CRC Report No. AVFL-20

Effects of Octane Number, Sensitivity, Ethanol Content, and Engine Compression Ratio on GTDI Engine Efficiency, Fuel Economy, and CO_2 Emissions

Final Report

November 2017

COORDINATING RESEARCH COUNCIL, INC.
5755 NORTH POINT PARKWAY • SUITE 265 • ALPHARETTA, GA 30022

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Final Report for Coordinating Research Council Project AVFL-20

C. Scott Sluder
David E. Smith
Martin Wissink
Oak Ridge National Laboratory

James E. Anderson
Thomas G. Leone
Michael H. Shelby
Ford Motor Company

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Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831-6283
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LIST OF ACRONYMS AND ABBREVIATIONS

AKI	Anti-Knock Index
ATDC	After Top Dead Center
ATI	Accurate Technologies Incorporated
AVFL	Advanced Vehicle/Fuel/Lubricants Committee of the Coordinating Research Council
BMEP	Brake Mean Effective Pressure
BRIC	Bandpass filter, Rectify, Integrate, and Compare
BTU	British Thermal Units
CA50	Crank Angle at 50% combustion
CAD	Crank Angle Degrees
CAFE	Corporate Average Fuel Economy
CAI	California Analytical Instruments, Inc.
CFD	Computational Fluid Dynamics
CR	Compression Ratio
DAS	Data Acquisition System
DHA	Detailed Hydrocarbon Analysis
ECU	Engine Control Unit
EEE	Exhaust and Evaporative Emissions Certification Gasoline
EPA	U.S. Environmental Protection Agency
EtOH	Ethanol
FTP	Federal Test Procedure
HC	Hydrocarbon
HP	Horsepower
HWFET	Highway Fuel Economy Test cycle
MBT	Maximum Brake Torque
MEP	Mean Effective Pressure
MON	Motor Octane Number
MPH	Miles per Hour
OEM	Original Equipment Manufacturer
ORNL	Oak Ridge National Laboratory
RON	Research Octane Number
RPM	Revolutions per Minute
RVP	Reid Vapor Pressure
SUV	Sport Utility Vehicle
UDDS	Urban Dynamometer Driving Schedule
US06	US06 drive cycle
USB	Universal Serial Bus

1. Executive Summary

As outlined in the CRC Annual Report for 2014[1], the AVFL-20 project was undertaken to "investigate efficiency advantages for increased octane number fuel quality that may be available from ethanol or other blend components in modern light-duty vehicles." Recently, studies have been published that show the potential for improving vehicle fuel efficiency through increasing fuel octane ratings[2,3,4,5,6,7,8]. These improvements are understood to derive from increases in the anti-knock qualities of the fuel that enable the use of increased compression ratio. Fuel efficiency benefits may also be obtained through vehicle system changes (such as engine downsizing and down-speeding) that result in the engine operating under conditions that produce higher efficiency. These changes often result in engine operation at higher brake mean effective pressure (BMEP) levels that are frequently limited by the onset of knock. Hence, the anti-knock characteristics of the fuel are an important part of the overall vehicle optimization strategy to achieve higher fuel efficiency.

The project was organized into three phases. In Phase 1, the fuels were designed and prepared. Target fuel properties were selected by the AVFL-20 panel members. These included research octane number (RON), ethanol content (volume %), and octane number sensitivity. Octane number sensitivity is the difference in the RON and motor octane number (MON) ratings. These parameters formed the axes of a cubic fuel design space. These fuels included blends with RON levels from 92 to 100, ethanol content from 10% to 30% by volume, and sensitivity from 6 to 12. Gage Products was selected as the fuel supplier. Gage reviewed the design matrix and determined that the fuel blend targeted to achieve 92 RON and a sensitivity of 6 with an ethanol content of 30% by volume was infeasible since the high ethanol content would result in an excessively high sensitivity level. Ultimately, 19 fuel blends were identified for inclusion in subsequent experimental efforts for the project.

In Phase 2, the 19 fuel blends were subjected to evaluation using a modern turbocharged, direct-injection gasoline engine provided by Ford Motor Company and equipped with pistons designed to deliver different compression ratios. The engine was installed in an engine dynamometer research cell at Oak

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[1] CRC Annual Report, 2014. Available on the web from: http://www.crcao.org/about/Annual%20Report/2014%20Annual%20Report/AR2014Final.pdf

[2] CRC Project No. CM-137-11-1b Report. Available on the web from: http://www.crcao.org/reports/recentstudies2012/CM-137-11-1b%20Task%202-5/CM-137-11-1b%20Final%20Report.pdf

[3] Stein, R., Polovina, D., Roth, K., Foster, M. et al., "Effect of Heat of Vaporization, Chemical Octane, and Sensitivity on Knock Limit for Ethanol-Gasoline Blends," SAE Int. J. Fuels Lubr. 5(2):2012, doi:10.4271/2012-01-1277.

[4] Leone, T., Olin, E., Anderson, J., Jung, H. et al, "Effects of Fuel Octane Rating and Ethanol Content on Knock, Fuel Economy, and CO2 for a Turbocharged DI Engine, "SAE Int. J. Fuels Lubr. 7(1):9-28, 2014, doi:10.4271/2014-01-1228.

[5] Splitter, D. and Szybist, J., "Intermediate Alcohol-Gasoline Blends, Fuels for enabling Increased Engine Efficiency and Powertrain Possibilities," SAE Int. J. Fuels Lubr. 7(1):29-47, 2014, doi:10.4271/2014-01-1231.

[6] Raymond L. Speth, Eric W. Chow, Robert Malina, Steven R. H. Barrett, John B. Heywood, and William H. Green, "Economic and Environmental Benefits of Higher-Octane Gasoline," Environ. Sci. Technol. 2014, 48, 6561-6568, doi:10.1021/es405557p.

[7] David S. Hirshfeld, Jeffrey A. Kolb, James E. Anderson, William Studzinski, and James Frusti, "Refining Economics of U.S. Gasoline: Octane Ratings and Ethanol Content," Environ. Sci. Technol., 48, 11064-11071, doi:10.1021/es5012668.

[8] Leone, Thomas G.,Anderson, James E., Davis, Richard S., et al., "The Effect of Compression Ratio, Fuel Octane Rating, and Ethanol Content on Spark-Ignition Engine Efficiency," Environ. Sci. Tech. 2015, 49, 10778-10789, doi:10.1021/acs.est.5b01420.

Ridge National Laboratory (ORNL). The data gathered during this phase focused on screening of the anti-knock performance of all 19 fuels using pistons that produced a geometric compression ratio of 11.4 at a fixed engine speed of 2,000 revolutions per minute (RPM) over a wide load range. Using these data, a subset of the fuels were selected and screened at the same conditions using either the original equipment manufacturer (OEM) pistons or pistons that produced a compression ratio of 13.2. The OEM pistons nominally produce a compression ratio of 10.1, though subsequent measurements with the hardware used for this project placed this compression ratio at 10.5. The resulting combustion data were reviewed by the project committee to reach a consensus on fuel and compression ratio pairs that should be studied in Phase 3. Fuel and compression ratio pairs were selected based on their ability to produce combustion phasing results that were similar to those produced by the OEM pistons and baseline (i.e. ~91 RON E10) fuels, or that allowed single-fuel comparisons between compression ratios. The fuel and compression ratio pairs were as follows: fuels #1, #10, and #15 at compression ratio 10.5, fuels #7 and #15 at compression ratio 11.4, and fuels #16 and #19 at compression ratio 13.2.

In Phase 3, engine fuel consumption maps were developed using the fuel / compression ratio pairs selected in Phase 2. These engine maps were comprised of fuel consumption measurements at approximately 75 conditions that encompassed the range of operation of the engine for each fuel. The fuel consumption maps were then employed in vehicle models representing both an "industry average" mid-size sedan and an "industry average" small sport utility vehicle (SUV) using the Autonomie model developed by Argonne National Laboratory for the U.S. Department of Energy. The Autonomie model is a vehicle model which can predict fuel economy changes that result from differing vehicle architectures and powertrain control strategies. Autonomie relies upon engine maps for information about engine efficiency at given engine speed and torque output conditions. The Autonomie model provided estimates of the impact of the different fuels and compression ratios on vehicle energy consumption (BTU/mile), volumetric fuel economy (miles/gallon), and tailpipe CO_2 emissions (g/mile) over three EPA-defined driving cycles: the urban dynamometer driving schedule (UDDS), the highway fuel economy test (HWFET), and the US06 cycle. Results were compared to those for the baseline case (the average results of 91 RON E10 fuels (#1 and #10) with the baseline OEM compression ratio. The results showed that decreases in vehicle energy consumption are possible on all three driving schedules with the higher RON fuels and increased CR. Opportunities for efficiency improvement are highest for the city and highway portions of the US06 cycle because of the more frequent occurrence of knock-limited engine conditions on this cycle. Depending on the fuel used, vehicle energy consumption decreased by 1-2% on the UDDS and HWFET cycles, and by up to 6% on the city and highway portions of the US06 cycle when compression ratio (CR) was raised from 10.5 to 11.4. Likewise, the higher compression ratio and resulting higher efficiency led to reductions in tailpipe CO_2 emissions for all fuels, with reductions of 0.6-5.3% on the UDDS and HWFET cycles and 2.2-7.9% on the US06 cycle, also in part due to differences in fuel CO_2 intensities.

For the E30 fuels studied at CR11.4, the energy efficiency improvements were not sufficient to overcome the lower volumetric energy density of the gasoline-ethanol blend, and so volumetric fuel economy declined relative to baseline conditions (i.e. 91 RON E10 at CR10.5). Since this study did not include fuels with ethanol levels between 10% and 30% by volume, there are no data to indicate whether intermediate blend levels could achieve fuel economy parity with the baseline. Increasing sensitivity and/or RON were shown to provide vehicle energy consumption decreases at both compression ratios. The only fuel which had a better volumetric fuel economy at CR11.4 than the baseline on all drive cycles was the E10 fuel having 96 RON and 10.7 octane sensitivity which are properties similar to those of premium grade gasolines in the market today. This study focused on improving efficiency by increasing compression ratio and varying combustion phasing without changing other engine parameters, such as bore diameter, stroke length, valve timing, fuel injection pressure, fuel injection phasing, and so on.

Attempts were made to gather data at CR13.2 for 4 fuels (#7, #15, #16, and #19). An engine failure occurred during these tests that required installation of a new engine. The new engine was found to have efficiency differences relative to the original engine. At the same time, the CR13.2 pistons were found to have performance that was lower than expected. As a result, further data collection at CR13.2 was discontinued.

2. INTRODUCTION

2.1 MOTIVATION AND REGULATORY BACKGROUND

The relationship between the ability of a fuel to resist undesired auto-ignition and the use of increased compression ratio to improve efficiency of spark-ignited (SI) engines has been investigated since the very early days of the automotive industry.[9,10,11] As a result of these early investigations, increasing compression ratio is a well-known path towards improvement in engine efficiency if the onset of knock can be avoided. For the last several decades, the automotive manufacturers have been able to continue to increase automotive fuel efficiency through the development of a number of technologies without higher gasoline octane ratings.[12] However, the introduction of new Corporate Average Fuel Economy (CAFE) standards in 2012 has created an unprecedented rate of increase in fuel economy requirements.[13] As a result of these more stringent fuel economy standards, automakers are faced with the need to adopt an "all-of-the-above" technology strategy to meet these requirements. Thus, there is a renewed interest in understanding the benefits and costs of increasing fuel octane ratings as a means of enabling further improvements in engine efficiency.

One frequently asked question is whether the automotive manufacturers could make greater use of existing premium-grade gasoline to enhance engine efficiency? Answering this question requires some explanation of how cars and the regulatory environment have changed in the last several decades. One of the key innovations that allowed the automobile manufacturers to increase engine efficiency without requiring increased octane was closed-loop knock detection and avoidance. The U.S. Environmental Protection Agency (EPA) quickly realized that the ability for vehicles to adjust their spark timing to avoid knock could lead to improved fuel economy, however these increases might not be realized by the public, where gasoline with an octane rating lower than that of certification gasoline is typical.[14] The EPA subsequently began requiring the manufacturers to prove, through testing with two different certification fuels, that either the knock sensor output does not alter spark timing during Federal Test Procedure (FTP) operation, or that the fuel economy difference between testing with 96 RON fuel and 91 RON fuels is 3% or less on any regulatory drive cycle. Manufacturers can design vehicles to gain an advantage greater than 3% through the use of premium fuel, but must specify in the owner's manual that premium fuel is required in order to gain credit for CAFE compliance. These vehicles are designated as "premium-required" vehicles. After several years of data collection, EPA agreed with an industry request that the manufacturers could attest in a written statement that one of the above conditions was true, rather than conducting certification tests with two fuels.[15] This approach was continued through the EPA Tier 2 emissions standards. Thus, for many years, all fuel economy results for regulatory compliance were determined using a premium-grade fuel, and a small detriment in fuel economy was accepted when regular-grade fuels were used. This procedure was changed in the Tier 3 emissions standards that took effect in model year 2017.

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[9] H.L. Horning, "Effect of Compression on Detonation and Its Control," SAE Technical Paper 230033, SAE International, 1923.
[10] G.A. Young and J.H. Holloway, "Control of Detonation," SAE Technical Paper 240001, SAE International, 1924.
[11] H.E. Hesselberg and W.G. Lovell, "The Potentialities of Fuel AntiKnock Quality," SAE Technical Paper 500150, SAE International, 1950.
[12] Pawlowski, A. and Splitter, D., "SI Engine Trends: A Historical Analysis with Future Projections," SAE Technical Paper 2015-01-0972, 2015, doi:10.4271/2015-01-0972.
[13] 77 Federal Register 62623-63200
[14] Larry C. Landman "Knock Sensor Vehicle Test Program," EPA report EPA/AA/CTAB/TA/82-1, U.S. Environmental Protection Agency, 1981.
[15] EPA letter to manufacturers, VPCD-97-01, January 24, 1997.

Beginning in model year 2017, the Tier 3 rules require the automotive manufacturers to use a regular-grade certification fuel unless the vehicle is "…designed specifically for operation on high-octane fuel and the manufacturer requires the use of premium gasoline as part of their warranty as indicated in the owner's manual."[16] The Tier 3 regulations also require that certification fuels be blended to include 10% ethanol, in recognition of this blend becoming dominant in the US marketplace in recent years. In principle, this new approach to the certification fuel octane requirement could allow the automobile manufacturers to begin gaining a fuel economy benefit from requiring premium fuel. Many OEMs, however, are concerned that mis-fuelling a vehicle that is designed specifically for premium (or even higher octane rating) fuel could result in significantly degraded performance or engine damage, both of which would cause customer dissatisfaction. According to a study by the Fuels Institute, only 48% of consumers surveyed know if their car has a recommended octane grade. Furthermore, only 2% of consumers surveyed understood that octane grade is a measure of the anti-knocking performance of gasoline.[17] The same Fuels Institute study demonstrated that the level of understanding of octane grade and anti-knock performance is strongly influenced by the age of the consumer. Older consumers (i.e. those who learned to drive prior to the proliferation of knock sensors on modern vehicles) were more likely to understand the linkage between octane grade and knock resistance than younger consumers. The price differential between regular grade and premium grade gasoline is also known to be a driver in selection of fuels by consumers, and could result in consumer hesitation about purchase of premium-required vehicles.

There are currently examples in the marketplace of vehicles that are designed to use regular-grade fuel, but that can produce more power if they are fueled with premium-grade fuel, particularly when operated under knock-limited conditions such as towing. Vehicles equipped with the Ford EcoBoost 1.6L turbocharged direct-injection engine used for this project are an example of this trend. These vehicles have the capability to both retard and to advance their spark timing in response to knock-detection algorithms that allow the engine control unit (ECU) to infer the relative anti-knock properties of the fuel in the vehicle tank and to adjust for environmental conditions that affect knock, such as temperature and humidity. Thus, they are able to avoid knock by retarding spark timing, but also to enhance performance and efficiency by advancing spark timing when a fuel with greater knock-resistance is present. Since the vehicles are designed for regular-grade fuel, the pre-2017 EPA limit on fuel efficiency difference of 3% discussed previously applies to these vehicles which have already undergone certification. The retail cost difference for premium grade fuel is generally greater than 3%, and so achieving increased fuel economy with premium fuel in such vehicles is not economical to many consumers under today's market and regulatory conditions. It is important to distinguish today's vehicles that can adjust to improved fuel anti-knock properties from a vehicle that is specifically designed for fuels with greater knock resistance. The latter vehicle would most likely utilize a higher compression ratio (and perhaps other technologies) to enhance work extraction from the combustion process in addition to spark timing changes, but would likely experience performance degradation and perhaps engine damage if it were fueled with a low-octane gasoline blend.

In light of these trends and interests, more information on the potential impact of high-octane fuels in near-term engine platforms was deemed necessary. As outlined in the CRC Annual Report for 2014[18], the AVFL20 project was undertaken to "investigate efficiency advantages for increased octane number fuel quality that may be available from ethanol or other blend components in modern light-duty vehicles."

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[16] 79 Federal Register 23527.

[17] John Eichberger, "Market Feasibility of Advanced Fuels and Vehicles," presented at the 2016 CRC Advanced Fuels and Engine Efficiency Workshop, Livermore, California, October 2016.

[18] CRC Annual Report, 2014. Available on the web from: http://www.crcao.org/about/Annual%20Report/2014%20Annual%20Report/AR2014Final.pdf

Recently, studies have been published that show the potential for improving vehicle fuel efficiency through increasing fuel octane ratings[19,20,21,22,23,24,25]. These improvements are understood to derive from improvement in the anti-knock qualities of the fuel that enable the use of increased compression ratio. Fuel efficiency benefits may also be obtained through vehicle-system level changes (such as engine downsizing and down-speeding) that result in the engine operating under conditions that produce higher efficiency. These changes often result in engine operation at higher brake mean effective pressure (BMEP) levels that are frequently limited by the onset of knock. Hence, the anti-knock characteristics of the fuel are an important part of the overall vehicle optimization strategy to achieve higher fuel efficiency.

2.2 KNOCK AVOIDANCE IMPACTS ON ENGINE EFFICIENCY

Closed-loop knock detection and avoidance most typically utilizes ignition retard as the control mechanism to move engine operation away from a knock condition when it is detected. Knock is a kinetically-driven process, and hence the pressure and temperature of the fuel-air mixture are important parameters that lead to the onset of knock for a given fuel. Thermodynamically, retarding ignition timing both delays and reduces the increases in pressure and temperature in the cylinder that give rise to knock. However, since the work output of the engine is also related to the in-cylinder pressure, these changes also reduce engine efficiency. Figure 2.1 shows this effect graphically using a log-pressure versus log-volume (P-V) diagram.

[19] CRC Project No. CM-137-11-1b Report. Available on the web from: http://www.crcao.org/reports/recentstudies2012/CM-137-11-1b%20Task%202-5/CM-137-11-1b%20Final%20Report.pdf

[20] Stein, R., Polovina, D., Roth, K., Foster, M. et al., "Effect of Heat of Vaporization, Chemical Octane, and Sensitivity on Knock Limit for Ethanol-Gasoline Blends," SAE Int. J. Fuels Lubr. 5(2):2012, doi:10.4271/2012-01-1277.

[21] Leone, T., Olin, E., Anderson, J., Jung, H. et al, "Effects of Fuel Octane Rating and Ethanol Content on Knock, Fuel Economy, and CO_2 for a Turbocharged DI Engine, "SAE Int. J. Fuels Lubr. 7(1):9-28, 2014, doi:10.4271/2014-01-1228.

[22] Splitter, D. and Szybist, J., "Intermediate Alcohol-Gasoline Blends, Fuels for enabling Increased Engine Efficiency and Powertrain Possibilities," SAE Int. J. Fuels Lubr. 7(1):29-47, 2014, doi:10.4271/2014-01-1231.

[23] Raymond L. Speth, Eric W. Chow, Robert Malina, Steven R. H. Barrett, John B. Heywood, and William H. Green, "Economic and Environmental Benefits of Higher-Octane Gasoline," Environ. Sci. Technol. 2014, 48, 6561-6568, doi:10.1021/es405557p.

[24] David S. Hirshfeld, Jeffrey A. Kolb, James E. Anderson, William Studzinski, and James Frusti, "Refining Economics of U.S. Gasoline: Octane Ratings and Ethanol Content," Environ. Sci. Technol., 48, 11064-11071, doi:10.1021/es5012668.

[25] C. Scott Sluder, David E. Smith, Brian H. West, "An Engine and Modeling Study on Potential Fuel Efficiency Benefits of a High-Octane E25 Gasoline Blend," Oak Ridge National Laboratory Technical Report #ORNL/TM-2017/357, 2017.

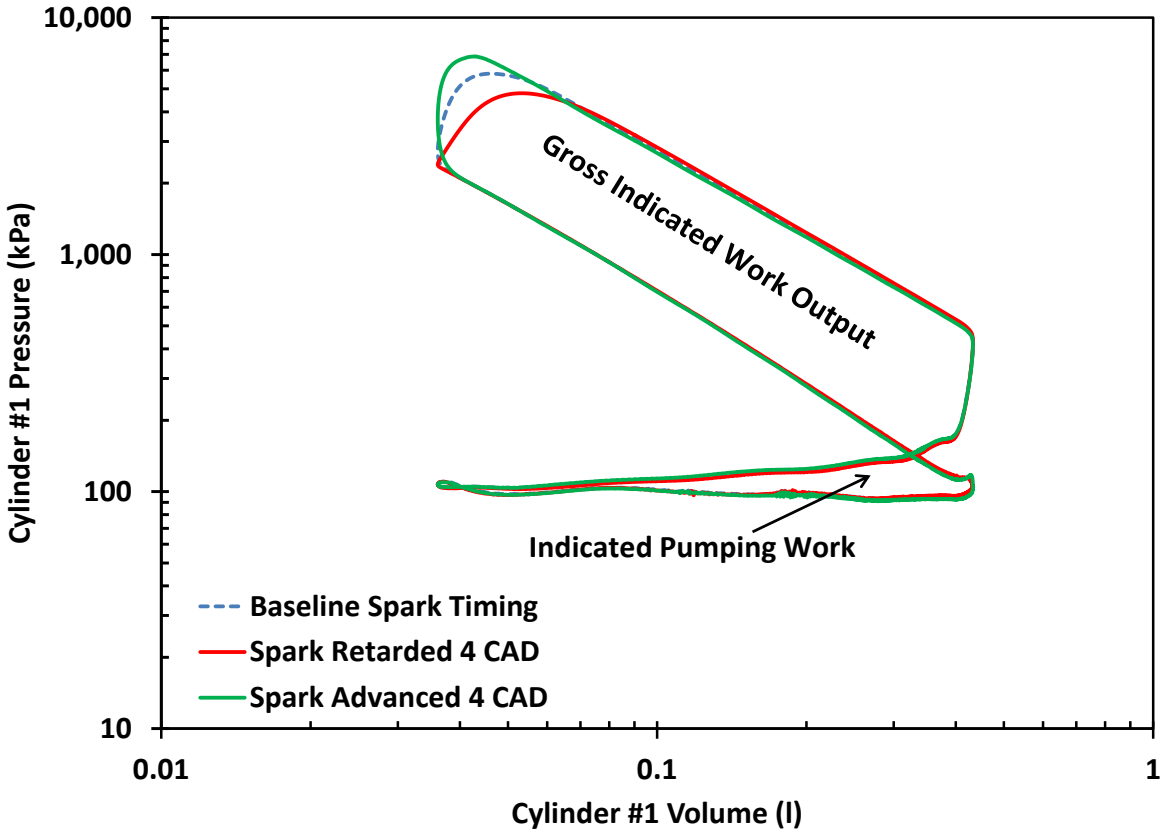

Figure 2.1. P-V diagram showing impact of spark timing on engine indicated work output.

