +/- 3.1 percent at a 95 percent confidence level.

7.3 Test Results

- Americans are six times more likely to choose a gasoline station based on price, rather than on the detergent additive in the fuel.
- Nearly all (96%) motorists primarily drive a vehicle that is powered by gasoline. Only 3% drive a vehicle that uses diesel fuel and 1% drive a vehicle that uses something else.
- Six in ten (63%) drivers believe there is a difference in the quality of the gasoline sold by different stations. One-third (34%) do not believe there is a difference and 3% don't know.
- Only one-third (34%) of drivers usually buy gasoline that contains a detergent[4]. Half (47%) do not buy gasoline with a detergent and 18% don't know if the fuel contains a detergent.
    - Baby boomers (41%) are more likely than Millennials (32%)[5] to buy gasoline with a detergent.
    - Men (44%) are more likely than women (26%) to buy gasoline with a detergent.
- Location (75%) and price (73%) are the primary reasons drivers choose the station where they typically purchase their gasoline. They are followed by rewards program (29%), gas contains a detergent (12%) and other reasons (7%).
    - Men (14%) are more likely than women (9%) to choose a gasoline station because the fuel contains a detergent.

8 Inquiry #5: Is there a retail price difference between TOP TIER and non-TOP TIER gasoline?

The graph below (fig. 13) displays the average daily fuel price differential over a 12-month period for thirty-nine fuel brands in the United States. These retailers represent the vast majority of fuel sold within the United States by volume. The average price difference between the TOP TIER and non-TOP TIER brands surveyed was three cents per gallon for this 12-month period.

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[4] When consumers were asked about whether or not they purchased fuels with a detergent, they were given examples of fuel brands with an enhanced detergent additive package, such as fuels that are part of the TOP TIER program. It should be noted that all fuels sold within the United States have at least a minimum level (LAC) of detergency as mandated by the EPA. For the purpose of this survey, LAC fuels were not considered a detergent fuel because they do not advertise a detergent additive package.

[5] There is no statistically significant difference when comparing Gen X to either Millennials or Baby Boomers,