The region representing the gross indicated work output is labeled on the figure. This region is bounded on the lower side by the compression stroke and on the upper side by the expansion stroke. The total area enclosed in this region is the integral of pressure over the swept volume for the engine expansion cycle, which defines the indicated gross work output for the engine. The region representing indicated pumping work is also shown. Pumping work quantifies the work done by the engine to pump air and exhaust through the engine during the non-combustion portion of the engine cycle. The difference between the gross work and the pumping work is the net, or useful, work output of the engine at the conditions shown. For the example shown in Figure 2.1, the engine was operated at approximately 1000 kPa brake mean effective pressure (BMEP) using the original pistons that produce a compression ratio of 10.1. AVFL-20 fuel #7, with a RON approximating premium grade gasoline was used. Three curves are shown: the nominal spark timing that the ECU commands is the dashed blue line. The green line was produced by advancing the spark timing 4 crank angle degrees (CAD), and the red line by retarding the spark timing 4 CAD. Retarding spark timing at this condition, such as to avoid knock, reduces the work produced by the engine and thus reduces its efficiency for fixed fuel energy input. Conversely, if a fuel with improved anti-knock characteristics can be used to avoid knock, more work can be produced by advancing spark timing, raising engine efficiency. The degree to which a penalty or improvement in fuel efficiency results depends both on the baseline combustion phasing and the magnitude of the adjustment to spark timing.

For purposes of comparing the fuel effects on knock-limited spark timing and the resulting combustion phasing, a useful metric is CA50, the crank angle at which 50% of the fuel mass has burned. It has been clearly shown that engine efficiency and net indicated mean effective pressure (NIMEP) deteriorate in a highly repeatable pattern as CA50 is retarded for a variety of operating conditions (Ayala et al., SAE 2006-01-0229), with the trend shown in Figure 2.2. Therefore, knock-limited CA50 values are used in

this study as the primary metric for comparing knock-limited combustion phasing at a given engine speed and load condition.

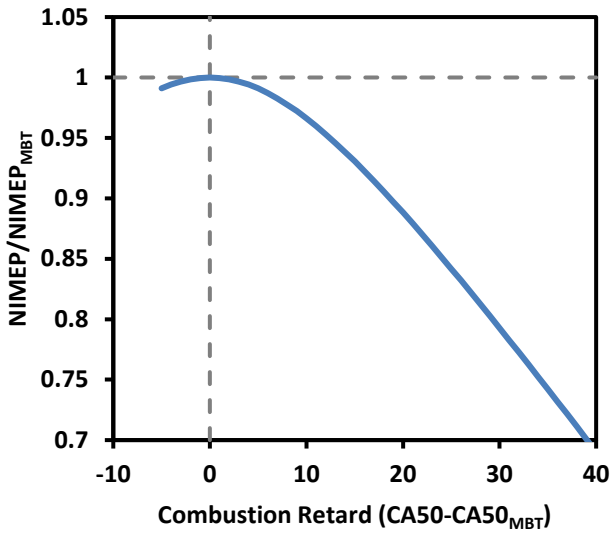

Figure 2.2. Generalized relationship between retarded combustion phasing (as CA50) and net indicated mean effective pressure as reported by Ayala et al. (2006).

Brake mean effective pressure (BMEP) is another related measure of engine output that is used extensively in this report. BMEP is the pressure acting on the piston for the entirety of the power stroke that would produce the same brake output torque as the actual cylinder pressure, which varies during the engine cycle. Since BMEP is a means of normalizing the output torque to the displacement of the engine, expressing engine output as BMEP enables comparisons of engine performance across engines of differing displacements.

3. PHASE 1: FUEL MATRIX DESIGN AND FUEL PRODUCTION

In Phase 1, target fuel properties were selected by the AVFL-20 panel members. These included research octane number (RON), ethanol content (volume %), and octane number sensitivity. Octane number sensitivity is the difference between RON and MON. These parameters formed the axes of a cubic fuel design space. 19 fuel blends were identified for inclusion in subsequent experimental efforts for the project. These fuels included blends with nominal RON levels from 92 to 100, ethanol content from 10% to 30%, and nominal octane sensitivity from 6 to 12. Gage Products of Ferndale, Michigan, was selected as the fuel blender for the project. Gage produced hand-blends targeting the combination of fuel properties desired in the experimental fuel matrix. Initial results demonstrated that target fuel #9 (101 RON, 30% ethanol, 6-8 octane sensitivity) was not feasible as the sensitivity could not be made low enough with an ethanol content of 30%. This fuel was removed from the matrix. Subsequently, a need was identified for a fuel between fuels 7 and 8 to represent a high-octane E15 blend (fuel #7.5). This target fuel essentially replaced fuel #9 in the final fuel matrix yielding a total of 19 fuels. A federal emissions certification gasoline (Haltermann EEE, batch CE2121LT10) was added to the screening study for comparison. Figure 3.1 shows the final cubic design space of the fuel matrix.

The range of properties of the test fuels was designed to overlap and extend the range of those currently available in the market. The most predominant gasolines today in the U.S. market are E10 regular grade with RON values 91-93 and octane sensitivities of 7-10 and E10 premium grades with 96-99 RON and octane sensitivities of 8-12. E0 and E15-E85 blends are also available in some markets.

Detailed hydrocarbon analysis (DHA) conducted by Chevron showed that several high-octane, low-sensitivity fuels contained higher than desired levels of isooctane. The project committee requested that Gage attempt to use more alkylate, if possible, to offset some of the neat isooctane blending for these fuels since high levels of isooctane blending were not typical in market gasolines. Gage was able to accommodate this request. Upon acceptance of the fuel formulations by the project committee, Gage blended 55 gallons of each fuel, sending one drum of each fuel to Oak Ridge National Laboratory (ORNL) and an additional sample to Chevron for analysis and comparison with the original handblends. To achieve some of the design targets, Gage had to add larger quantities of 1-hexene and/or cyclopentane to some of the fuels than are typically present in market gasolines.

Gage Products provided the results of several fuel analyses with the delivery of the first drum of each of the 19 fuels to ORNL. Certificates of Analysis are included in Appendix A; results for the three design variables (and additionally the MON) are summarized in Table 3.1.

Chevron prepared graphs comparing the RON and sensitivity values of the original handblends and the drums produced for Phase 2 studies. This comparison is shown in Figures 3.2 and 3.3, respectively. The drums were found to have properties that agreed well with the original hand blends upon which they were based. The RON values cluster into three groups, corresponding to the ~91, ~96, and ~101 levels envisioned during the matrix design. Within each group, the variation in RON is about 1 octane number. The sensitivity level also falls within two groups (~6-8 and ~10-12), as desired, with a variation of sensitivity of about 2 within each group with a trend towards slightly higher sensitivity for the higher RON fuels. Chevron also conducted DHA analyses on the fuel blends received for Phase 2. Graphical depictions of the results of these analyses are included in Appendix B. Another view of the fuel matrix is provided in Figures 3.4 and 3.5, in which the MON and sensitivity are plotted against RON with the ethanol content indicated by the marker color.

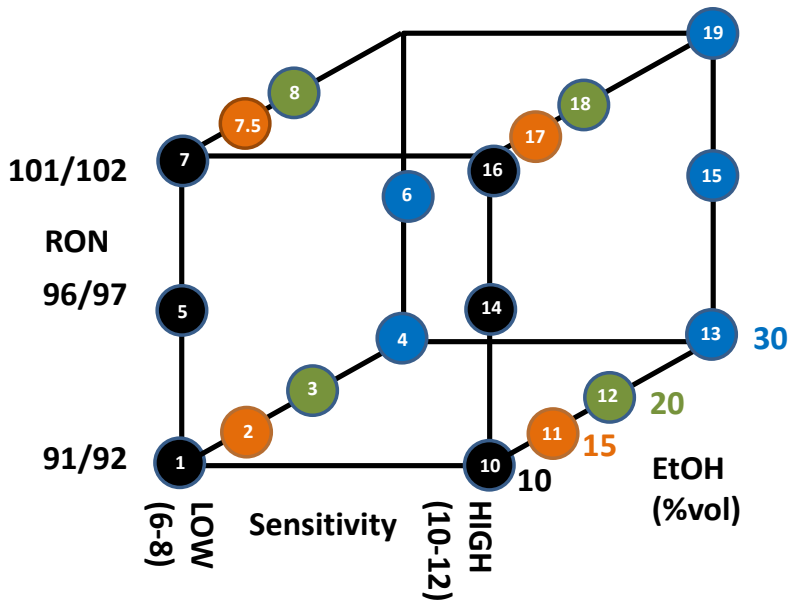

Figure 3.1. Cubic design space of AVFL-20 fuel matrix.

Table 3.1. Gage Products reported values for design variables (Phase 2 blends).

Fuel	RON	MON	Sensitivity	Ethanol Content (vol%)
1	91.0	84.5	6.5	9.9
2	91.4	85.0	6.4	14.6
3	91.4	84.5	6.9	20.3
4	91.7	84.7	7.0	30.2
5	96.4	89.0	7.4	10.2
6	96.3	88.4	7.9	30.0
7	100.0	92.4	7.2	10.3
7.5	99.8	91.3	8.5	15.3
8	99.6	91.2	8.4	20.1
10	91.1	80.7	10.4	10.0
11	91.6	80.8	10.8	14.8
12	91.4	81.2	10.2	19.6
13	91.9	81.2	10.7	29.9
14	96.2	85.5	10.7	10.0
15	96.4	84.9	11.5	30.0
16	101.5	89.5	12.0	9.9
17	101.0	89.6	11.4	15.1
18	101.1	89.1	12.0	20.3
19	101.0	89.0	12.0	29.9
EEE	97.4	89.0	8.4	0

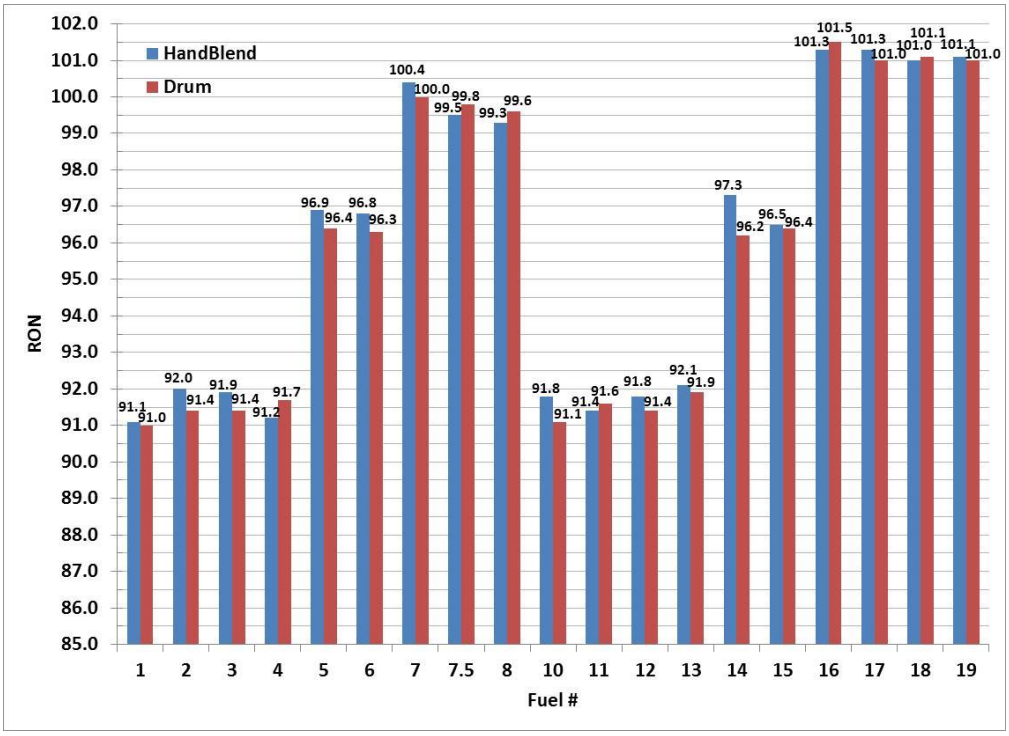

Figure 3.2. RON comparison for hand blends and drums produced for Phase 2.

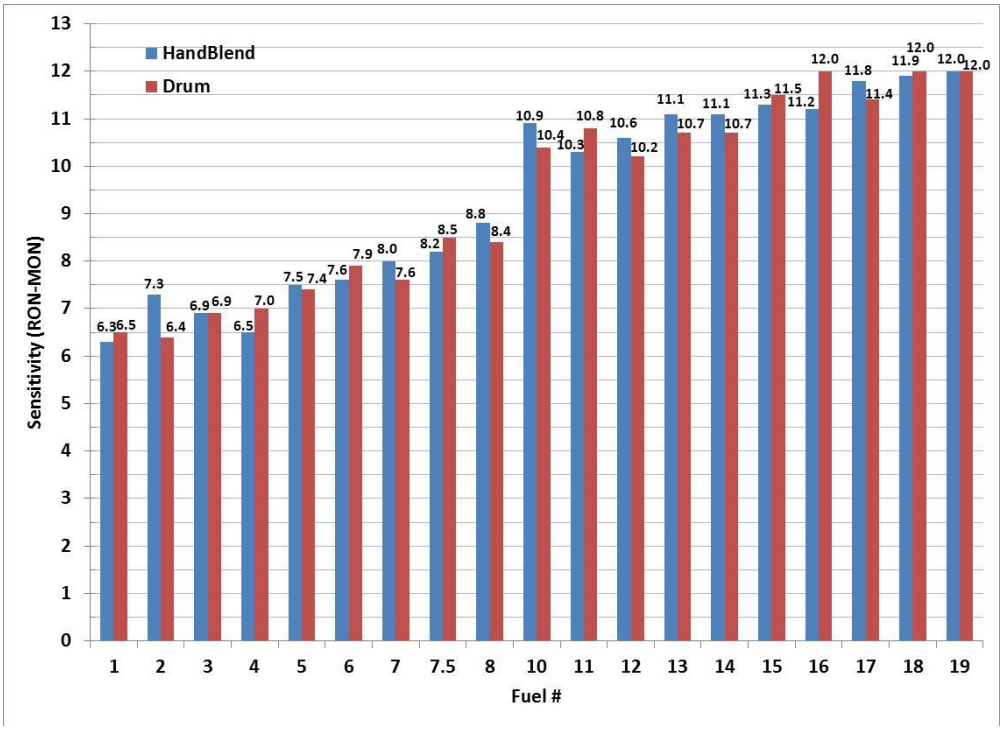

Figure 3.3. Sensitivity comparison for hand blends and drums produced for Phase 2.

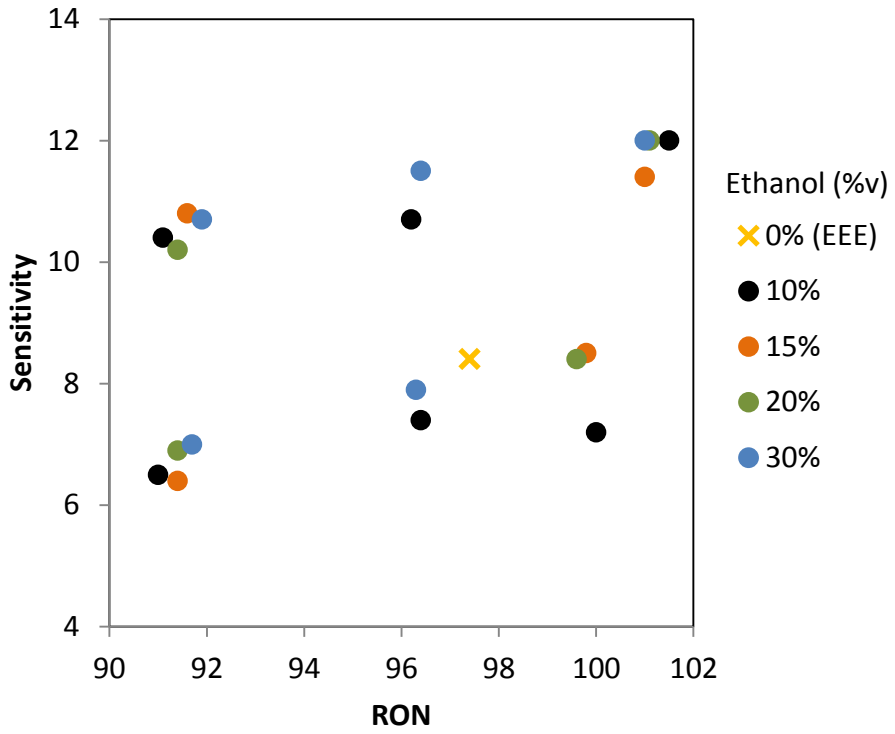

Figure 3.4. Phase 2 fuel octane sensitivity versus RON.

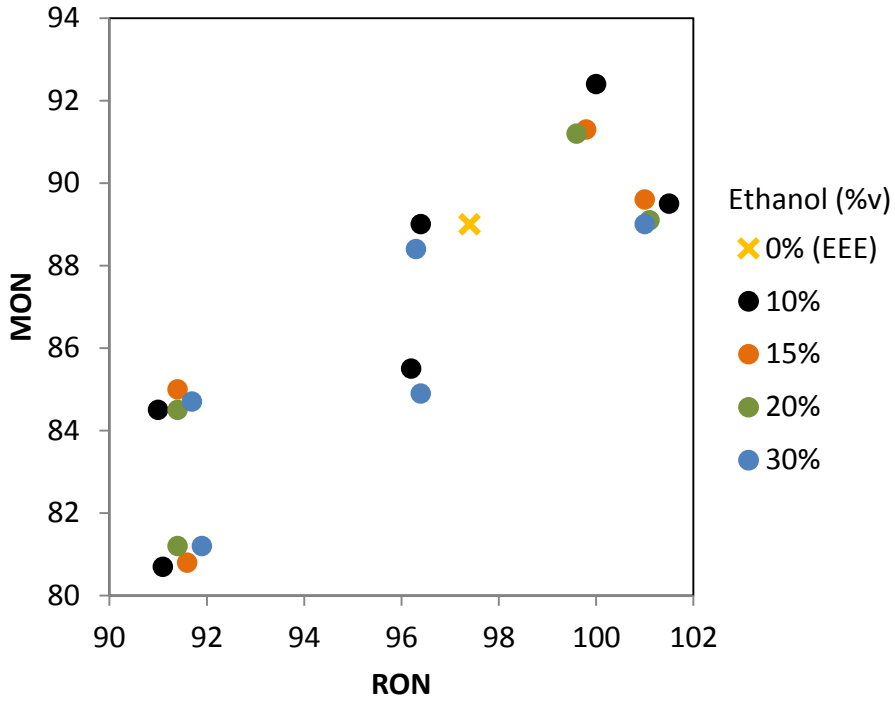

Figure 3.5. Phase 2 fuel MON versus RON.

4. HARDWARE AND FACILITIES FOR ENGINE STUDIES

4.1 ENGINE INSTALLATION

Engine studies were performed at ORNL using a model year 2013 Ford Ecoboost 1.6-liter, 4-cylinder engine. The production implementation of this engine features twin-independent cam phasing, center-mount direct fuel injection, and a single-stage turbocharger. The production pistons nominally produce a compression ratio of 10.1, though subsequent measurements of the hardware used for this project yielded a compression ratio of 10.5. Hereafter, the OEM pistons will be discussed as having a compression ratio of 10.5. The engine is rated to produce 178 horsepower (HP) at 5,800 RPM and a peak torque of 184 pound-feet (lb-ft) at 2400 RPM. The engine requires regular grade gasoline with at least 87 anti-knock index (AKI). The owner's manual for the 2013 Escape states that using a premium grade fuel with this engine will provide improved performance, and is recommended for severe duty such as trailer tow[26]. Fuel ethanol content for vehicles produced with this engine is specified to be 0-15%.

Additionally, ORNL procured piston blanks for the engine with technical assistance from Ford Motor Company. Blanks were used to produce two additional sets of pistons for the engine, one set that was designed to produce a compression ratio of approximately 12, and another set that was designed to produce a compression ratio of approximately 13. The compression ratios were later measured by using a liquid volume measurement technique, establishing that the new compression ratios were 11.4 and 13.2. The CR11.4 pistons have a bowl diameter of 55 millimeters (mm) and a depth of 7.75 mm from the top of the piston crown. This bowl diameter is approximately the same bowl diameter as used for the production pistons, but with a shallower bowl to yield an increased compression ratio. The OEM piston features a central dome, presumably to enhance in-cylinder charge motion, rather than a flat bottom with uniform depth. The top of the central dome is approximately 7.75mm from the top of the piston crown. This dimension was kept constant in the designs of the CR11.4 and CR13.2 pistons to assure clearance for the spark plug and fuel injector when the piston is at top dead-center. The CR13.2 pistons had a smaller bowl diameter of 38mm to further increase the compression ratio. A photograph of the three piston designs is shown in Figure 4.1.

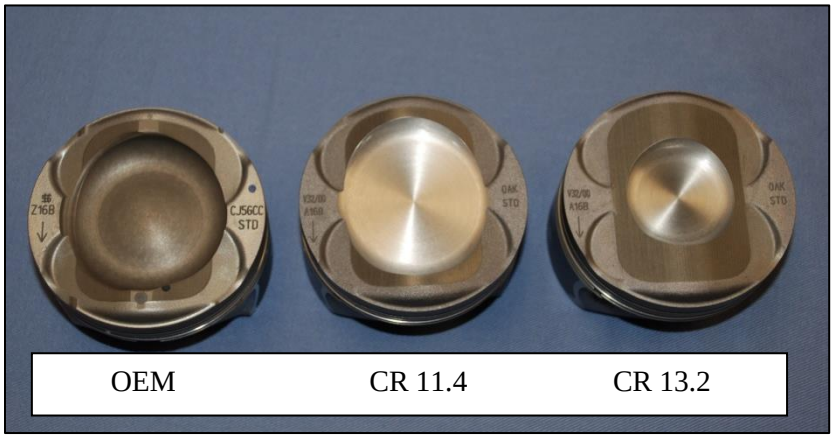

Figure 4.1. Photograph of the three piston designs.

The engine was installed in an engine dynamometer research cell at ORNL. Conditioned combustion air with control of both temperature and humidity was provided to the engine air intake. Heat exchangers

[26] 2013 Escape Owner's Manual, available online at: http://www.fordservicecontent.com/Ford_Content/catalog/owner_guides/13204om2e.pdf

were installed to allow control of the engine coolant temperature (approximately 95 °C), oil temperature (approximately 95 °C), and air temperature downstream of the intercooler (approximately 45 °C) through the use of process water as a heat sink. Temperature set points were maintained through the use of digital feedback controllers that actuated valves to control the flow of process water through the heat exchangers. A Dynamatic alternating-current (AC) dynamometer rated to absorb up to 233 HP and with a maximum speed of 6,000 RPM was used to provide a mechanical load to the engine output shaft. The engine was already in operation at the beginning of the AVFL-20 project and had been previously run at a variety of speeds and loads to break in the engine, which ensures that the piston rings are seated and that the friction and thermodynamic efficiency have stabilized. The dynamometer was controlled using a Dyne-Systems InterLoc-5 digital dynamometer controller. The InterLoc-5 also includes a digital throttle controller, which was used to actuate the accelerator pedal to control the torque output of the engine.

The engine was controlled using an engine control unit (ECU) provided by Ford Motor Company. The ECU contained a calibration for the engine that was similar to the calibration used for serial production, except that some features (such as anti-theft functions, transmission control, traction control, etc.) were disabled to facilitate operation in an engine test cell. Operator interface with the ECU was accomplished through Accurate Technologies Incorporated (ATI) Vision™ software. Vision allowed the operator to monitor, record, and change engine control parameters as needed to support the project. The Vision software communicated with the engine ECU through a universal serial bus (USB) linkage.

During experiments, the spark timing was adjusted to retard combustion phasing as necessary to avoid knock. As discussed previously, retarding spark timing causes combustion phasing to occur later in the cycle. A representative from Ford recommended limiting the crank angle location of 50% combustion (CA50) to no more than 30 CAD ATDC. This limit is based on the potential for unstable combustion if combustion is phased later than 30 CAD after TDC (ATDC) and also because retarding combustion phasing increases exhaust temperatures. Exhaust temperatures were limited to approximately 900 °C at the inlet of the turbine to protect the turbocharger from excessive heat that could decrease its reliability. Once the limits on CA50 and turbine inlet temperature were reached, air/fuel ratio enrichment was used to reduce the propensity for knock and the exhaust temperature. A lower limit of 0.75 (recommended by the Ford representative) was established for the relative air/fuel ratio (λ). Operation at λ values less than 0.75 creates excessive degradation of fuel efficiency and high levels of CO and hydrocarbon (HC) emissions. Enrichment generally was not needed at engine speeds below 2,000 RPM, but was used at some 2,500 RPM and 5,000 RPM high load conditions.

4.2 EMISSIONS MEASUREMENTS AND DATA ACQUISITION

Gaseous emissions from the engine were measured using standard methods: a heated photochemiluminescence analyzer for oxides-of-nitrogen (NO_X), a heated flame ionization detector for hydrocarbons (HCs), non-dispersive infrared detectors for carbon monoxide (CO) and carbon dioxide (CO_2), and a paramagnetic detector for oxygen (O_2). All of these instruments were manufactured by California Analytical Instruments, Incorporated (CAI). Particulate mass emissions were measured using an AVL Model 483 Micro-Soot Sensor. The micro-soot sensor uses an infrared photoacoustic detection method for soot. The instrument directly reports the mass concentration (mass of soot per volume of exhaust gas) in the engine exhaust pipe. The nature of the measurement process prevents droplets of unburned fuel from being measured as soot.

A custom Labview™ data acquisition system (DAS) was established and configured to receive analog inputs from the emission instrumentation as well as thermocouples and pressure sensors that are typical devices for measuring temperatures and pressures throughout the engine and associated components. The

DAS provides the ability to collect the laboratory data streams to data files as well as providing online visual feedback to support safe and reliable test cell operation.

4.3 COMBUSTION ANALYSIS SYSTEM

A DRIVVEN µDCAT combustion analysis system was used to support the project. (DRIVVEN has subsequently been purchased by National Instruments, and newer versions of the same software system and associated hardware modules are now sold through National Instruments Powertrain Controls.) Combustion analysis is accomplished through high-speed measurement of the pressure in the combustion cylinders synchronously with the rotational position of the crankshaft. In combination with the known (from engine geometric information) volume of the combustion cylinders at each crankshaft rotation position, these data can be used to evaluate the combustion process. This process is a powerful means for examining engine performance, but it is important to recognize that the only measurements are the relevant pressures. Other metrics such as cylinder gas temperature, heat release rates, and combustion durations are values derived from the pressure data and are not independent measurements.

4.3.1 Cylinder Pressure Measurements

Cylinder pressure measurements were accomplished by mounting high-speed piezoelectric pressure transducers into each combustion chamber. Kistler 6052CU20 transducers were used for this purpose. These transducers were mounted in each combustion chamber through ports machined into the cylinder head. The transducers were connected to Kistler model 5010 charge amplifiers, which convert the signals from the pressure transducers to analog voltages for measurement by the µDCAT system.

A BEI rotary encoder was installed to measure the rotation of the engine crankshaft. The encoder had a resolution of 1,800 pulses per revolution, or 1 pulse every 0.2 crank angle degrees (CAD). The rotational position of the engine crankshaft directly determines the piston position and thus the instantaneous volume of the cylinders. The µDCAT system recorded the signal from the pressure transducers synchronously at each electrical pulse produced by the encoder.

Piezoelectric pressure transducers require a reference measurement at a known pressure in order to convert their signals to an engineering value. The process of making this comparison and establishing the pressure being measured by the piezoelectric transducer is frequently referred to as “pegging”. Pegging was accomplished in this application by using a low-speed transducer mounted in the engine intake manifold. The µDCAT system measured this pressure at a fixed location in the engine cycle where the intake valves were open. At this point, the cylinder pressure is, to a good approximation, the same as the intake manifold pressure, allowing the cylinder pressure transducer readings to be correctly referenced to a known pressure during each engine cycle.

4.3.2 Knock Detection

The µDCAT system incorporates a knock-detection algorithm that can utilize several different signal sources to detect knock in the engine. Audible knock is a result of the undesired autoignition of unburned pockets of fuel and air mixture in the cylinder. When an autoignition occurs, it causes pressure waves to propagate through the cylinder at known frequencies that are related to the cylinder dimensions and the in-cylinder gas temperature. An automotive knock sensor responds to the transmission of these pressure waves through the cylinder walls. However, since the forcing functions for the signals measured by a knock sensor are the pressure waves within the cylinder, measuring the in-cylinder pressure can be used to detect knock. For this project, the cylinder #1 pressure signal was split to both a synchronous

measurement channel (for combustion characterization) and a high-speed asynchronous channel (for knock detection). The high-speed asynchronous channel sampled the pressure in cylinder #1 on a time basis, rather than on a crank-angle basis, so that high-frequency oscillation in the pressure can be measured.

The algorithm used for knock detection in the µDCAT system is a BRIC method: that is, the signal is first **B**andpass filtered, **R**ectified, **I**ntegrated, and then **C**ompared with the same signal in a non-knocking portion of the engine cycle. The first step, bandpass filtering, restricts the signal analysis to the target frequency range. The µDCAT system calculates the frequencies that are characteristic of knock for the engine, and allows the user to select the cutoff frequencies for the knock-detection algorithm. In this case, the cutoff frequencies were selected as 10 kHz and 50 kHz. This frequency range was selected to include the primary knocking frequency and the first harmonic frequency. This filter is applied to pressure measurements conducted in the crank-angle space where knock is possible (0 CAD ATDC to 50 CAD ATDC) and in a crank angle space where knock is not possible (-210 CAD ATDC to -180 CAD ATDC). Next, both signals are rectified and integrated to produce a numerical metric that is proportional to the energy contained in the pressure pulsations in both the knocking and non-knocking portions of the engine cycle. Finally, the signal from the knocking region is divided by the signal from the non-knocking region, producing a final value that indicates the strength of the signal in the knock region relative to that of the non-knocking region. This value is reported as a nondimensional metric of knock intensity. This measurement was only carried out for cylinder number 1, which was assumed to be representative of the other cylinders. The in-cylinder pressure traces for all four cylinders were also examined at each condition, allowing the operator to visually assess whether there were gross differences in the knock behavior of all four cylinders. No gross differences in the onset of knock among the cylinders was noted during this study.

5. PHASE 2: ANTI-KNOCK SCREENING

Phase 2 of the project was to conduct an anti-knock screening study on 19 fuel blends that were finalized during Phase 1. To accomplish the anti-knock screening, a load sweep was conducted at 2,000 RPM for each fuel in the Ford 1.6L engine. In principle, it is possible to increase the engine compression ratio and the fuel anti-knock properties together, improving efficiency without compromising the ability of the engine to produce its rated torque as a result of the onset of knock. The objective of the anti-knock screening was to identify fuel and compression ratio combinations that closely approximated the combustion phasing and engine performance of the original engine when fueled with a baseline (~91 RON) gasoline and to down-select fuel / CR pairs for the more in-depth engine studies in Phase 3.

5.1.1 Fuel Anti-knock Screening Process

The first step was to purge the fuel system and introduce the desired test fuel. This process began with draining the source and return lines for the low-pressure fuel pump to remove as much of the previous fuel as possible. Then the source line was placed in the desired drum of fuel and a quantity of approximately 2 quarts of fuel was pumped through the pump system and out through return line into a waste can to purge the low pressure pump and remaining tubing with the new fuel. Fuel was pumped into a waste can (instead of flowing back to the fuel drum through the return line) to prevent cross-contamination of the fuel drum by return flow once the return line was connected to the fuel drum. Once the low-pressure pump was purged, the return line was connected to the desired fuel drum. Next, approximately 1 gallon of fuel was pumped through the transfer line to the engine and rejected through a purge port into a waste can. The purge port was located as close as practical to the inlet of the high-pressure fuel pump on the engine and allowed rapid changeover of the fuel in the longer transfer line. Finally, the fuel changeover was completed by operating the engine. The engine was first started and allowed to reach operating temperature at 2,000 RPM and a BMEP of approximately 200 kPa. Once the engine reached operating temperature, the engine BMEP was increased to approximately 800 – 1000 kPa to increase the fuel consumption rate. This condition was held for 15 minutes to burn whatever volume of the previous fuel might still have been present in the fuel pump, fuel rail, and transfer line. Once this operating condition was completed, the engine was returned to a brake torque of 10 ft-lbs and collection of data was initiated.

The engine control unit (ECU) adapts to the anti-knock quality of the fuel by detecting knock and either advancing or retarding the spark timing to maximize engine efficiency while avoiding knocking conditions. The authority of the anti-knock algorithms in the ECU to advance or retard spark is set by tables that contain numerical limit values for different engine conditions. Prior to the collection of data, the values in both the spark advance limit and spark retard limit tables were set to zero at all conditions so that avoidance of knock was controlled by the engine operator and not the ECU. This step was taken because the ECU anti-knock calibration could not be assumed to respond to knock consistently when non-standard pistons were used to change the compression ratio.

Next, the engine was operated at target brake torque points that were spaced nominally at 10 ft-lb increments, beginning with 10 ft-lbs. At each point, the commanded spark timing was adjusted to achieve a target 50% mass fraction burned location (CA50) of ~5 crank angle degrees (CAD) after top dead-center (ATDC). On-screen traces for fuel consumption and emissions were monitored to determine when the readings reached steady values. Once this occurred, data collection was initiated. Engine performance, combustion, and emissions data were collected simultaneously. Upon completion of data collection, the engine torque output was increased by physically actuating the accelerator pedal using a digital throttle controller to move to the next desired condition.

As engine load was increased, CA50 phasing was held approximately constant at 5 CAD ATDC until the increased load caused the onset of knock, at which point CA50 timing was retarded by retarding spark timing. The region of operation for each fuel where knock did not occur (where the CA50 phasing was held approximately constant at 5 CAD ATDC) was defined as the maximum brake torque, or MBT region. The onset of knock generally occurred at engine torques of 60 – 90 ft-lbs (depending on fuel and compression ratio), corresponding to brake mean effective pressure (BMEP) levels of approximately 600 – 900 kPa. Once the onset of knock was observed, the CA50 phasing was set at the most advanced point possible while remaining at a borderline knock condition.

On-screen displays of the non-dimensional knock intensity metric described previously were used to ascertain when a borderline knock condition was achieved. A knock intensity trend chart provided a means for observing the knock intensity that resulted from changes in spark timing. Spark timing was initially advanced until knock was observed as a sudden, large increase in the knock intensity for a small increase in spark advance. Once knock was encountered, the spark timing was retarded in 0.5 degree increments to remove the knocking condition.

5.1.2 CA50 Phasing Results

All 19 fuels were screened at compression ratio 11.4. This compression ratio was chosen as a compromise for screening all fuels while assuring that none produced excessively advanced or retarded combustion phasing. A subset of the fuel matrix was then screened at CR13.2, followed by another subset at CR10.5. A federal emissions certification gasoline (Haltermann EEE, batch CE2121LT10) was added to the screening study for comparison. Table 5.1 shows the fuels and CRs at which they were screened. In general, fuels tested at CR 10.5 were 91 RON while fuels tested at CR 13.2 were 101 RON. Fuels 5, 15, and EEE (all ~96 RON) were tested at all three CRs.

The knock-limited CA50 results for CR11.4 are shown in Figures 5.1, 5.2, and 5.3, for the 91-RON, 96-RON, and 101-RON fuels, respectively. In these figures, the CA50 is plotted as a function of BMEP. Images of the fuel matrix are included identifying the fuels compared in that figure. The symbol and line colors indicate differing ethanol content. Filled symbols are used for low-sensitivity fuels and open symbols for high-sensitivity fuels.

In general, the CA50 data for CR 11.4 show that the fuels within a RON group perform similarly to one another. The CA50 data for the low-RON fuels do not indicate great differences within the variability of the data. The mid-RON fuels are also self-similar in terms of CA50, but fuel #15 has CA50 phasing in the highest load, highly retarded region that is several degrees more advanced than the other ethanol fuels. The performance of the E0 EEE fuel is better than that of fuel #15 up to a BMEP of about 1000 kPa. The results for the high-RON fuels indicate that combustion tends to be more advanced at high loads for the high-sensitivity fuels, although there doesn't appear to be an effect of ethanol content for those fuels. This trend is also evident with the low-RON and mid-RON fuels, but is most clearly seen with the high-RON fuels. Overall, the phasing of CA50 in the knock-limited load range correlated with the RON level of the fuels, as expected, with the high-RON fuels showing combustion phasing about 5-10 CAD more advanced than the low-RON fuels at CR11.4. The overlap of the curves for fuels #16, #17, #18, and #19 suggest that there are no particular observable combustion phasing benefits of higher ethanol content for the fuels having similar high RON and sensitivity values at this compression ratio.

Table 5.1. Fuel and compression ratio pairs selected for anti-knock screening.

Fuel #	1	2	3	4	5	6	7	7.5	8	10	11	12	13	14	15	16	17	18	19	EEE
CR10.5	X			X	X					X	X	X	X		X					X
CR11.4	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
CR13.2					X		X		X						X	X	X	X	X	X

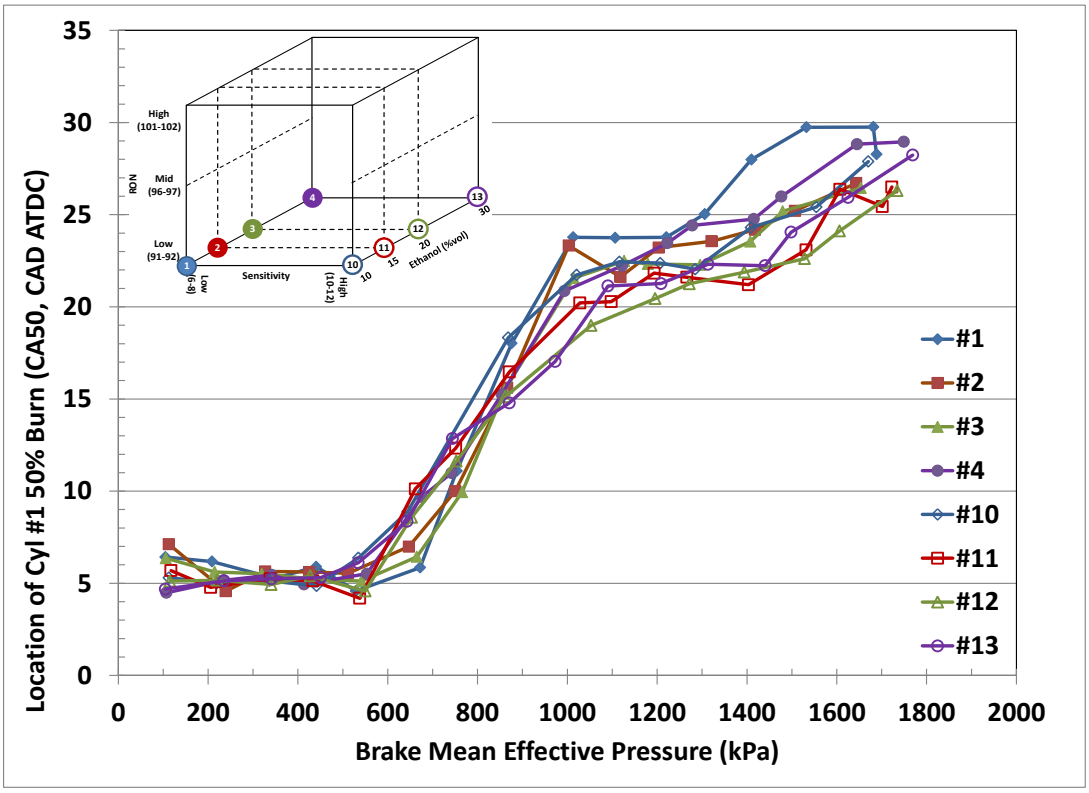

Figure 5.1. CR11.4 anti-knock screening CA50 results for 91-92 RON fuels (knock-limited CA50).

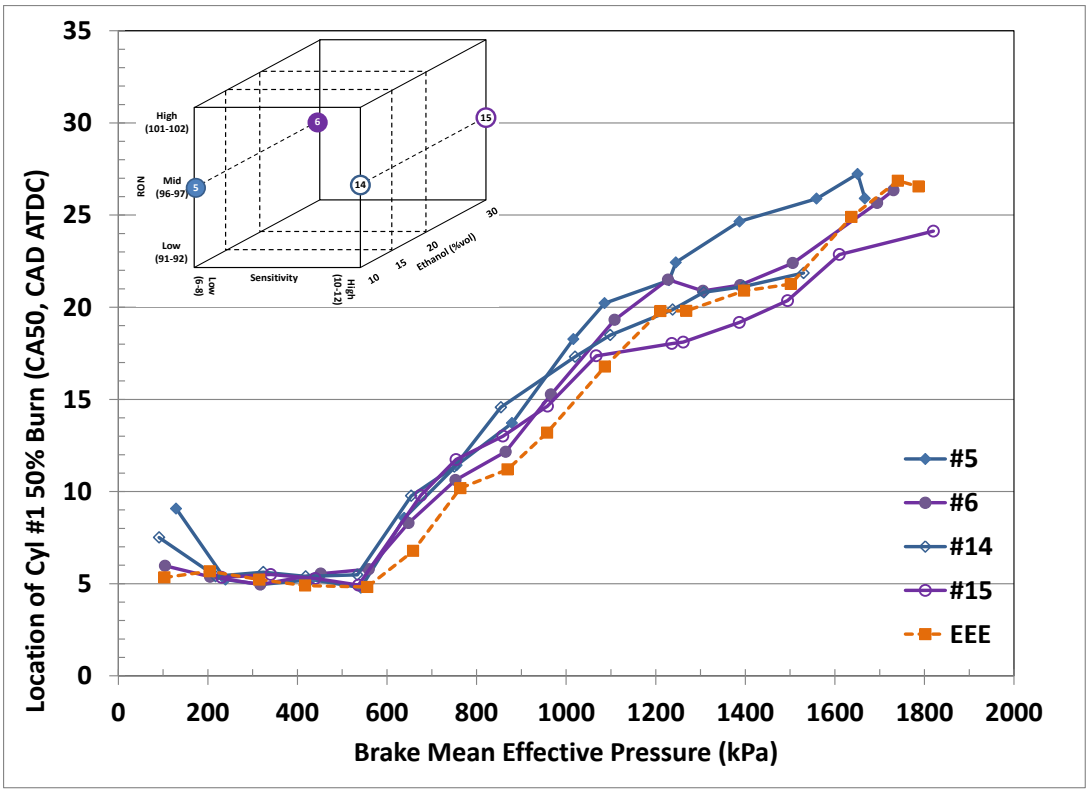

Figure 5.2. CR11.4 anti-knock screening CA50 results for 96-97 RON fuels.

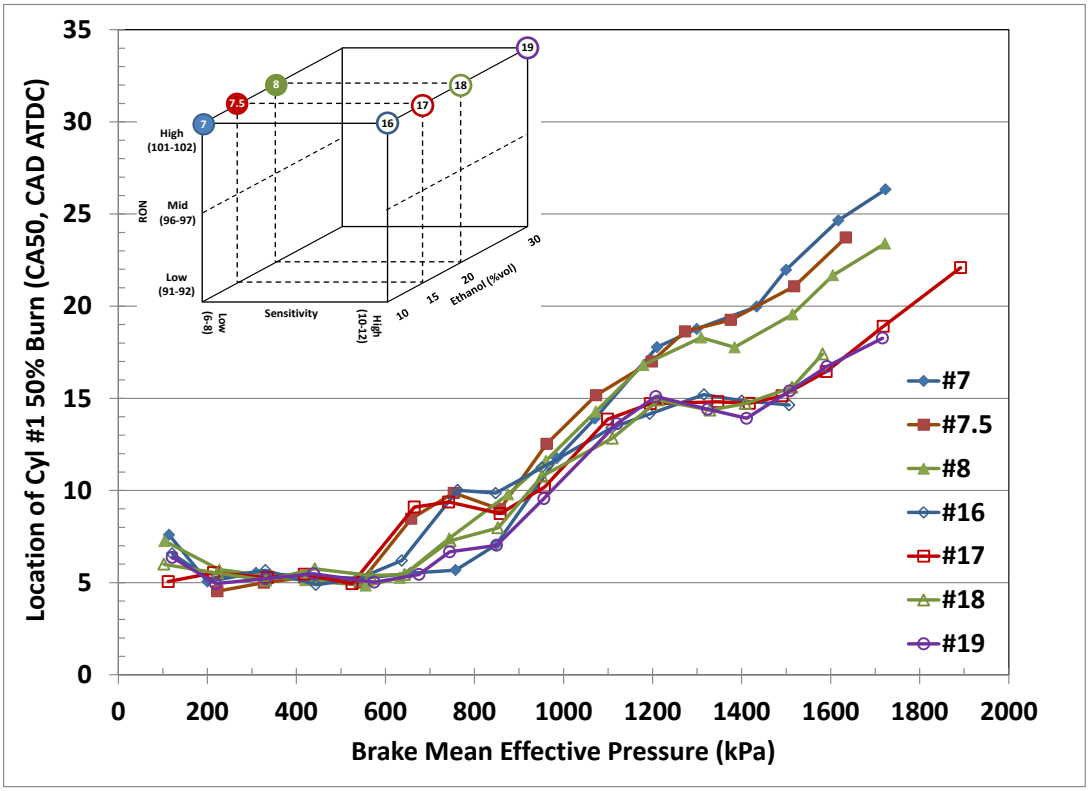

Figure 5.3. CR11.4 anti-knock screening CA50 results for 101-102 RON fuels.