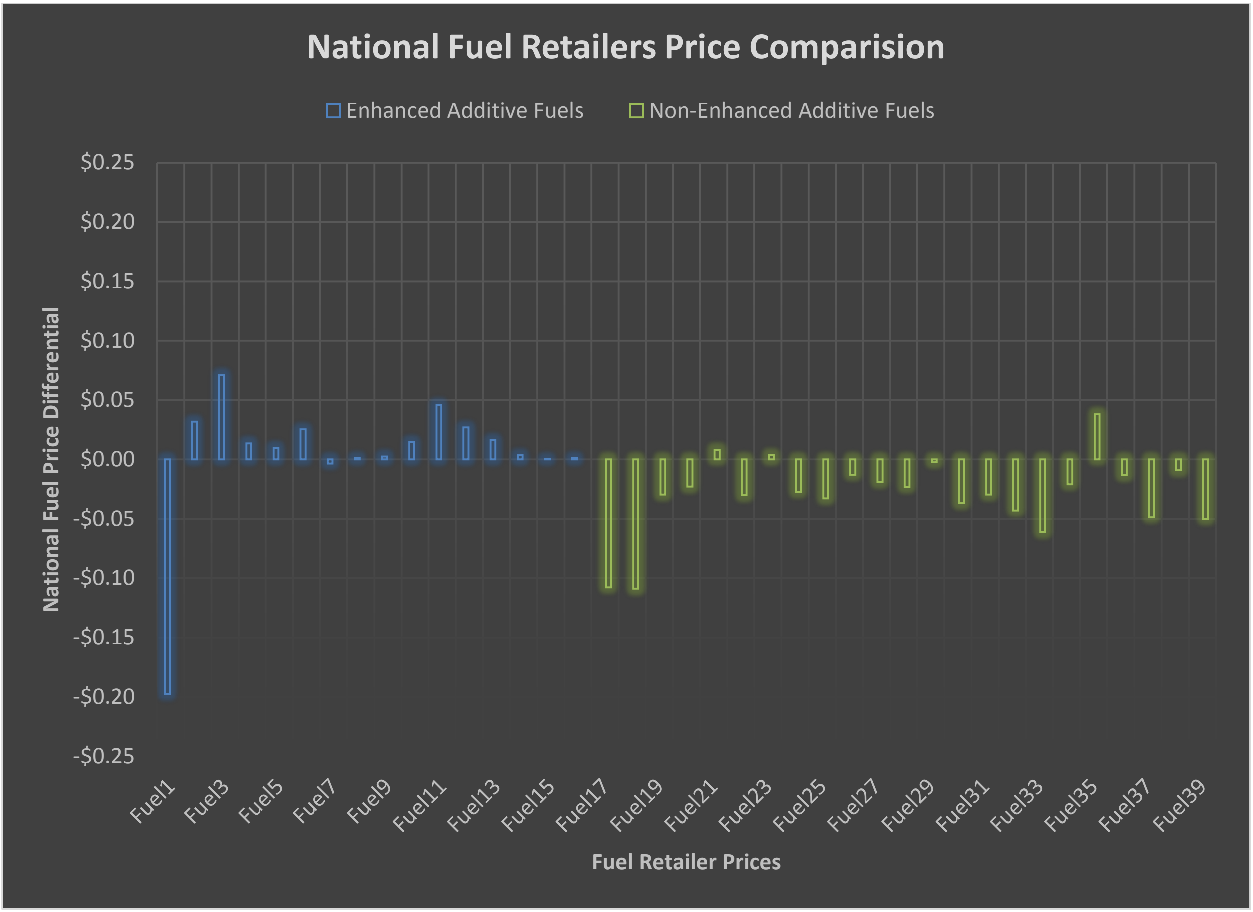

Figure 13: National Fuel Retailers Price Comparison

9 Key Findings

1. The test engine operated on a TOP TIER gasoline averaged 19 times fewer intake valve deposits than when it was operated on non- TOP TIER gasoline. (based on the ASTM D6201 test - TOP TIER gasoline averaged 34.1mg of deposits per intake valve versus non- TOP TIER average of 660.6mg)
2. Based upon secondary research findings, long-term use of a gasoline without an enhanced additive package can lead to reductions in fuel economy of 2-4%, drivability issues, and increased emissions.
3. In most cases, carbon deposits can be reduced or removed from critical engine components by switching to a gasoline that meets TOP TIER standards.

4. Approximately six in ten drivers (63%) believe there is a difference in the quality of gasoline sold by retailers, yet only (12%) of drivers purchase gasoline based upon its detergent additive package. The primary motivation for choosing a particular gas station is location / convenience (75%), followed closely by the price of the fuel (73%).
5. Most TOP TIER gasolines do not cost significantly more than non-TOP TIER gasoline. The average price difference between the TOP TIER and non-TOP TIER brands surveyed was three cents per gallon over a 12-month period.

10 Summary Recommendations

1. If concerned with engine performance, fuel economy and emissions, motorists should select a gasoline that meets TOP TIER standards.
2. Motorists whose cars have a rough idle, cold starting issues or running problems such as hesitation during acceleration may be experiencing the side effects of engine carbon deposits. If these drivers routinely purchase a gasoline that does not meet TOP TIER standards, switching to a TOP TIER gasoline for several tank fill-ups may help remove the deposits and potentially resolve the drivability problems.
3. It is possible to purchase TOP TIER gasoline for only pennies more per gallon than non-TOP TIER gasoline. The practice of driving to a specific TOP TIER gasoline retailer may be less convenient in some situations, but long-term it will often save money through better fuel economy and reduced need for repairs.
4. Some consumers may associate gasoline quality with fuel grade (premium vs. regular) or octane number, which is a mistaken assumption. Motorists should use the fuel grade recommended by the vehicle manufacturer in the owner’s manual.