The CA50 results for the CR13.2 condition are shown in Figure 5.4, with the same symbols for fuel identification as were used for the CR11.4 results. In addition to the high-RON fuels, the mid-RON fuels (#5, #15, and EEE) were also run. The mid-RON fuels are shown using orange dashed lines to distinguish them from the high-RON fuels. At CR13.2, the results again show a separation between the low- and high-sensitivity fuels. The high-sensitivity fuels have a significantly more advanced CA50 phasing. It is also interesting to note that the CA50 phasing for the two low-sensitivity, high-RON fuels were similar (fuel #8) or more retarded at BMEP above 1000 kPa (fuel #7) than the high-sensitivity, mid-RON fuel (#15). The other mid-RON fuels (#5 and EEE) had more retarded CA50 timing than the high-RON fuels, as expected. Also evident from the CR13.2 data is the fact that fuels without sufficient anti-knock qualities result in CA50 reaching the limit of 30 CAD ATDC at lower BMEP levels. The lower achievable BMEP level means that these fuels, when used with CR13.2, would cause a performance detriment compared to fuels with greater anti-knock qualities. The overlap of the curves for fuels #16, #17, #18, and #19 suggest that there are no particular observable benefits of higher ethanol content for the fuels having similar high RON and sensitivity values at this compression ratio.

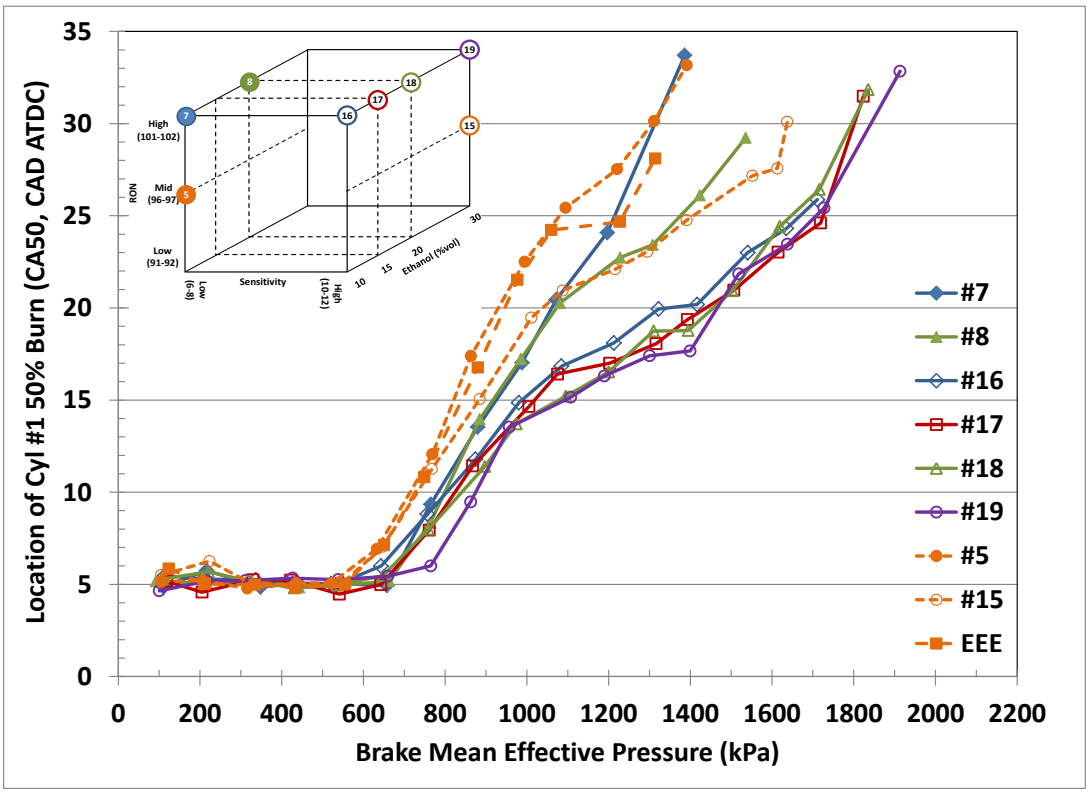

Figure 5.4. CR13.2 anti-knock screening CA50 results.

The CR10.5 CA50 results are shown in Figure 5.5. Once again, the mid-RON fuels are shown with dashed-orange lines to distinguish them from the low-RON fuels in this graph. In this case, the mid-RON fuels have more advanced CA50 than the low-RON fuels, as expected. The low-RON fuels had generally similar knock limits to each other. Surprisingly, fuel #10 (a high sensitivity E10) was slightly more knock-limited than fuel #1 (a low sensitivity E10). The low-RON, low-sensitivity fuels had MON levels of about 85, compared to about 81 MON for the high-sensitivity fuels. Fuel #10 has a MON of just less than 81, compared with marginally higher MON values for fuels 11-13. However, the results from fuels #5 (up to a BMEP of about 1300 kPa) and #15 show that if RON is higher, high sensitivity produces less

knock-limited phasing than the other ethanol-containing fuels, as was also observed at both CR11.4 and CR13.2. At the same RON (96) and same sensitivity (7), fuel EEE (E0) offers better knock resistance than fuel #5 (E10) at all compression ratios studied. Interestingly, the results of the low-sensitivity, E0 EEE fuel track those of fuel #15.

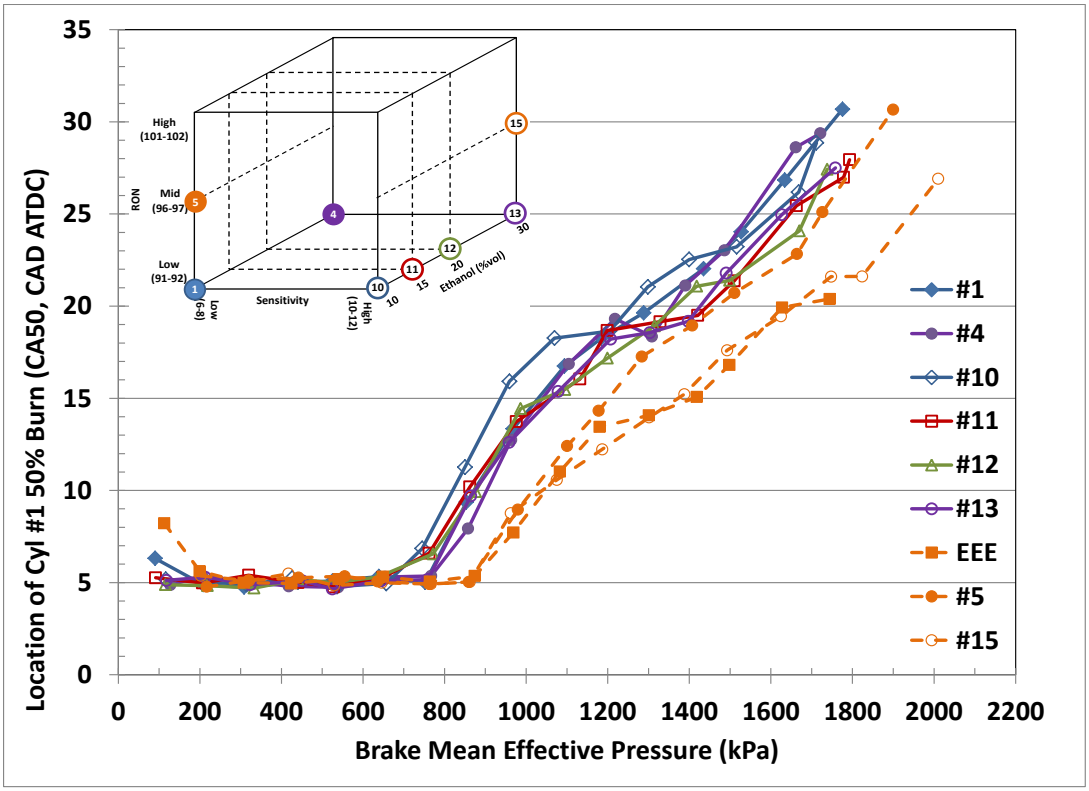

Figure 5.5. CR10.5 anti-knock screening CA50 results.

5.1.3 CA50 Results Relative to Baseline Condition

While the CA50 results discussed above are informative, it is useful to compare them to a baseline condition to aid in establishing fuel and CR pairs that approximate the performance of the OEM engine and marketplace fuels. For this purpose, the CA50 data for fuel #1 at the CR10.5 condition were taken as a baseline condition, since the octane values of fuel #1 approximates a regular-grade E10 marketplace fuel. Since the BMEP points for all of the fuels exhibit some variability, the knock-limited CA50 data for fuel #1 was fit with a third-order curve to allow calculation of a baseline CA50 for each of the BMEP levels where data was logged for the other fuels. The baseline CA50 data and curve fit are shown in Figure 5.6, with red data points indicating results in the maximum brake torque (MBT) region and blue data points indicating knock-limited conditions that were used for the third-order curve. The baseline CA50 was then calculated at each BMEP point for all fuel and CR pairs and subtracted from the observed CA50 to produce a metric of ΔCA50. At this point, the combustion phasing versus BMEP plots that have been discussed previously were re-created using the ΔCA50 metric. These plots are shown as Figures 5.7 – 5.11 and are presented in the same order and with the same symbols for fuel identification as used previously. In these figures, a value of zero indicates that the CA50 was the same as that observed for the baseline condition. Values greater than zero indicate that the CA50 was more retarded than baseline, and values less than zero indicate that the CA50 was more advanced than the baseline. A fuel-CR pair that

exactly matches the performance of the baseline condition would therefore have a flat line at zero, and that fuel would enable use of that CR with the same knock behavior as the baseline condition. Fuel-CR pairs that approximate the baseline condition would have values that are either slightly positive or negative, with slightly negative being more desirable. Large positive values indicate that the selected CR requires more knock resistance than the fuel provides, while large negative values indicate that that the fuel has more knock resistance than the selected CR can effectively utilize.

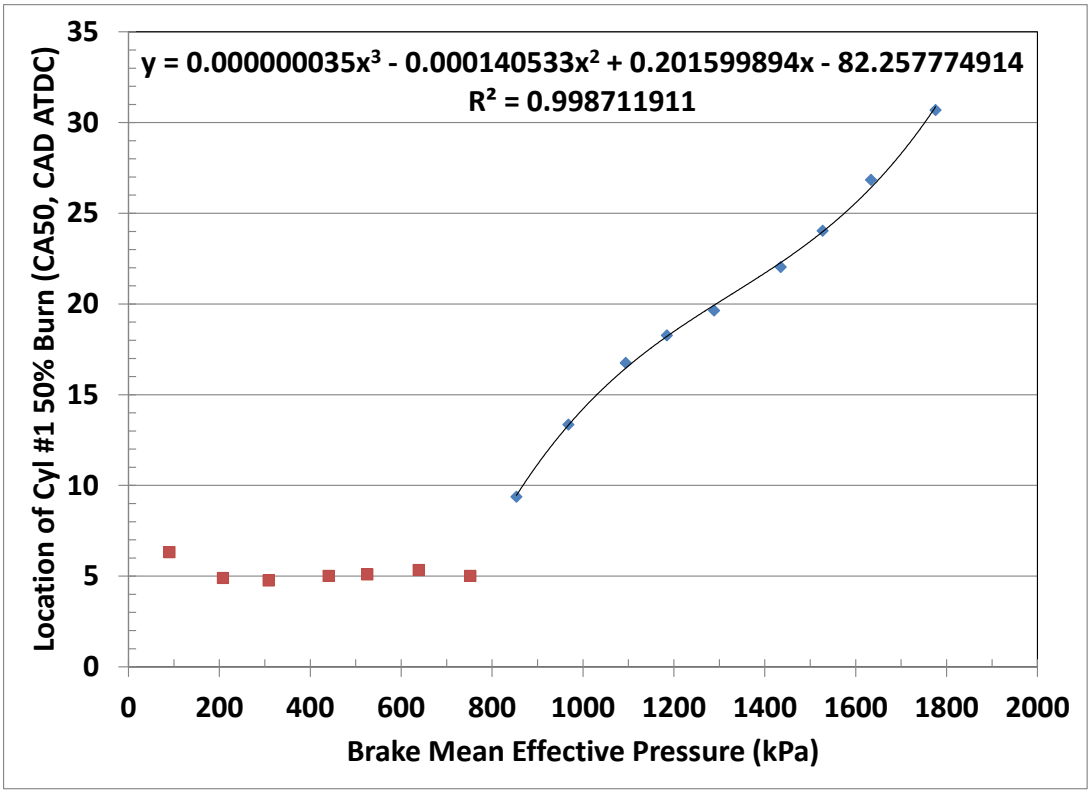

Figure 5.6. CR10.5 fuel #1 CA50 data and curve fit for the knock-limited region of the data.

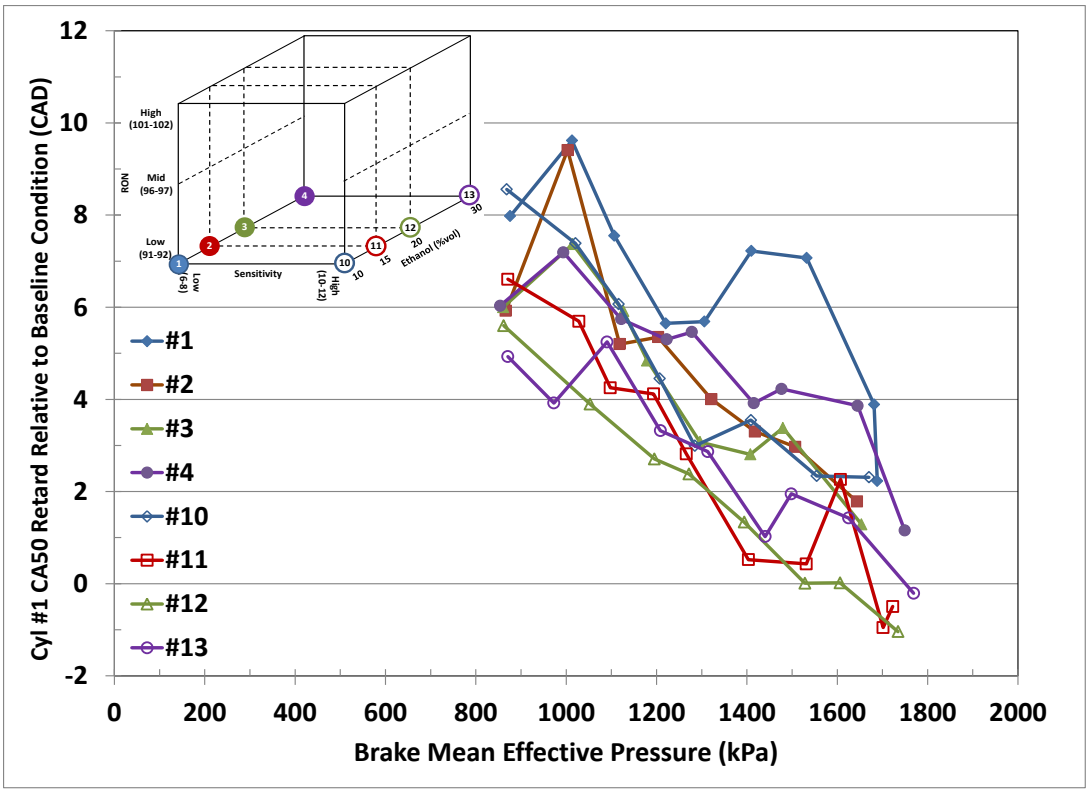

Figure 5.7. CR11.4 ΔCA50 results for 91-92 RON fuels (relative to fuel#1 at CR10.5).

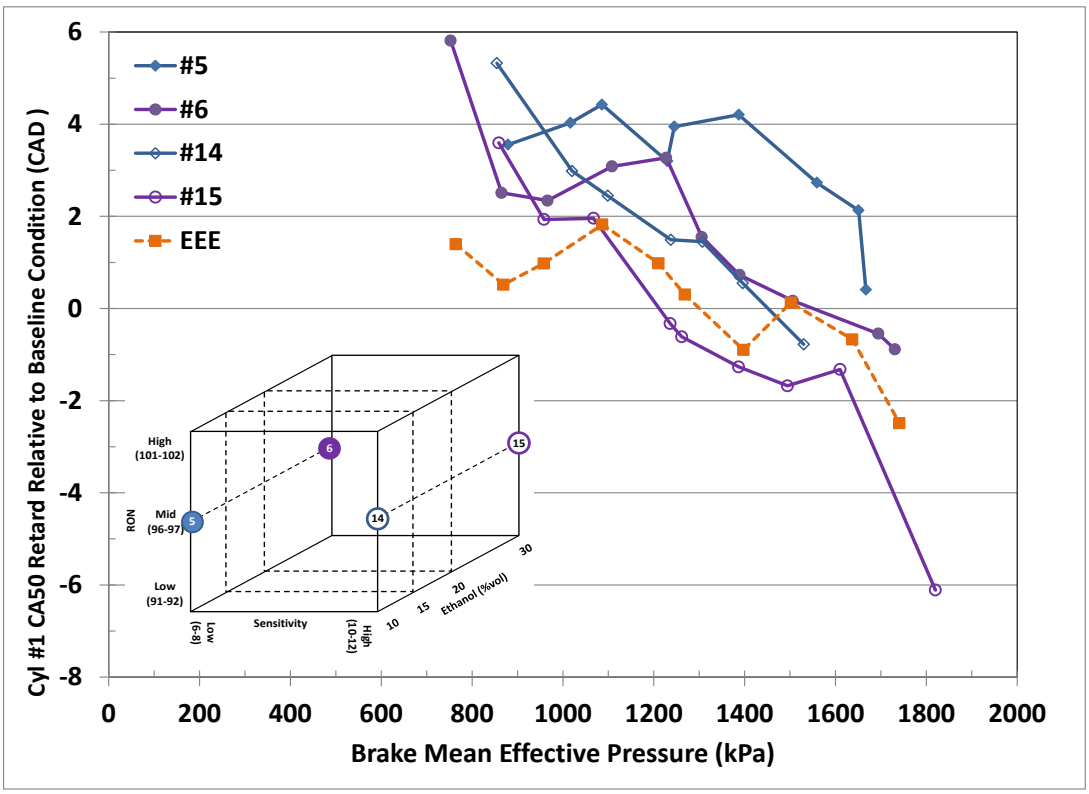

Figure 5.8. CR11.4 ΔCA50 results for 96-97 RON fuels (relative to fuel#1 at CR10.5).

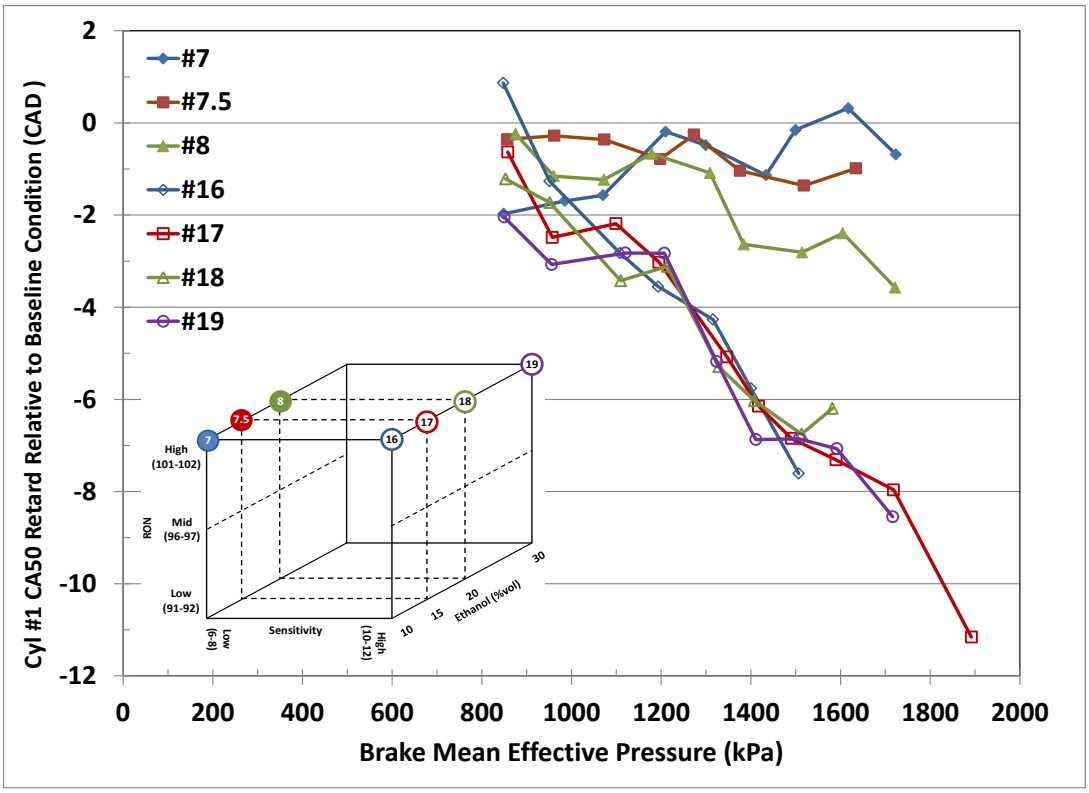

Figure 5.9. CR11.4 ΔCA50 results for 100-101 RON fuels (relative to fuel #1 at CR10.5).

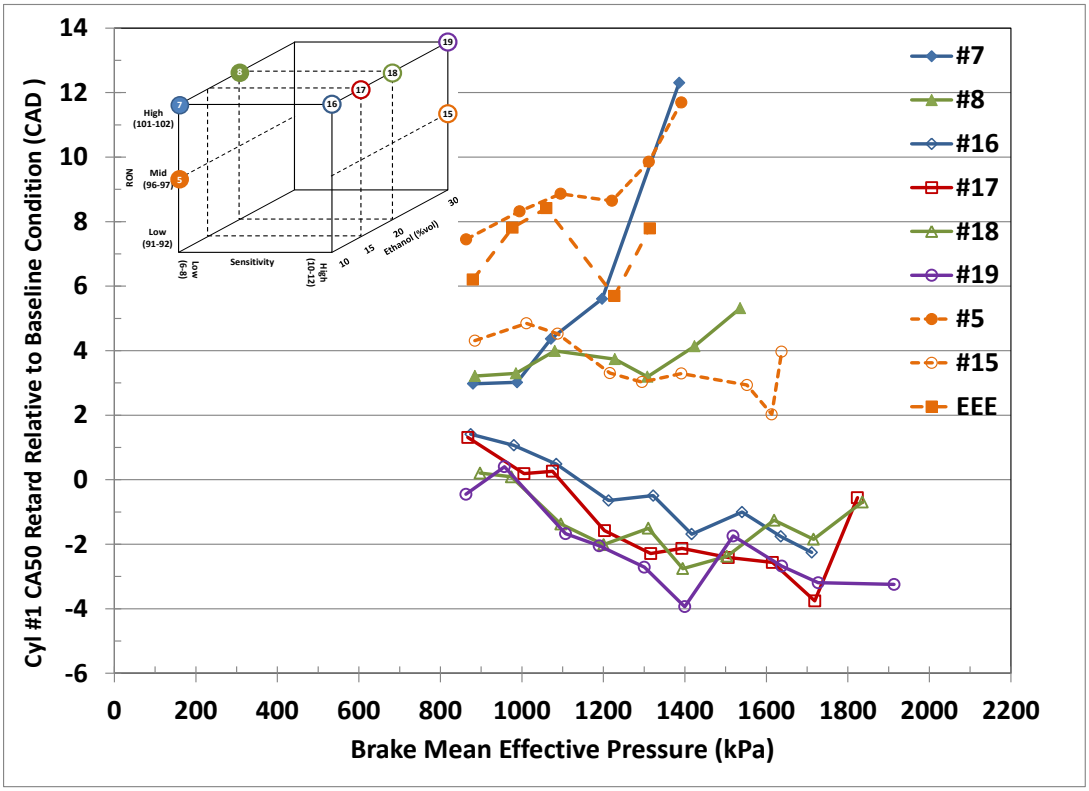

Figure 5.10. CR13.2 ΔCA50 results (relative to fuel#1 at CR10.5).

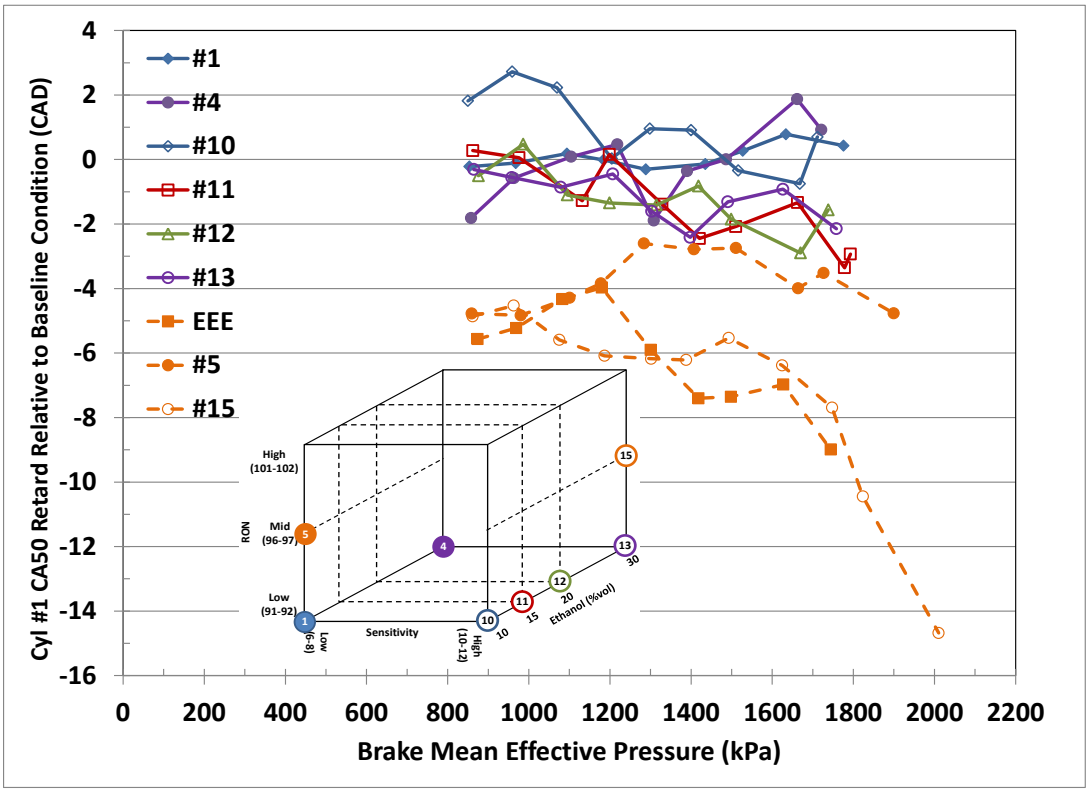

Figure 5.11. CR10.5 ΔCA50 results (relative to fuel#1 at CR10.5).

The CR11.4 results for the low-RON fuels show that all ΔCA50 values are positive, indicating that none of these fuels provide sufficient knock resistance for use with CR11.4. The mid-RON fuels show ΔCA50 trends that cross zero or are only positive or negative by a few degrees, indicating that ~96-97 RON fuels enable CR11.4 with approximately the same knock behavior as the baseline. Fuel #15 and EEE are good examples of this trend. The results for the 101-102 RON fuels at CR11.4 show that the low-sensitivity fuels have small positive or negative values, while the high-sensitivity fuels have large negative values at high BMEP levels, with no apparent benefits of higher ethanol content.

The CR13.2 ΔCA50 results show that the mid-RON fuels (with the possible exception of #15) have large positive values and thus do not provide sufficient knock resistance for use with CR13.2. Fuels #15 and #8 have similar performance, as noted previously. Fuel #7 shows significantly more retarded phasing than #8; the same pattern is also apparent at CR11.4. Fuel #8 has higher ethanol content, perhaps indicating that the ethanol content is affording more advanced combustion phasing at the same RON and sensitivity level. The high-RON, high-sensitivity fuels all show near-zero values at moderate loads and negative values at high loads, with no obvious trend with ethanol content. In general, the high-RON, high-sensitivity fuels seem to be the best candidates for use with CR13.2 with approximately the same knock behavior as the baseline.

The CR10.5 data show that the low-RON fuels have ΔCA50 values that generally fall between ±2 CAD of baseline, indicating that they are very similar to the baseline case, as could be expected, with no discernable effect of ethanol content. The mid-RON fuels have negative ΔCA50 values, which is not surprising since this engine is known to achieve higher performance when premium fuel is used. In particular, fuel #15 with high sensitivity and 30% ethanol content shows the most negative values, although the mid RON E0 EEE fuel shows similar results, at least up to 1700 kPa BMEP.

5.1.4 Fuel/CR Recommendations for Phase 3

The Phase 2 data were reviewed by the AVFL-20 project committee to down-select to 7 fuels that would be included in the Phase 3 engine mapping and vehicle modeling stage of the project. These selections are summarized in Table 5.2. After considerable discussion, the working group agreed to recommend study of fuels #1, #10, and #15 at CR10.5, followed by fuels #6, #7, #14, and #15 at CR11.4. Finally, fuels #7, #14, #15, #16, and #19 would be studied at CR13.2. Thus a total of 12 fuel-CR combinations were selected for Phase 3 testing. The project committee selected these fuels on the basis of their performance at the different compression ratios, with consideration for allowing comparisons among RON, sensitivity, and ethanol content from the Phase 3 data. These recommendations were presented to and approved by the AVFL committee.

Table 5.2. Fuel / CR pairs selected for Phase 3 studies.

Fuel	CR 10.5	CR11.4	CR13.2
#1	√		
#6		√	
#7		√	√
#10	√		
#14		√	√
#15	√	√	√
#16			√
#19			√

6. PHASE 3 – ENGINE MAPPING AND VEHICLE MODELING

Phase 3 of the project focused on generating engine maps to support vehicle modeling using the fuels down-selected from the Phase 2 anti-knock screening study.

6.1 PHASE 3 FUEL PROPERTIES

CRC commissioned Gage Products to produce three 55-gallon drums of each of the selected fuels. The 3-drum volume was judged to be sufficient to support both AVFL-20 Phase 3 as well as AVFL-20a project activities, allowing both projects to use fuels manufactured as one batch. Gage provided measurements of RON, MON, density, RVP, distillation, and aromatic, olefin, and saturate content. Copies of the certificates of analysis provided by Gage are included in Appendix D, and summarized in Table 6.1. The properties of the Phase 3 fuels were confirmed to agree very closely with those of the Phase 2 fuels. Figure 6.1 shows the net heating value comparison, with the error bars representing the stated repeatability for ASTM D4809.

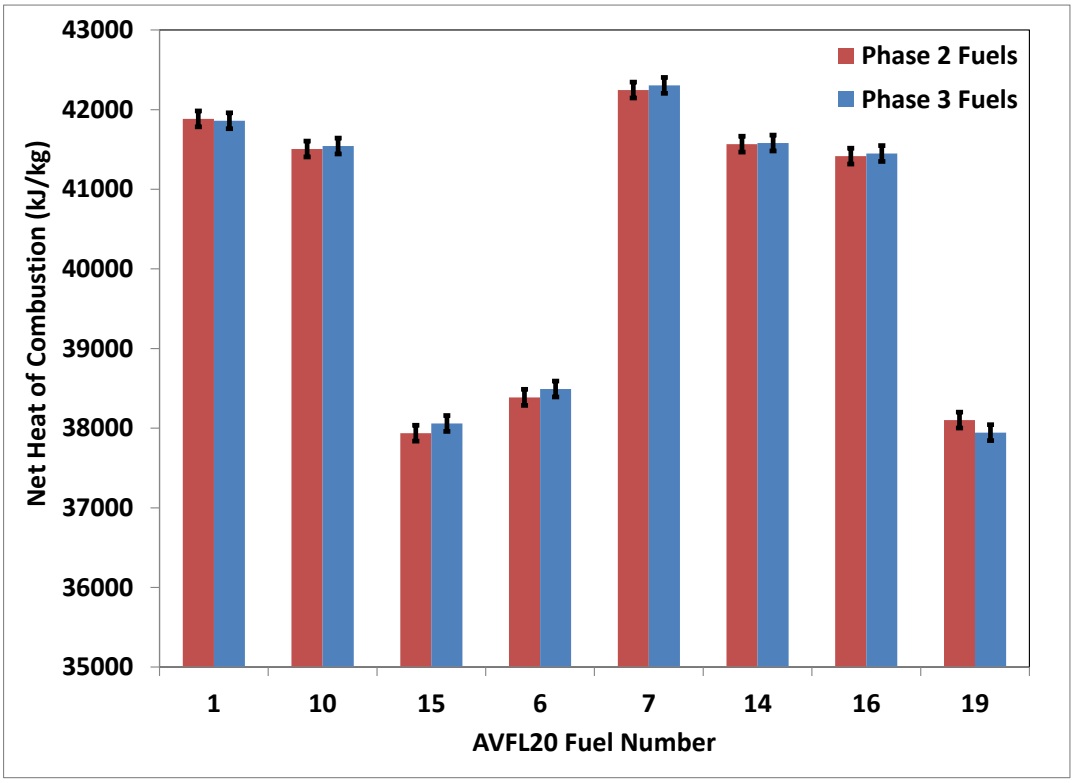

Figure 6.1. Comparison of ASTM D4809 Net Heating Value results for Phase 2 and Phase 3 fuels.

At the conclusion of Phase 2, the OEM CR10.5 pistons were re-installed in the engine. Thus, for Phase 3 the first maps conducted were for the fuels selected for evaluation at the lowest compression ratio, 10.5. The run order for the fuels was #1, #10, and #15. Following the CR10.5 studies, the CR11.4 pistons were installed and data collected for fuels #6, #7, #14, and then #15. Finally, the CR13.2 pistons were installed with the intention of collecting data for fuels #7, #15, #16, and #19.

Table 6.1. Gage Products reported values for design variables in Phase 3 fuels.

Fuel	RON	MON	Sensitivity	Ethanol Content (Vol%)
1	91.8	84.5	7.3	10.4
6	96.0	88.5	7.5	30.0
7	100.1	92.5	7.6	10.1
10	91.4	81.0	10.4	10.0
14	96.6	85.5	11.1	10.4
15	96.5	84.9	11.6	30.4
16	101.1	89.3	11.8	10.2
19	101.0	89.0	12.0	29.9

6.2 ENGINE MAPPING

The methods and procedures detailed previously for the Phase 2 studies were also adopted for use in the Phase 3 efforts. The automotive members of the project committee showed data indicating that operation in the speed range from 2,500 RPM to 5,000 RPM on standard drive cycles is very sparse, making data collection in that region less important to vehicle models aimed at the standardized drive cycles. The project technical committee, after considerable discussion, agreed that an abbreviated mapping procedure be used. This procedure focused on collecting engine data at 1,000 RPM, 1,500 RPM, 2,000 RPM, 2,500 RPM, and 5,000 RPM in nominal 100 kPa BMEP load increments at each speed. Additionally, the maximum torque achievable at speeds between 2,500 RPM and 5,000 RPM was collected in 500 RPM increments. Eliminating data collection at speeds between 2,500 RPM and 5,000 RPM allowed a larger number of fuels to be included in the Phase 3 study. Generally, data collection was initiated at 1,000 RPM and moved upward in engine speed until all desired data had been collected. Figure 6.2 shows the speed and load conditions for a typical engine map.

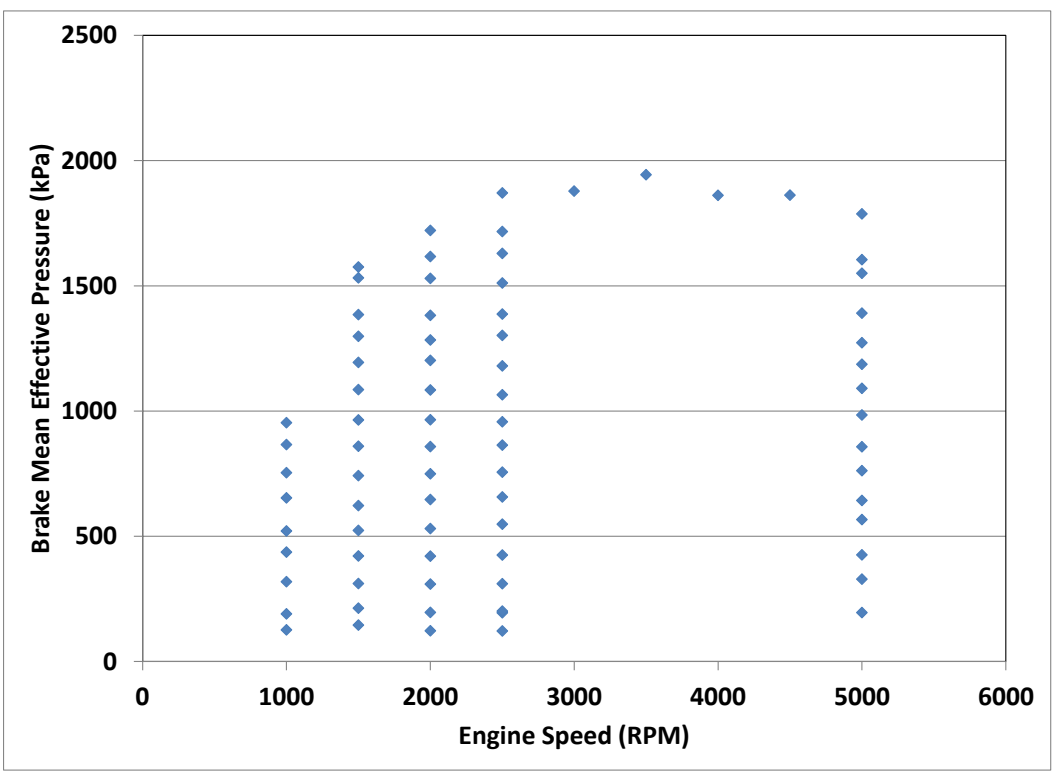

Figure 6.2. Speed and load conditions investigated for the engine map of fuel #1 at CR10.5.

In the absence of knock, the CA50 phasing was adjusted to approximately 5 CAD ATDC, which is typical of MBT phasing. Both positive and negative offsets to the spark timing were needed to accomplish this phasing, depending upon the engine condition and fuel used. As the load was increased and the engine began to experience knock, the spark timing was adjusted at each operating condition to locate the timing at which the knock intensity increased substantially for a small change in spark timing. This condition was then taken as the threshold of knock onset. Once this point was identified, spark timing was set slightly retarded of the threshold and data collection was initiated.

6.2.1 Results for Fuels Studied at CR10.5

Based on the results of the Phase 2 studies, three fuels were selected for use with CR10.5 in Phase 3 of the project. These included #1 and #10, which have a low RON, low ethanol content, and vary in sensitivity. Additionally, #15 was selected to be tested at all 3 CRs. Fuel #15 has a mid-level RON, a high ethanol content, and high sensitivity.

6.2.1.1 Combustion Phasing

The CA50 results at the five engine speeds studied for fuel #1, #10, and #15 are shown in Figures 6.3 – 6.5, respectively. CA50 results for these three fuels are compared at one single engine speed (2000 RPM) in Figure 6.6. As expected, the BMEP where knock begins to occur rises as the engine speed increases for all three fuels. Fuels #1 and #10 exhibit CA50 trends that are similar, as might be expected based on the similarity of their RON ratings. Fuel #15 has more advanced CA50 resulting from its higher RON rating. The CA50 trends for the three fuels are shown together for 2,000 RPM in Figure 6.6. Readers may note that the 1,000 RPM trends often end at CA50 values that are much less than the 30 CAD ATDC limit. At 1,000 RPM, the maximum torque output of the engine is limited by available intake air mass, as the turbocharger is not able to produce full boost at this low speed. Hence, maximum torque at 1,000 RPM is achieved before the CA50 limit is reached.

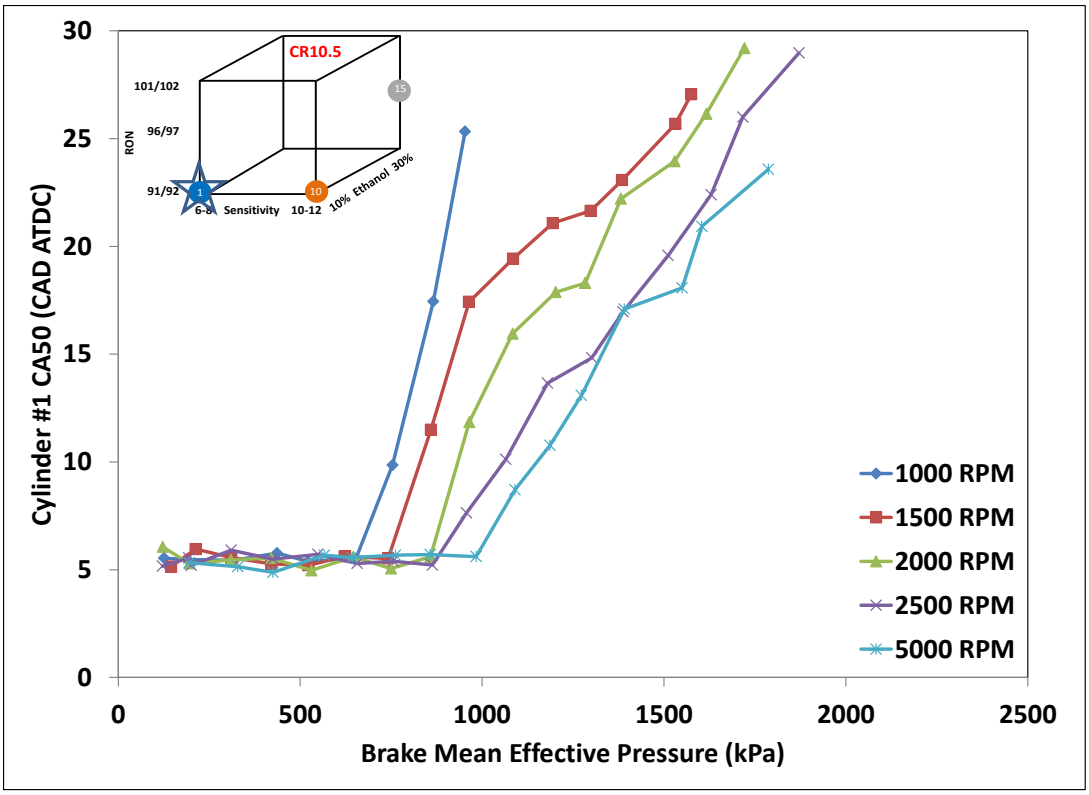

Figure 6.3. Combustion phasing (CA50) results for fuel #1 at CR10.5.

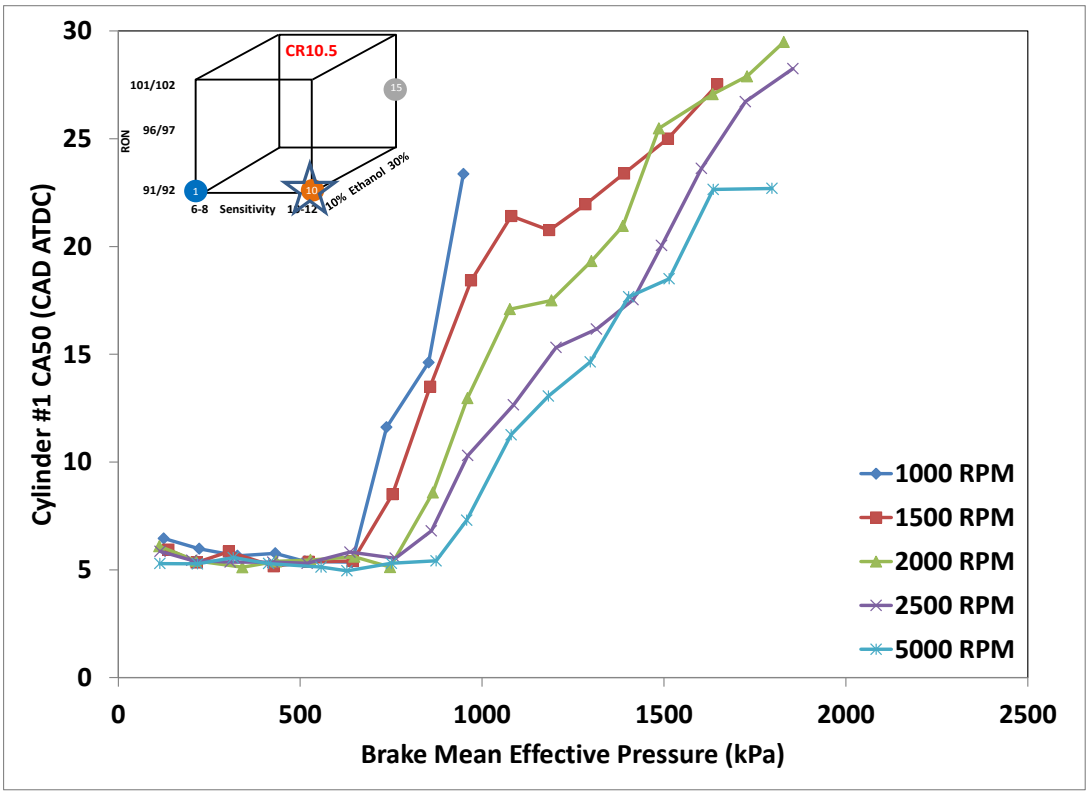

Figure 6.4. Combustion phasing (CA50) results for fuel #10 at CR10.5.