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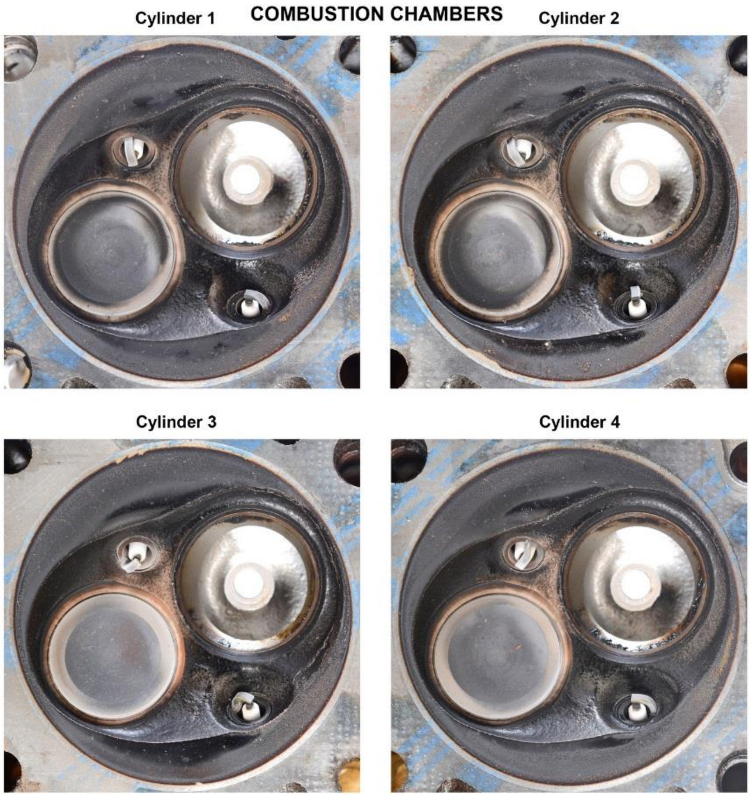
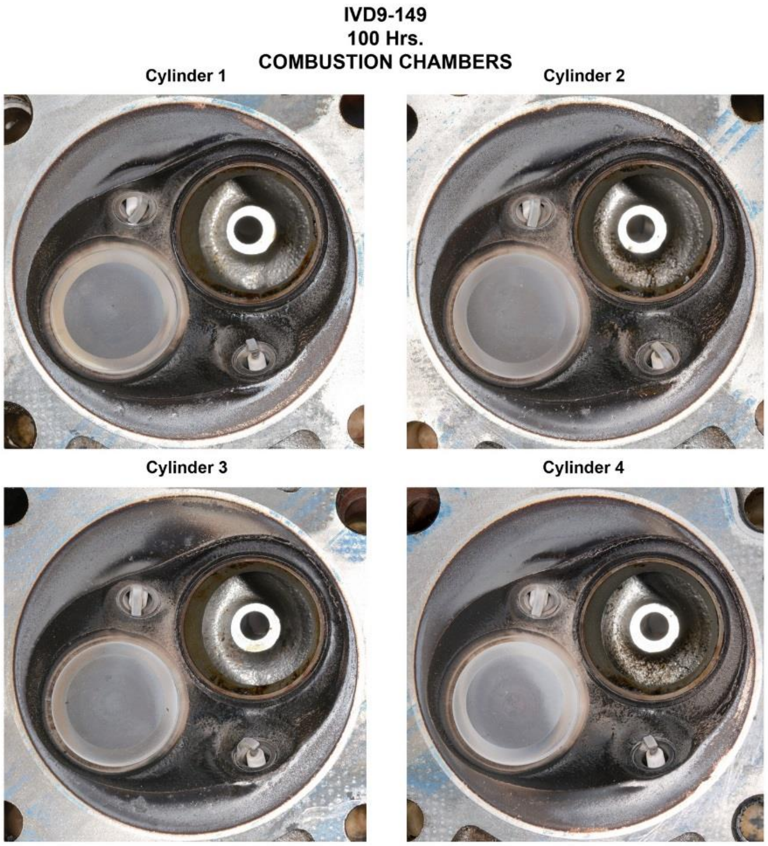
12 Appendices