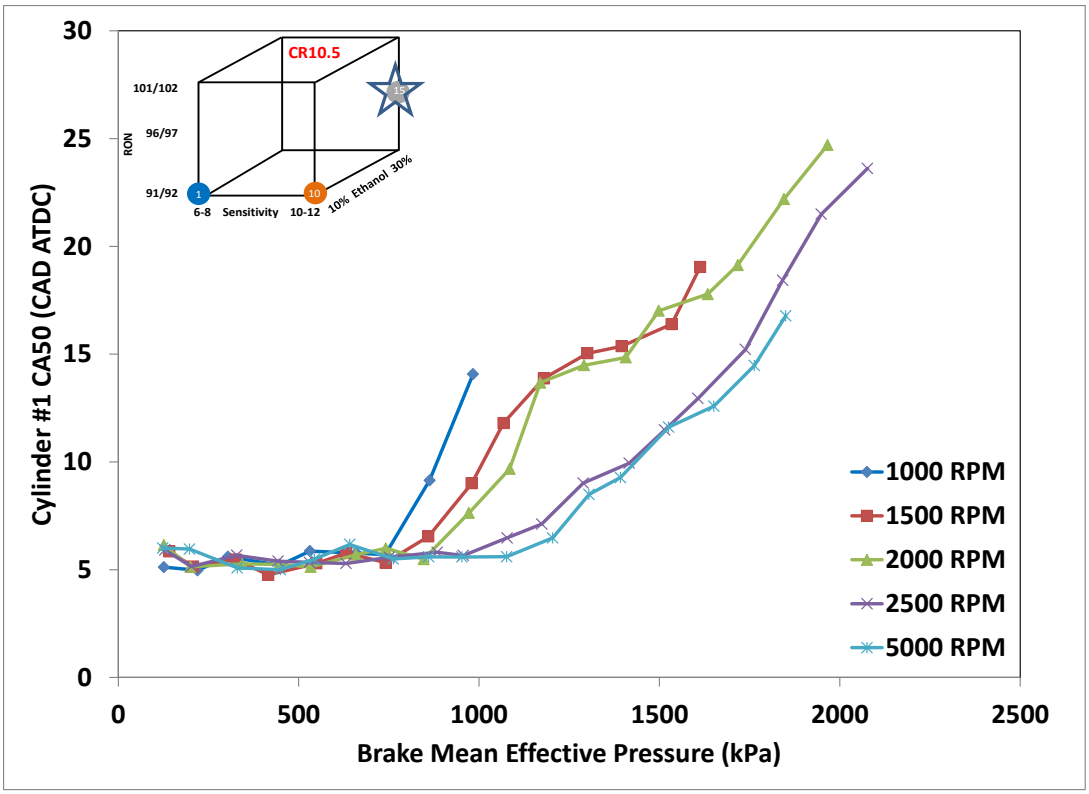

Figure 6.5. Combustion phasing (CA50) results for fuel #15 at CR10.5.

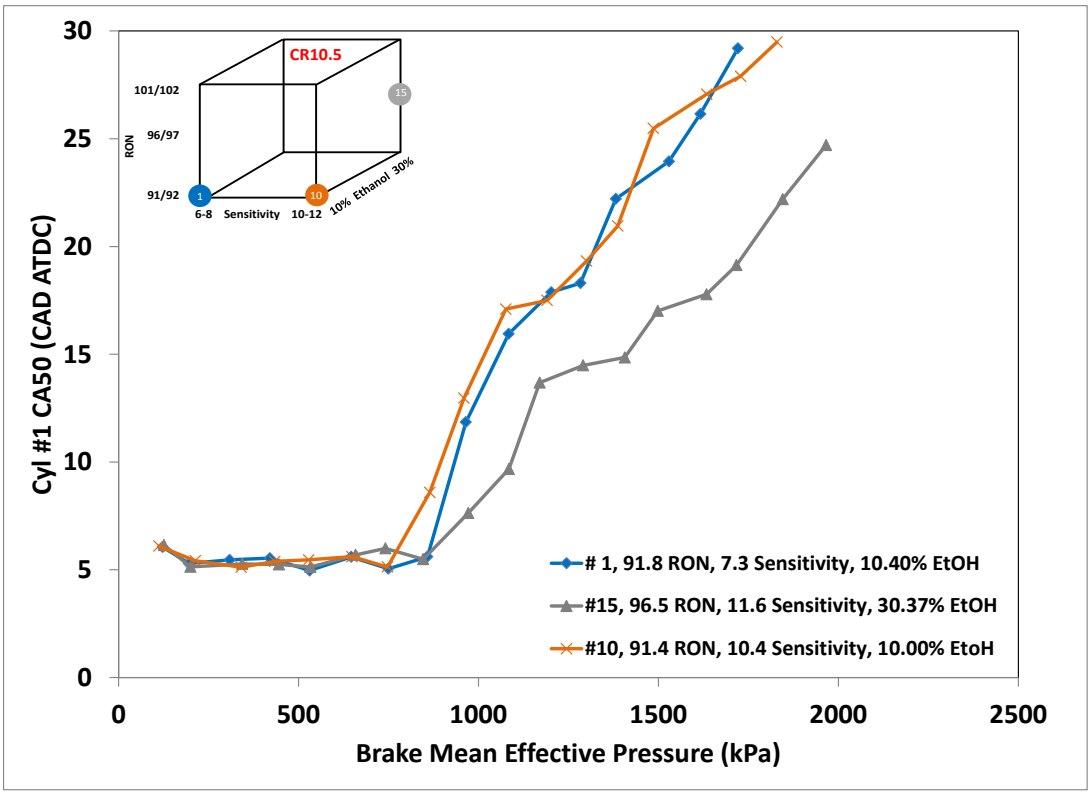

Figure 6.6. Comparison of CA50 at 2,000 RPM for fuels #1, #10, and #15.

6.2.1.2 Fuel Mean Effective Pressure

Fuel mean effective pressure (MEP) is a measure of the fuel energy consumed by the engine at a given torque output, normalized to the displacement of the engine.[27,28,29] The concept is similar to the normalization of engine torque output accomplished by the brake mean effective pressure metric. Engine brake thermal efficiency at a given condition is equal to BMEP divided by fuel MEP. Fuel MEP is generally not a strong function of engine speed, although at low speeds heat transfer losses can cause it to increase. Similarly, at high speeds friction increases and causes fuel MEP to increase. In general, fuel MEP is a linear function of BMEP over a wide operating range and accounts for heating value differences between fuels. Therefore, a linear regression of fuel MEP and BMEP data for non-knock limited load conditions is a means of examining the change in fuel energy consumption resulting from the use of different compression ratios. Best-fit lines were established in the MBT region (at all engine speeds) for all of the fuels examined at each compression ratio using the data from engine speeds of 1,500 – 2,500.

An example is shown as the dashed black line in Figure 6.7, which shows the best-fit line for the three fuels studied at CR10.5. The results for all three fuels fall onto one line, indicating that the fuel consumption measurements produced during experiments combined with the net heat of combustion for each fuel agree well in the MBT region, as expected. The relationship determined by this regression was used to calculate the fuel consumption rate for all fuels for conditions within the MBT region to aid in reducing the impact of experimental noise during vehicle modeling. Measured fuel consumption values for each individual fuel were used for BMEP levels beyond the MBT region. An example fuel consumption map for fuel #1 is shown in Figure 6.8. In this plot, filled symbols represent points in the MBT region, open symbols represent points that are in the knock-limited region. Different engine speeds are represented by the color of the plot symbol. The data in Figure 6.8 do not fall onto one line because the fuel consumption values in Figure 6.8 are dependent on engine speed. Fuel MEP values, as shown in Figure 6.7, are not dependent on engine speed since fuel MEP is a measure of energy consumption per engine cycle.

[27] Wei Wu and Marc Ross, "Spark-Ignition Engine Fuel Consumption Modeling," SAE Technical Paper #1999-01-0554, SAE International, 1999.
[28] P.J. Shayler, J.P. Chick, and D. Eade, "A Method of Predicting Brake Specific Fuel Consumption Maps," SAE Technical Paper #1999-01-0556, SAE International, 1999,
[29] Marc Ross and Feng An, "The Use of Fuel by Spark Ignition Engines," SAE Technical Paper #930329, SAE International, 1993.

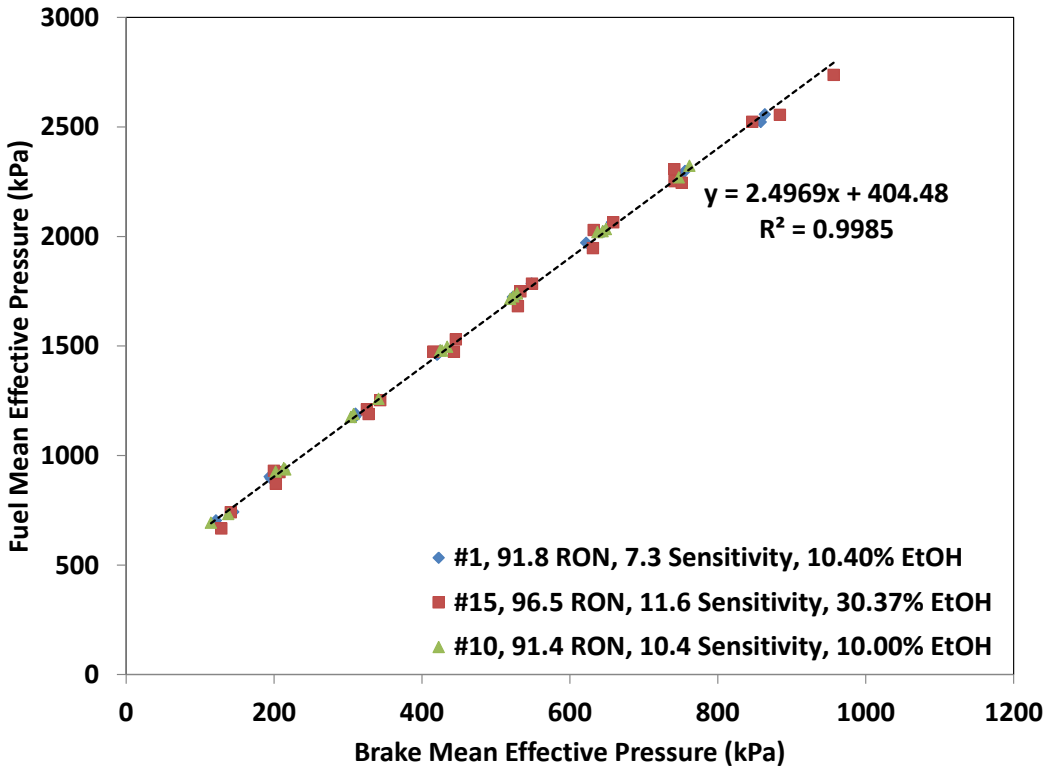

Figure 6.7. Comparison of fuel MEP best-fit lines for fuels #1, #10, and #15 at CR10.5 (in MBT region).

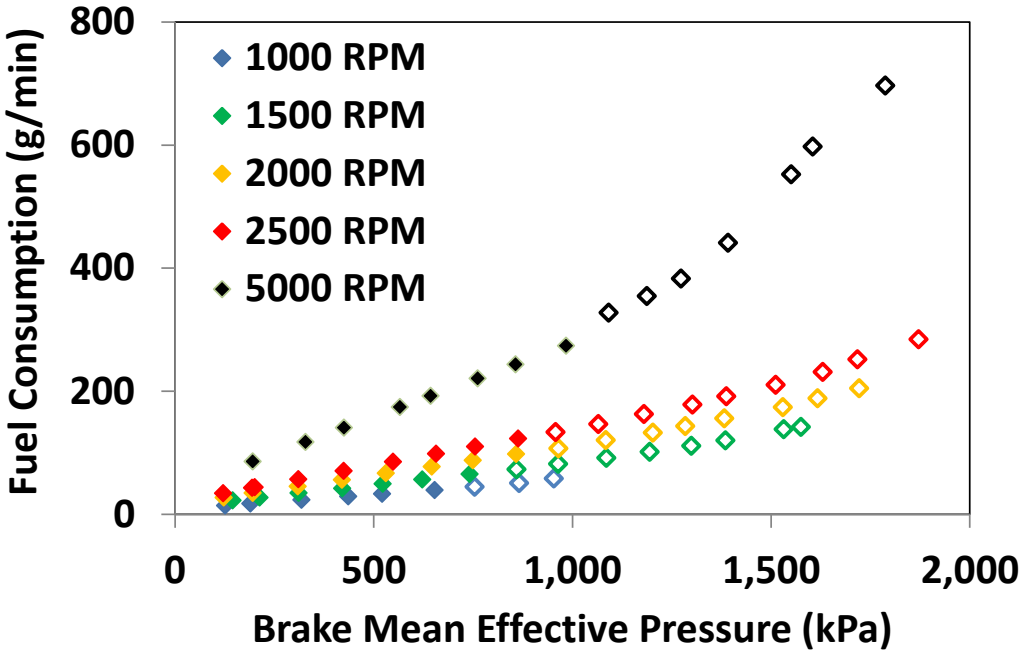

Figure 6.8. Fuel consumption map for fuel #1 at CR10.5 ("Open" symbols – knock limited region).

6.2.2 Results for Fuels Studied at CR11.4

Based on the results from Phase 2, four fuels were chosen for study in Phase 3 at CR11.4. These were #6, #7, #14, and #15. Fuels #7 and #14 had low ethanol content and differed in both sensitivity and RON rating. Fuels #6 and #15 had high ethanol content, mid-level RON, and differed in sensitivity. Additionally, #14 and #15 had nominally the same sensitivity and RON rating, but differed in ethanol content.

6.2.2.1 Combustion Phasing

Figures 6.9 – 6.12 show the CA50 timing for the four fuels studied at CR11.4. As was observed at CR10.1, the delay in combustion phasing that was needed to avoid knock decreased as engine speed increased. As shown in Figure 6.13 fuel #7 enables higher BMEP output prior to the onset of knock, but fuel #15 required less ignition retard as BMEP increased. This tendency was observed at all engine speeds and was found to be repeatable in multiple experiments with these fuels.

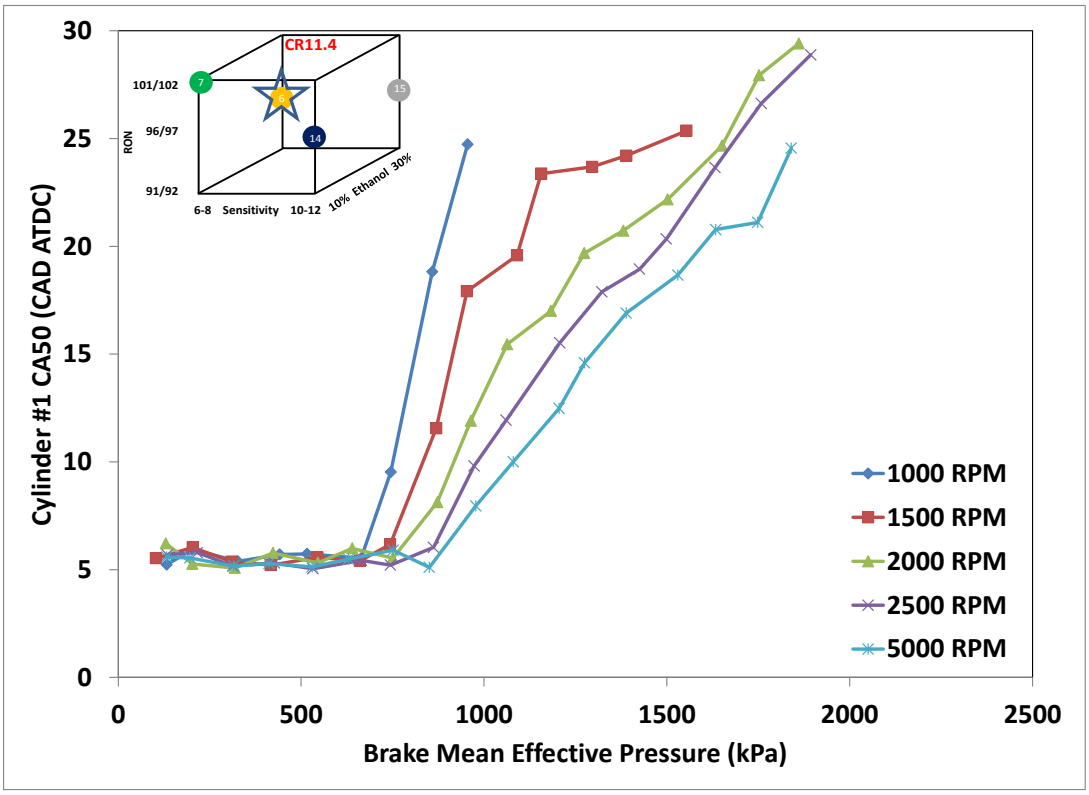

Figure 6.9. Combustion phasing (CA50) results for fuel #6 at CR11.4.

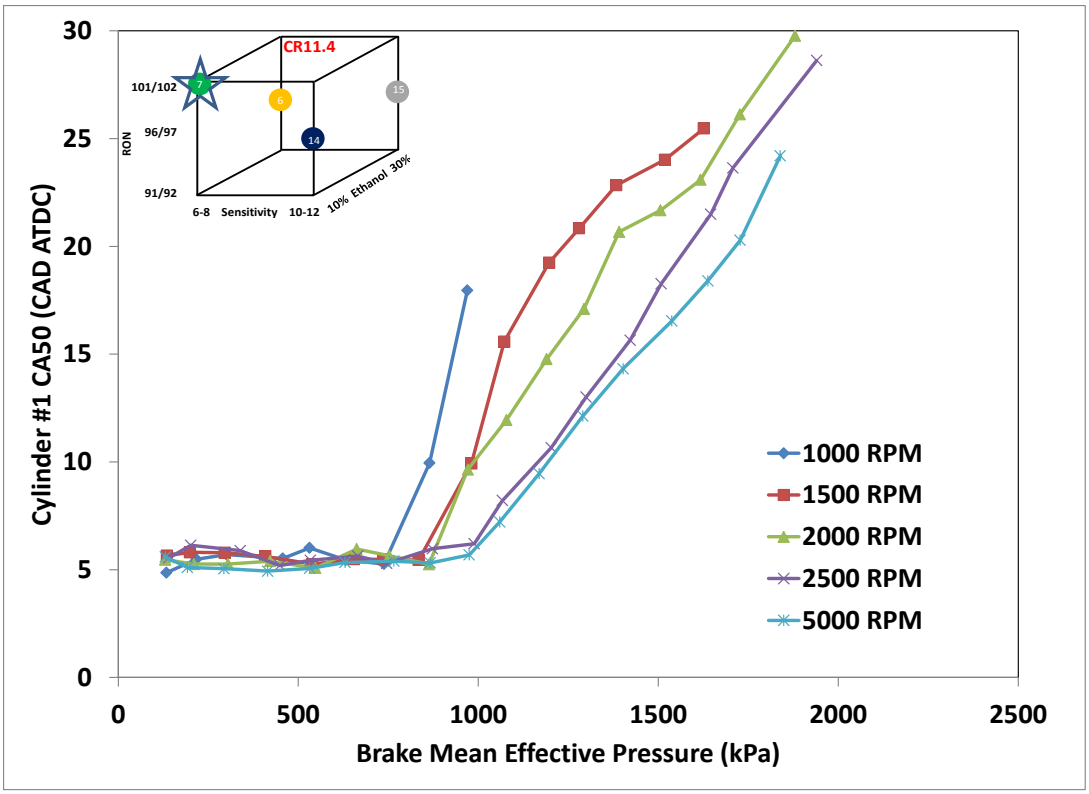

Figure 6.10. Combustion phasing (CA50) results for fuel #7 at CR11.4.

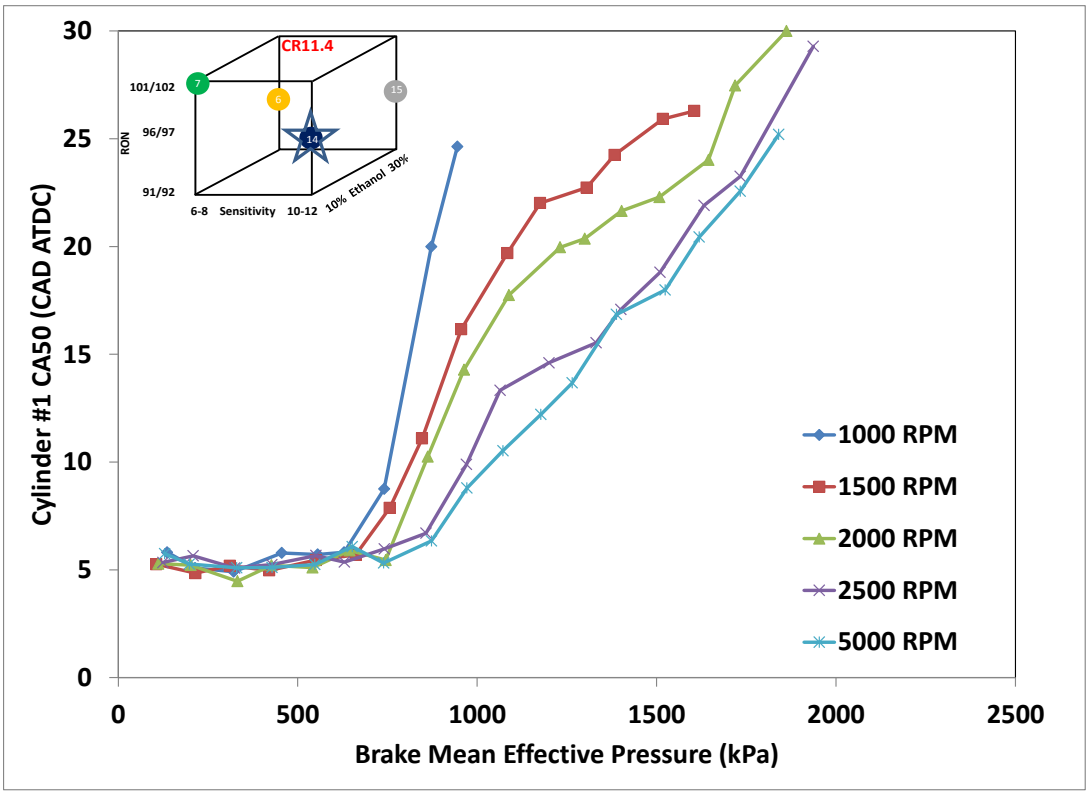

Figure 6.11. Combustion phasing (CA50) results for fuel #14 at CR11.4.

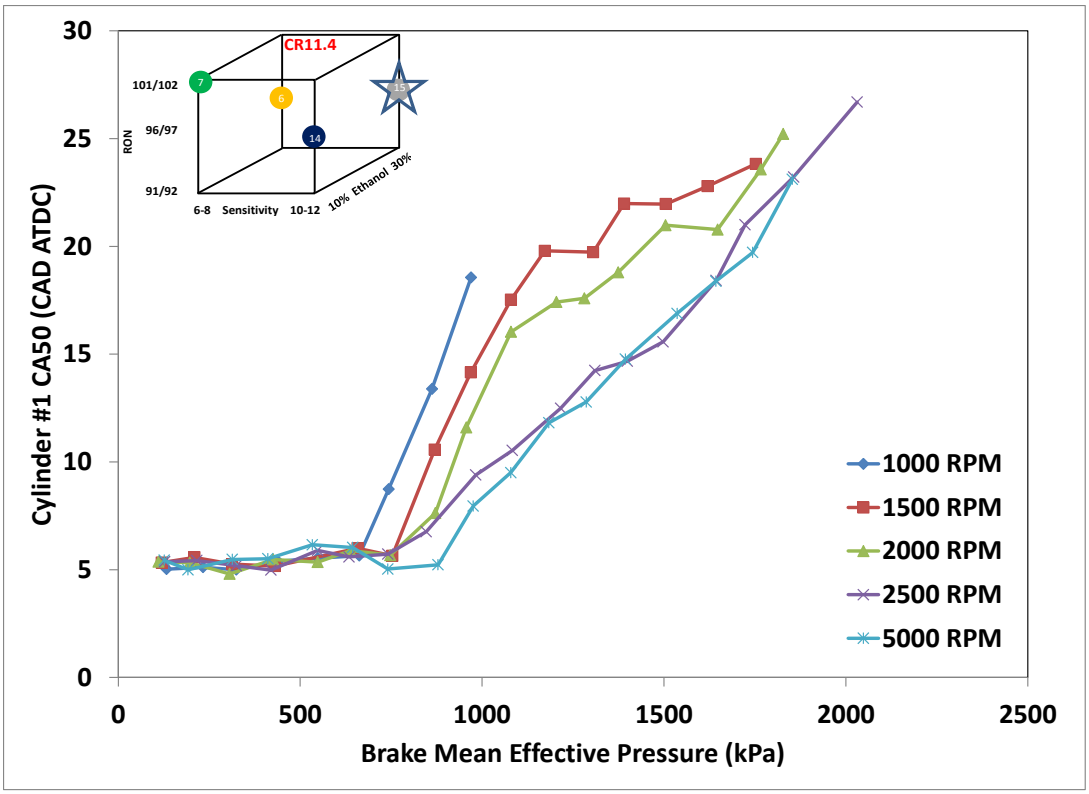

Figure 6.12. Combustion phasing (CA50) results for fuel #15 at CR11.4.

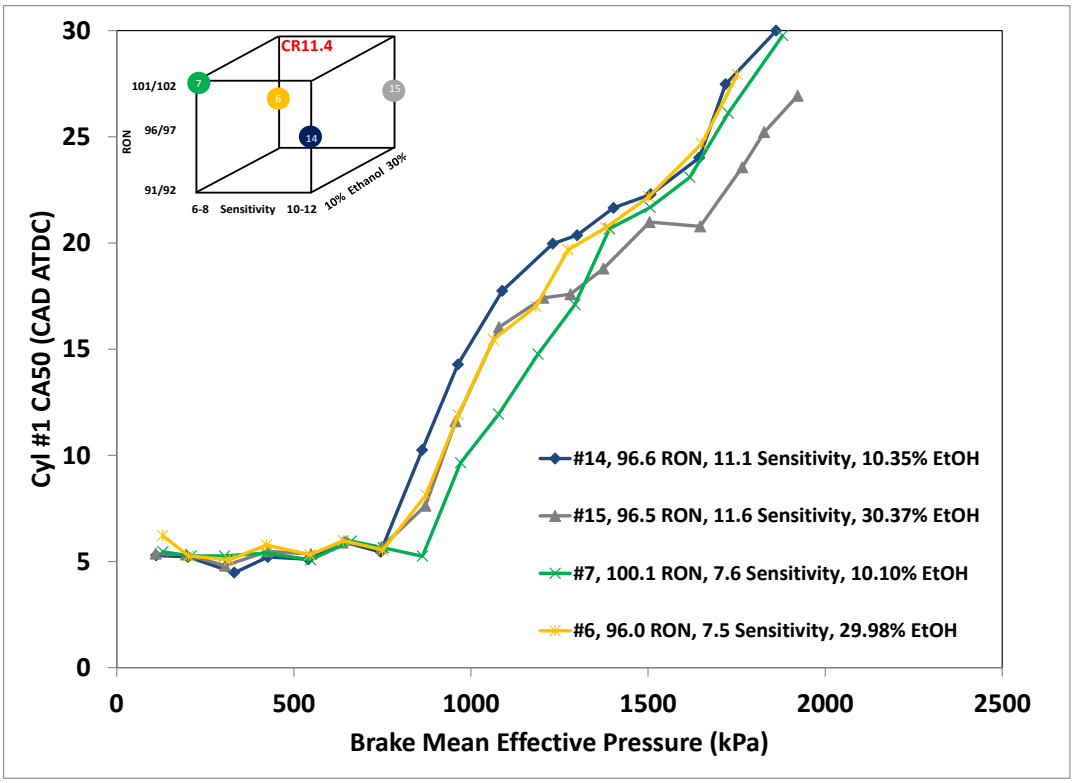

Figure 6.13. Comparison of CA50 results for fuels studied at CR11.4 at 2,000 RPM.

6.2.2.2 Fuel Mean Effective Pressure

Figure 6.14 shows the fuel MEP for all fuels studied at CR11.4 in the MBT region. The observed trends in the fuel MEP for individual fuels were very similar to those identified and discussed in the CR10.5 results. The linear regression for the CR11.4 data produced a slope of 2.4314 kPa/kPa and an intercept of 417.56 kPa. The slope is numerically smaller than that determined at CR10.5, with only a marginally higher intercept value. The marginally higher intercept value is consistent with higher friction torque, which is often experienced when compression ratio is increased (due to higher cylinder pressure which leads to higher loads on the piston rings, higher piston side forces, and higher bearing loads). The lower slope indicates an overall efficiency increase for CR11.4 compared to CR10.5 in the MBT region, as expected. The average efficiency improvement in the MBT region is 1%. A curve fit to the data of several recent studies provides a benchmark that can be used to evaluate these results.[30] The curve fit to the data in that paper shows that the increase in efficiency from CR10.5 to CR11.4 is approximately 1.7%.

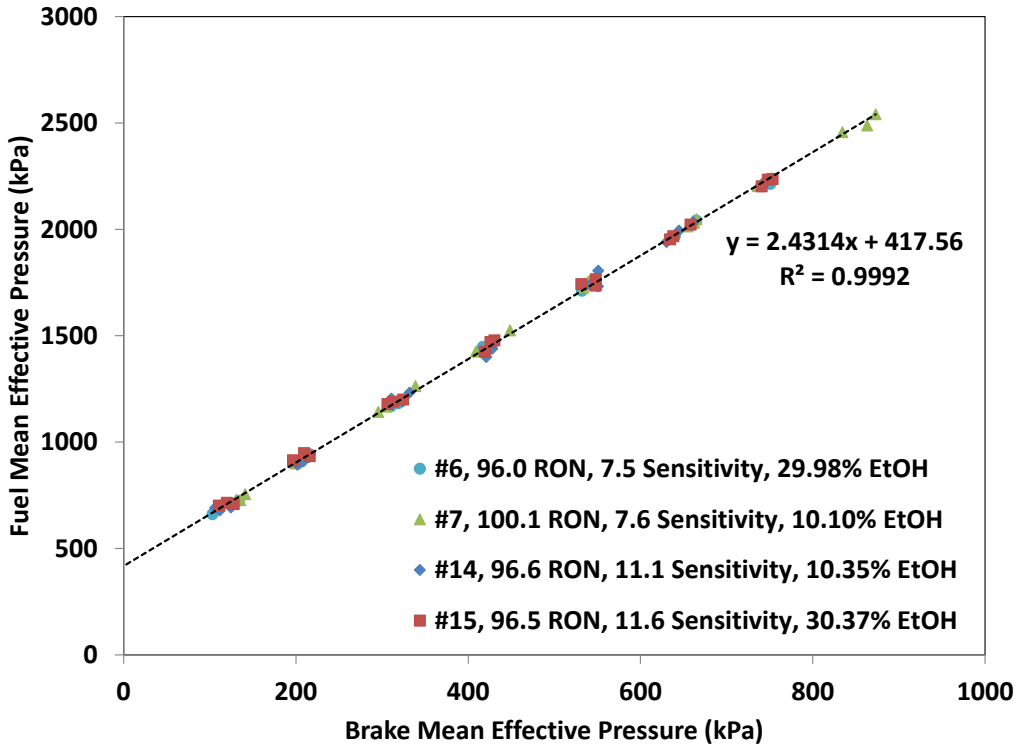

Figure 6.14. Fuel MEP in the MBT region for all fuels studied at CR11.4.

[30] Leone, Thomas G.,Anderson, James E., Davis, Richard S., et al., "The Effect of Compression Ratio, Fuel Octane Rating, and Ethanol Content on Spark-Ignition Engine Efficiency," Environ. Sci. Tech. 2015, 49, 10778-10789, doi:10.1021/acs.est.5b01420.

6.2.3 Results for Fuels Studied at CR13.2

Four fuels were selected for study at CR13.2 in Phase 3. These fuels were #7, #15, #16 and #19. Fuel #15 had mid-level RON, while fuels #7, #16, and #19 had high-level RON. Fuel #7 had low sensitivity; fuels #15, #16, and #19 had high sensitivity. Fuels #7 and #16 had low ethanol content, while fuels #15 and #19 had high ethanol content.

6.2.3.1 Issues with the CR13.2 Pistons

During experiments with the CR13.2 pistons, an engine failure occurred that prevented collection of data for fuels #15 and #19. A new engine was installed, but had different efficiency than the original engine, likely because of small differences in manufacturing in addition to changes in the state of the original engine resulting from numerous re-builds and considerable run time. This difference would have confounded the results for the CR13.2 condition unless a new baseline was established for this engine prior to resumption of tests with the CR13.2 pistons. Additionally, data from the CR13.2 pistons had not shown as much improvement in fuel efficiency as had been observed in previous studies.[31],[32]

A computational fluid dynamics (CFD) study was undertaken by Ford Motor Company to examine the potential causes of this shortcoming in an effort to determine the most beneficial path for study of the CR13.2 condition. Solid models were generated for the piston crowns and used together with engine and fuel data from the study to support the CFD analyses. Figure 6.15 shows an example solid model for the CR13.2 piston crown.

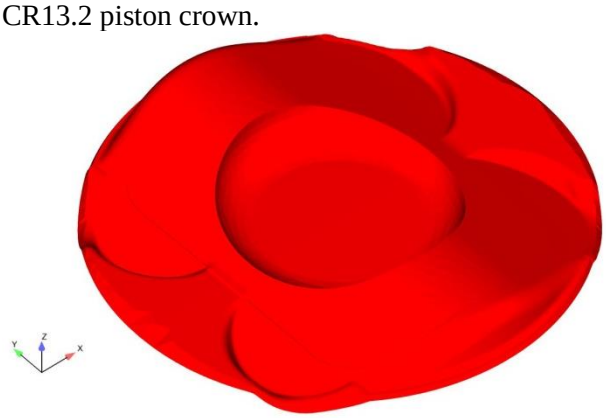

Figure 6.15. Solid model of the CR13.2 piston crown.

The CFD study showed that the relatively small diameter bowl in the CR13.2 pistons increased the likelihood of impingement of the fuel spray on the piston, confined flame propagation, and extended combustion later into the cycle compared to the baseline OEM piston. All of these factors limit the combustion efficiency and are likely contributors to the lower-than-expected efficiency increase for these pistons. Extension of the combustion event later into the cycle was also observed in the CFD study for the CR11.4 pistons, but to lesser extent owing to the larger diameter of the CR11.4 piston bowl that was more comparable to the OEM piston. Based on the results of the CFD analysis, the AVFL-20 project committee deemed that conducting baseline experiments on the new engine for the purpose of continuing study with the existing CR13.2 pistons was not likely to provide beneficial information, and thus discontinued study at the CR13.2 pistons. Study of fuel efficiency benefits of CRs higher than 11.4 in

[31] Smith, P., Heywood, J., and Cheng, W., "Effects of Compression Ratio on Spark-Ignited Engine Efficiency," SAE Technical Paper 2014-01-2599, 2014.
[32] Leone, T., Olin, E., Anderson, J., Jung, H. et al., "Effects of Fuel Octane Rating and Ethanol Content on Knock, Fuel Economy, and CO2 for a Turbocharged DI Engine," SAE Int. J. Fuels Lubr. 7(1):2014.

this engine was suggested for a potential future project. Existing data at CR13.2 with the original engine are nevertheless included in this report for completeness.

6.2.3.2 Combustion Phasing

Figures 6.16 and 6.17 show the CA50 versus BMEP for fuels #7 and #16, respectively. As was observed at CR10.5 and CR11.4, the amount of phasing retard to avoid knock decreased as engine speed increased. In general, fuel #16 required less combustion phasing retard than fuel #7 at similar BMEP and engine speed as was observed during the Phase 2 screening.

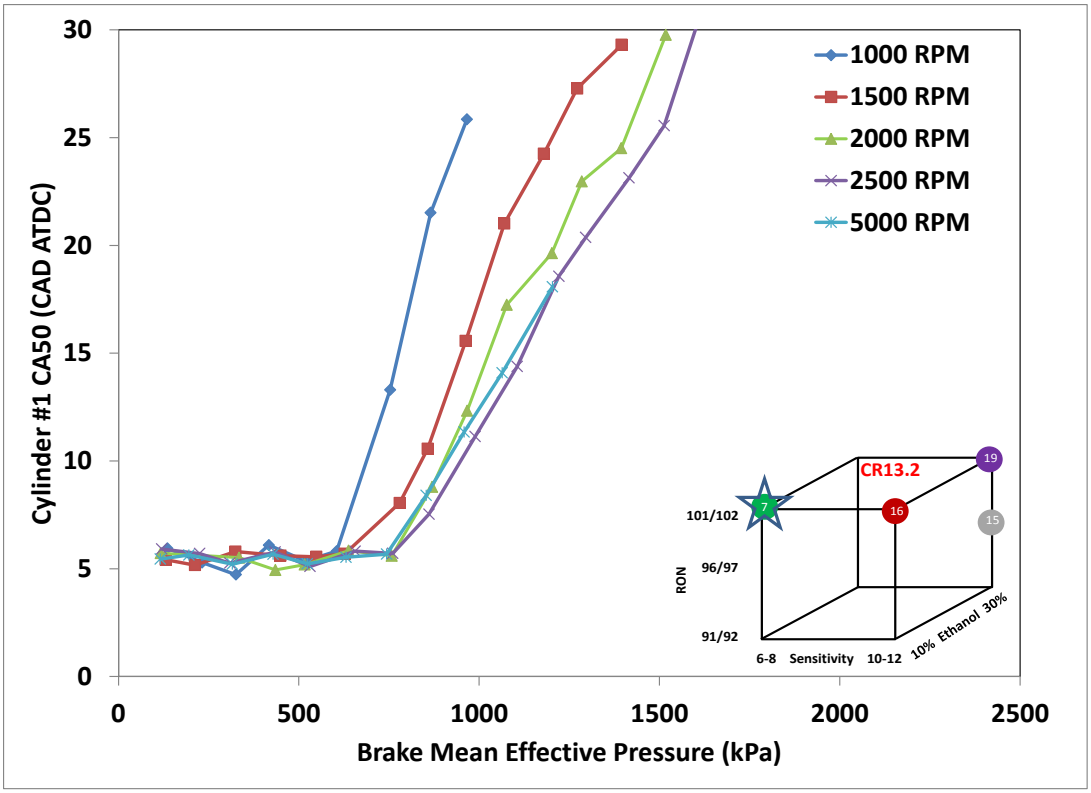

Figure 6.16. CA50 versus BMEP for fuel #7 at CR13.2.

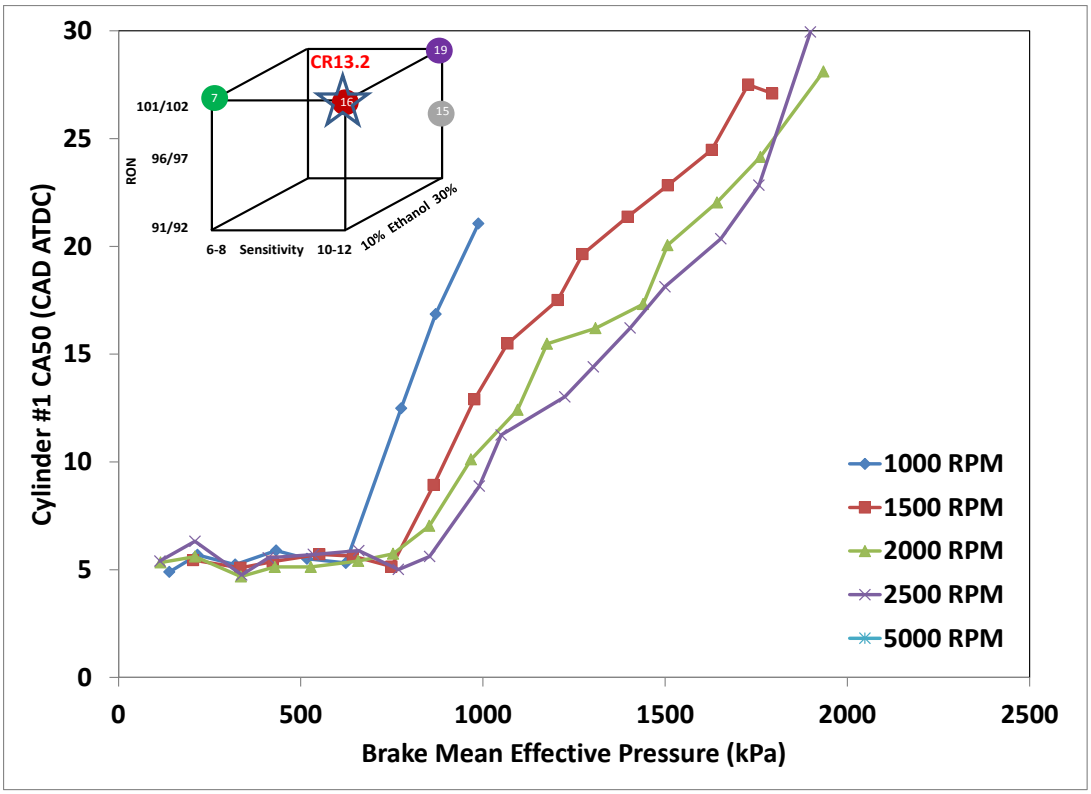

Figure 6.17. CA50 versus BMEP for fuel #16 at CR13.2. Data were not collected at 5,000 RPM due to engine failure.

6.3 VEHICLE MODELING

Vehicle modeling allows the engine data gathered during this project to be used to estimate the fuel consumption and CO_2 emissions from vehicles that might use similar engines with the different compression ratios and fuels studied in this project. The vehicle modeling for this project was carried out using the Autonomie model, which was developed at Argonne National Laboratory with support from the U.S. Department of Energy. The Autonomie model has been extensively benchmarked, and offers the advantage of being a non-proprietary modeling tool designed to assess fuel consumption for conventional and hybrid vehicle designs. [33,34,35,36]

6.3.1 Parameters Describing the Model Vehicles

Several parameters are needed in vehicle simulation models to describe the aerodynamic and inertial loads placed on the vehicle and its powertrain during operation. Aerodynamic and inertial loads at the tire-road interface are specified by the dynamometer target coefficients and test weight that are available

[33] Kim, N., Rousseau, A., and Rask, E., "Autonomie Model Validation with Test Data for 2010 Toyota Prius," SAE Technical Paper 2012-01-1040, 2012, doi:10.4271/2012-01-1040.
[34] Kim, N., Duoba, M., and Rousseau, A., "Validating Volt PHEV Model with Dynamometer Test Data Using Autonomie," SAE Int. J. Passeng. Cars – Mech. Syst. 6(2):2013, doi:10.4271/2013-01-1458.
[35] Lee, D., Rousseau, A., and Rask, E., "Development and Validation of the Ford Focus Battery Electric Vehicle Model," SAE Technical Paper 2014-01-1809, 2014, doi:10.4271/2014-01-1809.
[36] Kim, N., Rousseau, A., and Lohse-Busch, H., "Advanced Automatic Transmission Model Validation Using Dyanamometer Test Data," SAE Technical Paper 2014-01-1778, 2014, doi:10.4271/2014-01-1778.

in the EPA certification test database for all vehicles sold in the U.S. The EPA "Equivalent Test Weight" (ETW) allows calculation of inertial forces acting on the vehicle. Aerodynamic and friction forces at the interface of the vehicle tires and the roadway are described by a quadratic function of vehicle speed. In this relationship, the "A" parameter is the fixed force that is independent of vehicle speed. The "B" parameter is the coefficient of vehicle speed, and the "C" parameter is the coefficient of vehicle speed to the second power. The forces at the wheel are translated to forces at the engine output shaft through the differential and transmission. Hence, the relevant gear ratios and final drive ratio also need to be specified. Two target vehicle configurations suitable for the 1.6L EcoBoost engine were of interest for this project: an industry-average mid-size sedan and industry-average small sport utility vehicle (SUV).

A data mining effort was conducted using the 2014 EPA certification test database as a source for the required information to support vehicle model development. Each record in the database was augmented with vehicle size class to enable analysis of the certification data by vehicle size.[37] The next step was to analyze the data for the mid-size sedan and the SUV size classes. Parameters such as dynamometer target coefficients were examined as a function of the power density and the specific displacement ratio for all of the vehicles in the EPA database for the appropriate vehicle size class. Figure 6.18 shows an example of the result of this analysis for target coefficient C.