12.1.1 Fuel#1 – IVD9-147


IVD9-147
100 Hrs.
COMBUSTION CHAMBERS

12.1.2 Fuel#2 -IVD9-149


IVD9-149
100 Hrs.
INTAKE VALVES

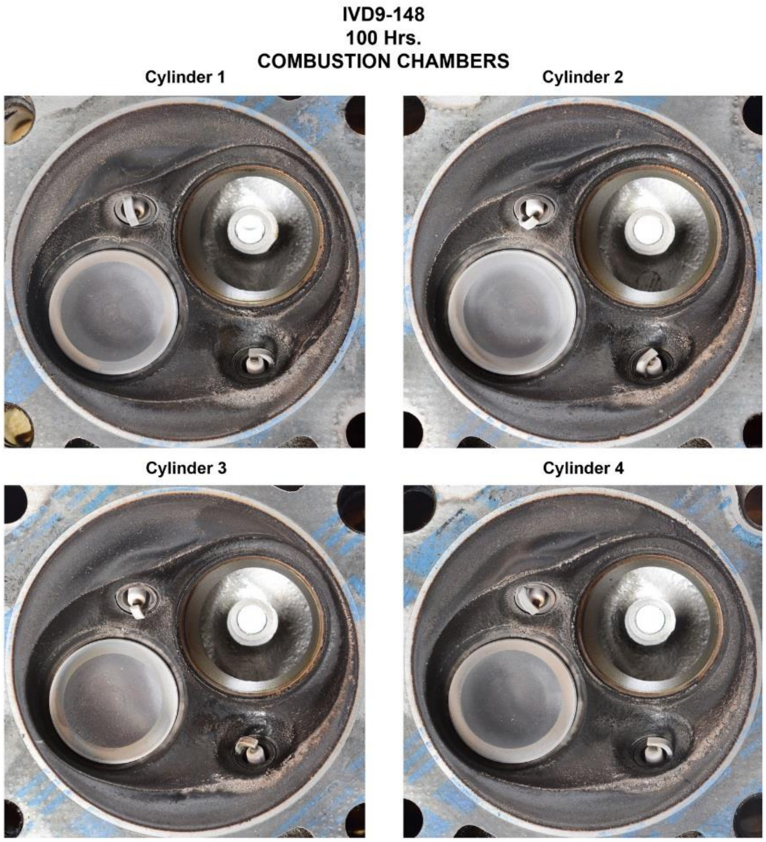


12.1.3 Fuel#3- IVD9-151


IVD9-151
100 Hrs.
COMBUSTION CHAMBERS

12.1.4 Fuel#4- IVD9-148


IVD9-148
100 Hrs.
INTAKE VALVES



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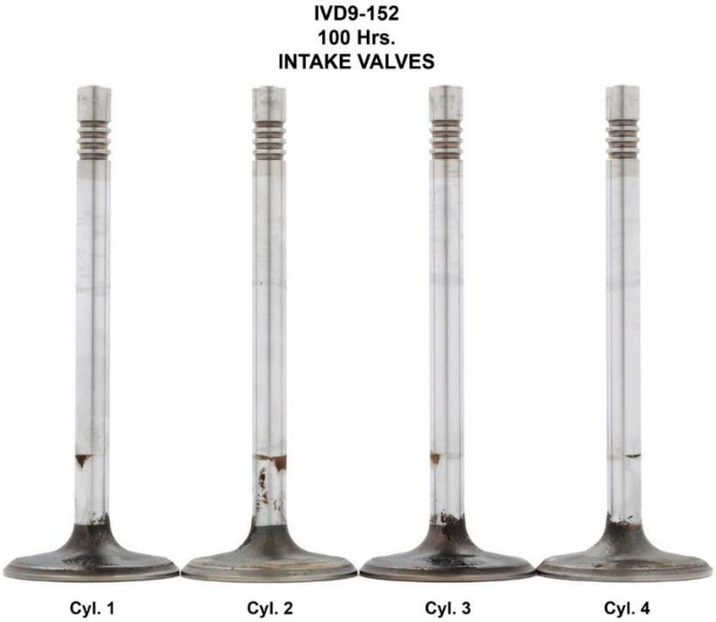
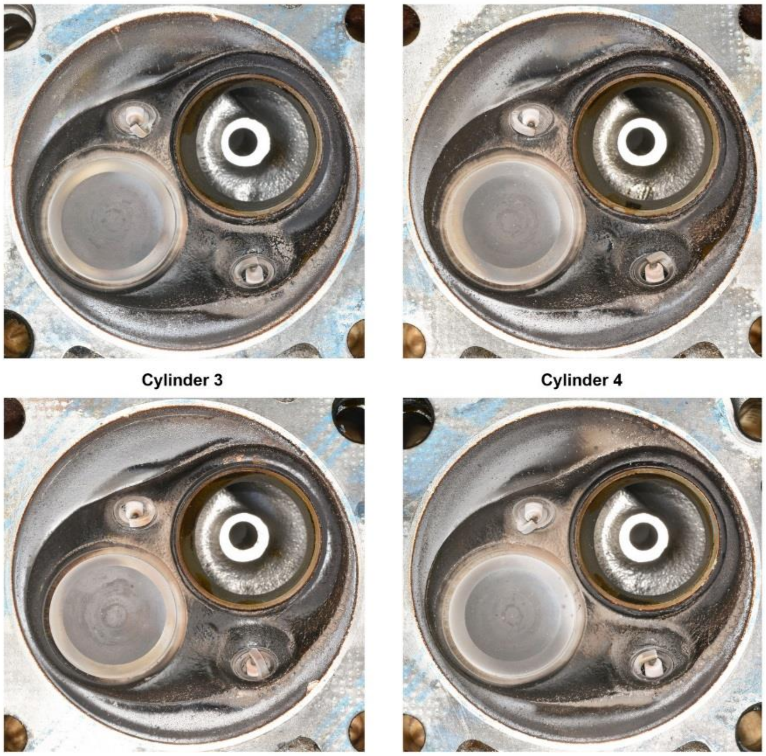
12.1.6 Fuel#6- IVD9-152





IVD9-152
100 Hrs.
COMBUSTION CHAMBERS

Cylinder 1

Cylinder 2

Cylinder 3

Cylinder 4