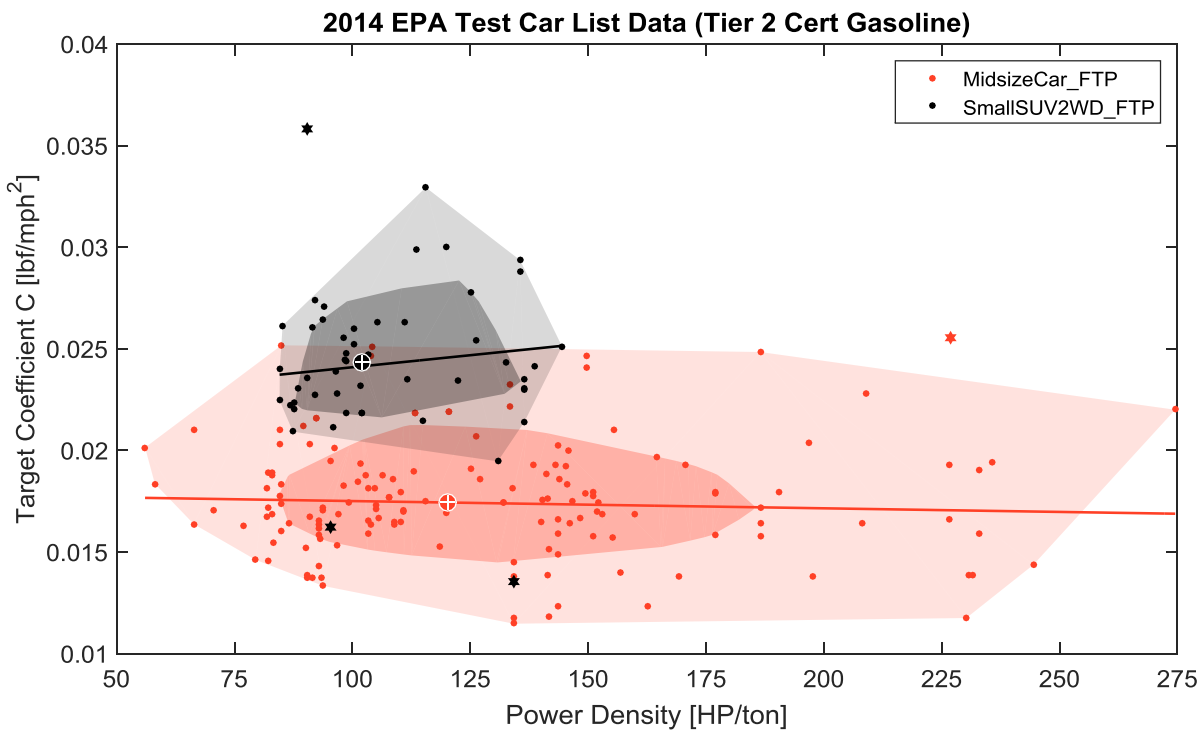

Figure 6.18. Target coefficient C versus vehicle power density for midsize sedans and small SUVs in the EPA certification test database.

In this example, the midsize sedan results for the FTP cycle are shown in shades of red, while the results for small SUVs for the FTP cycle are shown in shades of gray. The lighter region for each vehicle group denotes the range of variation for all of the data in the database, with the exception of statistical outliers. Statistical outliers are shown by stars that fall outside the bounds of the shaded areas. The darker regions

[37] 2014 Certified Vehicle Test Result Report Data (XLS), available online at https://www3.epa.gov/otaq/cert/documents/cert-tst/14actrr.xls

denote the interquartile range of the data for each vehicle size. The larger circular icon on each line shows the geometric median of the data for each vehicle size class. As shown by the example data, target coefficient C for mid-size sedans is relatively insensitive to the vehicle power density. Using the same process as for target coefficient C, the EPA certification database was analyzed to determine target coefficients A and B, and the engineering test weight for the mid-size sedan and small SUV vehicle configurations. The geometric median of the data for each parameter was adopted for use in the vehicle modeling efforts for this project.

Once the median power density for the target vehicle configurations was determined, these results were used to select production vehicle examples that had similar power density to the median. These examples provided a means of selecting final drive and transmission gear ratios for use in the vehicle models. The 2014 Ford Fusion and 2015 Ford Escape, both equipped with the 1.6L Ecoboost engine used in this study, had power densities that were very close to the median. After consultation with the AVFL-20 project committee, the transmission gear ratios from these vehicles were adopted for use in the vehicle models for this project. Table 6.1 summarizes the parameters used in the vehicle models for this project.

Table 6.1. Parameters for Vehicle Models

Parameter	Mid-Size Sedan	Small SUV
Target Coefficient A (lbf)	34.0501	31.3622
Target Coefficient B (lbf / MPH)	0.2061	0.3408
Target Coefficient C (lbf / MPH^2)	0.0178	0.0235
Equivalent Test Weight (lbs)	4000	4000
1st Gear Ratio	3.73	4.584
2nd Gear Ratio	2.05	2.964
3rd Gear Ratio	1.36	1.912
4th Gear Ratio	1.03	1.446
5th Gear Ratio	0.82	1.000
6th Gear Ratio	0.69	0.746
Final Drive Ratio	4.07	3.21
Tire Rolling Radius (m)	0.32775	0.32775

6.3.2 Vehicle Gear Shift Points

The baseline Autonomie shift algorithm calculates low-load gear shift points based on the engine speed that produces most efficient operation. Higher load shift points are calculated based on the maximum torque of the engine. Initially, the engine speed profile predicted by Autonomie for the small SUV when using a typical certification drive cycle was notably higher than actual test data from a 2015 Ford Escape, as shown in Figure 6.19. The data shown in Figure 6.22 are for a UDDS cycle followed by a US06 cycle. The Autonomie shift algorithm includes the ability to adjust the shift point calculations through setting the engine speed where maximum efficiency is obtained. Adjustment of this parameter to 2,000 RPM caused the Autonomie shift algorithm to calculate shift points that were similar to data from the 2015 Escape. It is important to note that this adjustment was not the result of providing a particular shift schedule to the model, but rather a change that enabled the model to more closely mirror the performance of an actual vehicle. Once this change was accomplished, the engine speed profile predicted by the model was acceptably similar to test data, as shown in Figure 6.20.

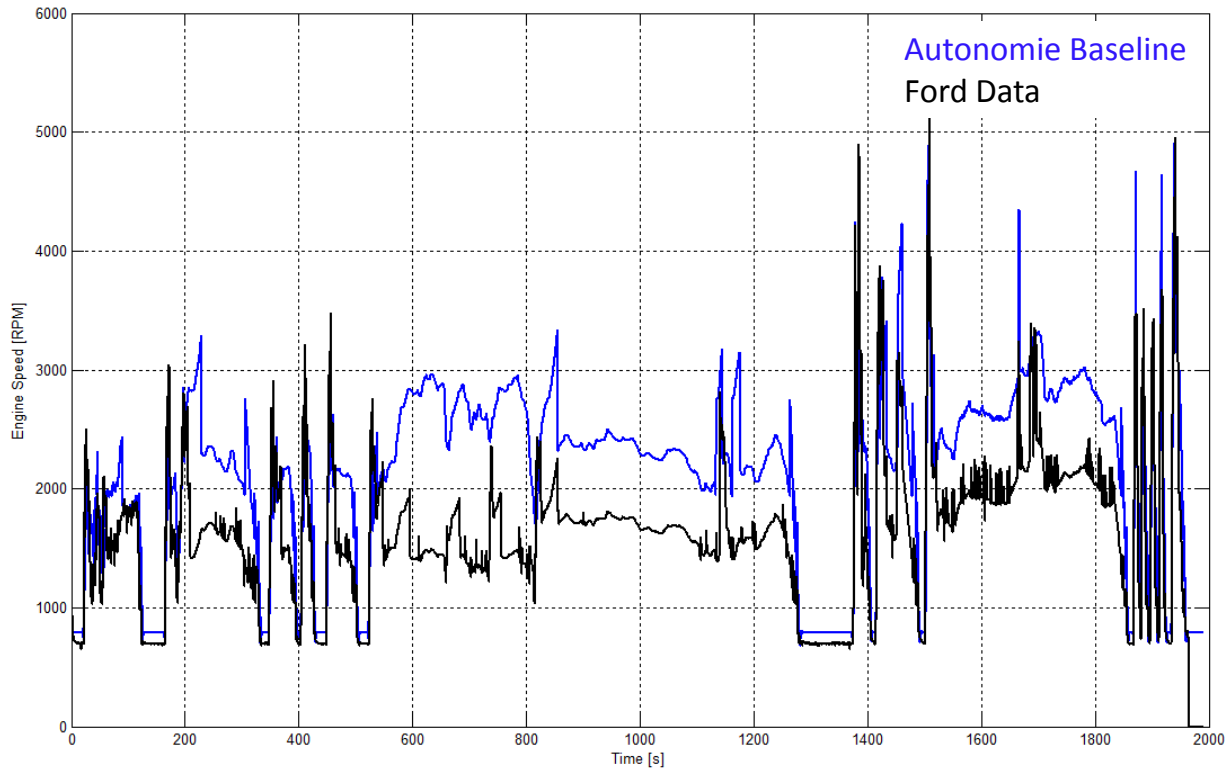

Figure 6.19. Comparison of engine speeds calculated using the Autonomie baseline shift algorithm with results from a 2015 Ford Escape.

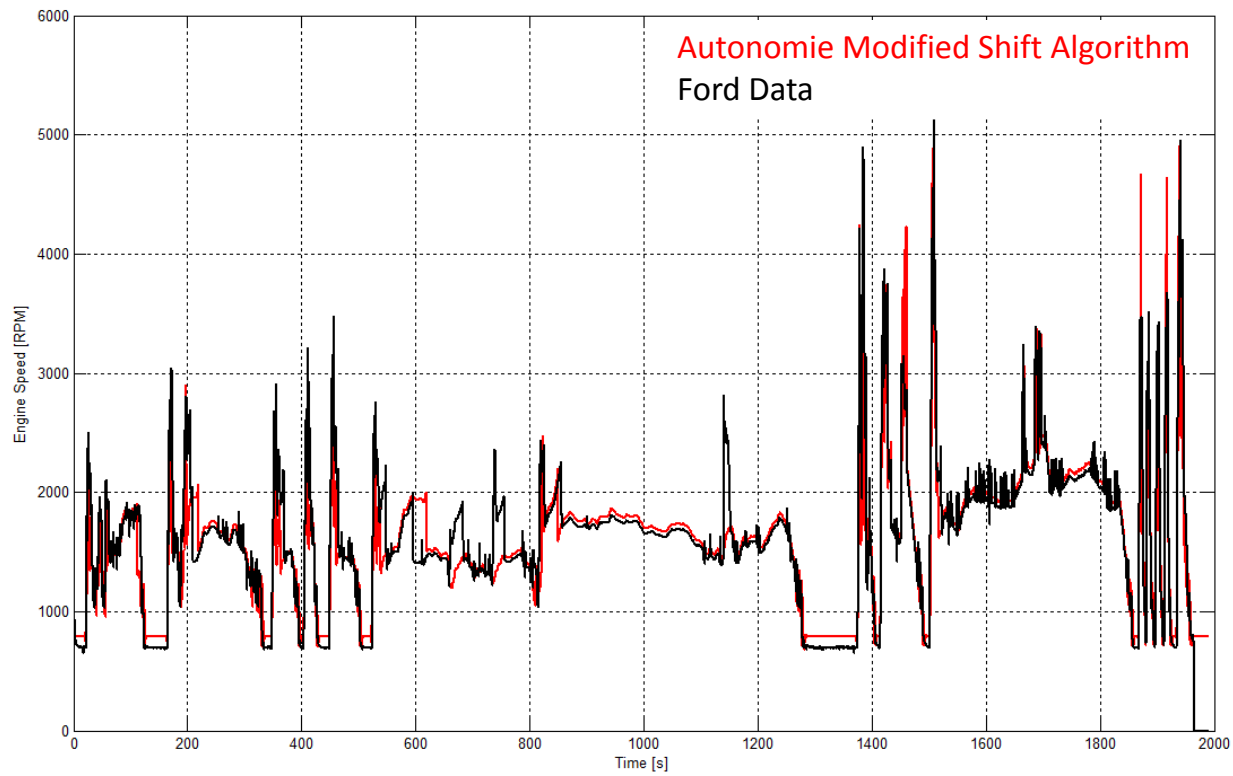

Figure 6.20. Comparison of engine speeds using the adjusted Autonomie shift algorithm with results from a 2015 Ford Escape.

6.3.3 Effect of Reduced Engine Map Data Content on Fuel Economy Results

The engine map procedure used for this project focused most of the data collection at engine speeds less than 2,500 RPM, where previous experience had demonstrated that vehicles operate most frequently. The model relied on interpolation to calculate fuel consumption data in the range between 2,500 RPM to 5,000 RPM. This strategy was not expected to cause significant issues with vehicle model results, but an assessment was conducted to quantify the impact. For this purpose, data collected previously in a study funded by the U.S. Department of Energy was used. These data were gathered on the Ford 1.6L engine equipped with the CR10.5 pistons and using a retail 87 AKI E10 fuel. The map generated with this fuel contained points between 2,500 RPM and 5,000 RPM in addition to the lower speed data. The data between 2,500 RPM and 5,000 RPM were then removed to create a second engine map that duplicated the map procedure in use for this project. By using the same vehicle model with these two versions of the 87 AKI E10 engine map, differences in results could be directly attributed to the difference in the data content of the engine map. Figure 6.21 shows the results of this comparison.

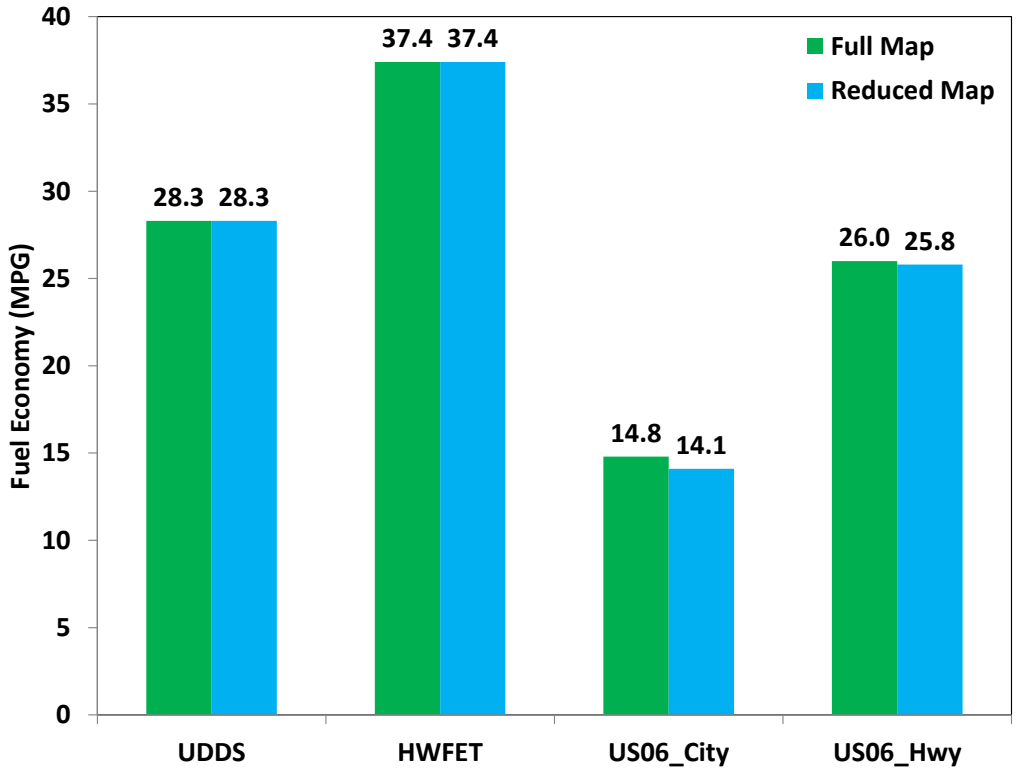

Figure 6.21. Comparison of vehicle model results for full and reduced engine map.

The urban dynamometer driving schedule (UDDS) is the same driving schedule as Phases 1 and 2 of the Federal Test Procedure (FTP) driving schedule. The UDDS and the highway fuel economy test (HWFET) fuel economy results are not significantly impacted by the reduction in data content of the engine map. Both the city portion (US06_City) and highway portion (US06_Hwy) of the US06 cycle have marginally lower modeled fuel economy resulting from the reduction in data content of the engine map. The difference for the city portion and highway portion of the US06 cycle is 4% and 1%, respectively. However, since the purpose of this study is to evaluate the potential impacts of different fuels and/or CR with the same type of engine map, the small difference in absolute US06 fuel economy resulting from the use of the reduced engine map is not likely to significantly influence conclusions about the differences between fuels and/or CR. Therefore, the reduced map approach was used.

6.3.4 Vehicle Model Results – CR10.5

Figure 6.22 shows an example of the second-by-second engine conditions predicted by Autonomie for the UDDS cycle and the US06_City cycle for fuel #1 at CR10.5 for the midsize sedan. These results show that low-load cycles such as the UDDS include a large fraction of operation in the MBT region, while high-load cycles such as the US06_City cycle include more operation in the knock-limited regime. The model output indicates that knock-limited operation occurs at ~7.5% of the operating points included in the UDDS cycle, and at ~32.5% of points included in the US06_City cycle for this CR and fuel combination. Figures 6.23-6.24 show the volumetric fuel economy (miles/gallon) and energy consumption (BTU/mile) results, respectively, for the mid-size sedan using fuels #1 (low RON, low S, E10), #10 (low RON, high S, E10), and #15 (mid RON, high S, E30) with the CR10.5 pistons. Figure 6.25 shows the volumetric heating values for all of the fuels.

Fuel #15 had the lowest volumetric fuel economy on all drive cycles due to its lower volumetric heating value owing to its higher ethanol content. Fuel #15 had 0-6.4% poorer fuel economy than fuel #1 and 0-8.2% poorer fuel economy than fuel #10. Fuels #1 and #10 have similar RON ratings and ethanol content, but fuel #10 demonstrates marginally higher volumetric fuel economy on all drive cycles studied. Comparisons of volumetric fuel economy don't enable conclusions to be drawn about whether differences are due to the higher sensitivity of #10 compared with #1, or higher volumetric heating value, or both. So, the volumetric fuel economy results were re-cast in terms of engine efficiency or energy consumption, in units of BTU/mile, to visualize differences among these three fuels without the confounding effect of differences in volumetric heating value. Fuel #10 consumes marginally more energy per mile than fuel #1. Figure 6.28 shows the volumetric heating values for all of the fuels. Examination of the volumetric heating values in Figure 6.25 for these fuels shows that fuel #10 has just over 2% more energy per gallon than fuel #1, which is likely the primary reason for fuel #10 having marginally higher volumetric fuel economy despite exhibiting similar or slightly poorer efficiency. The slightly higher energy consumption for #10 (0-1.1% relative difference depending on drive cycle) also suggests that its higher sensitivity was not beneficial at this compression ratio. Fuel #15 showed the lowest energy consumption on all cycles, demonstrating that increasing RON rating can improve engine efficiency at CR10.5, although it is not enough to overcome the lower volumetric heating value of this E30 fuel except on the city portion of the US06 cycle. This result is not surprising, since this engine is advertised to achieve greater performance when premium-grade fuel is used.

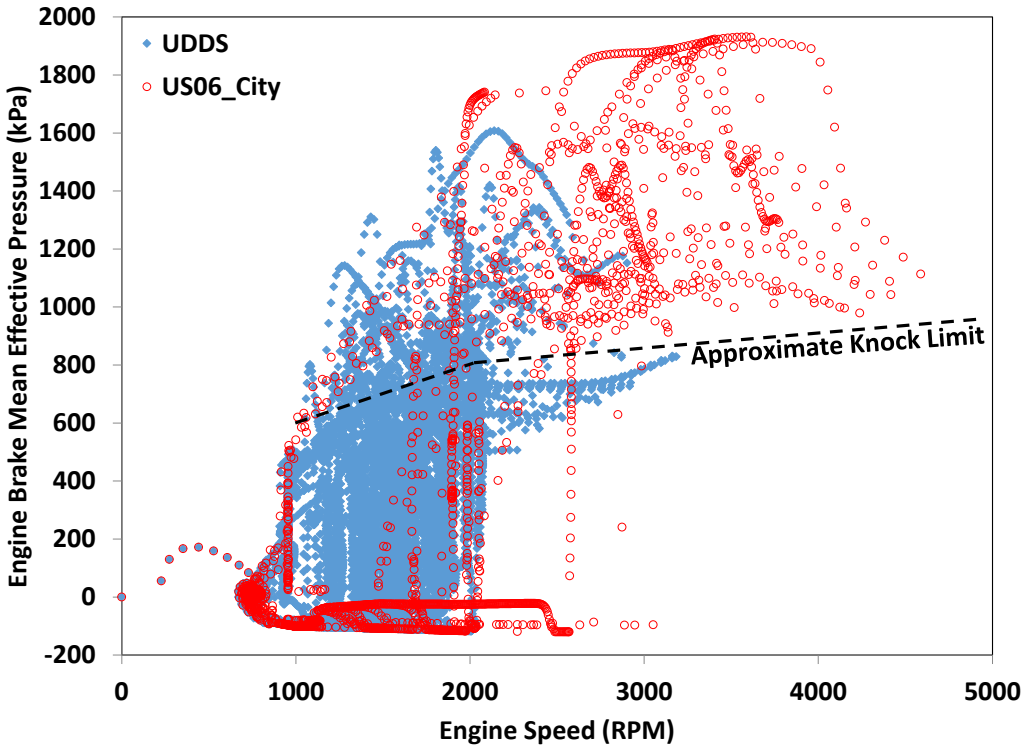

Figure 6.22. Operating points predicted by Autonomie for the mid-size sedan using CR10.5 and fuel #1 on the UDDS city portion of the US06 cycles. Each data point represents one second of operation.

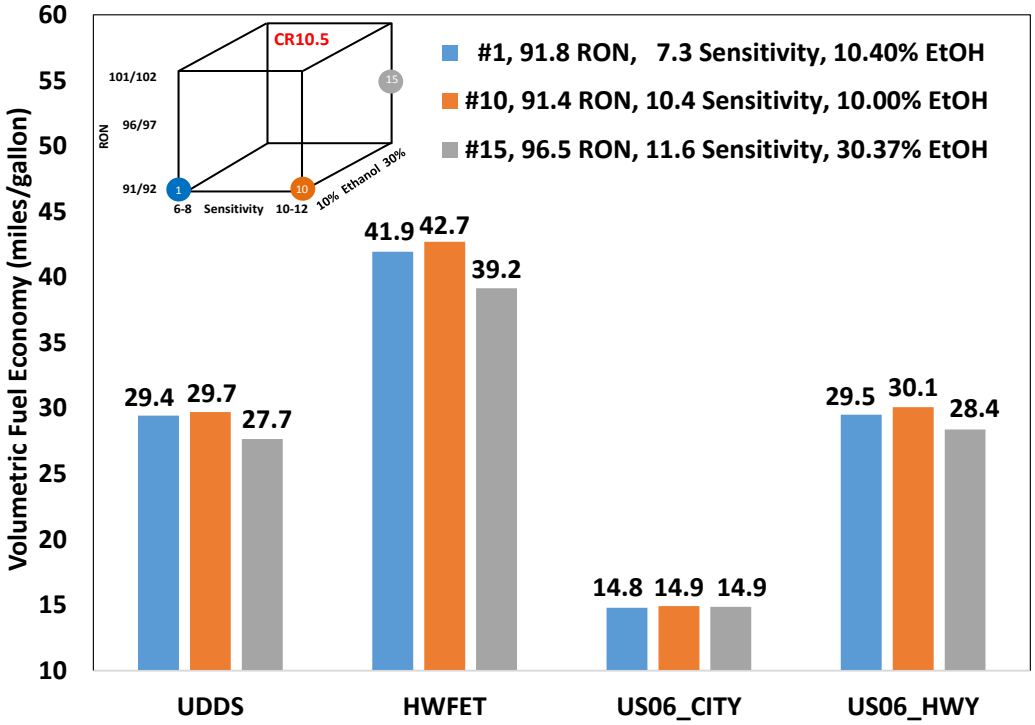

Figure 6.23. Volumetric fuel economy results for the mid-size sedan with CR10.5 pistons.

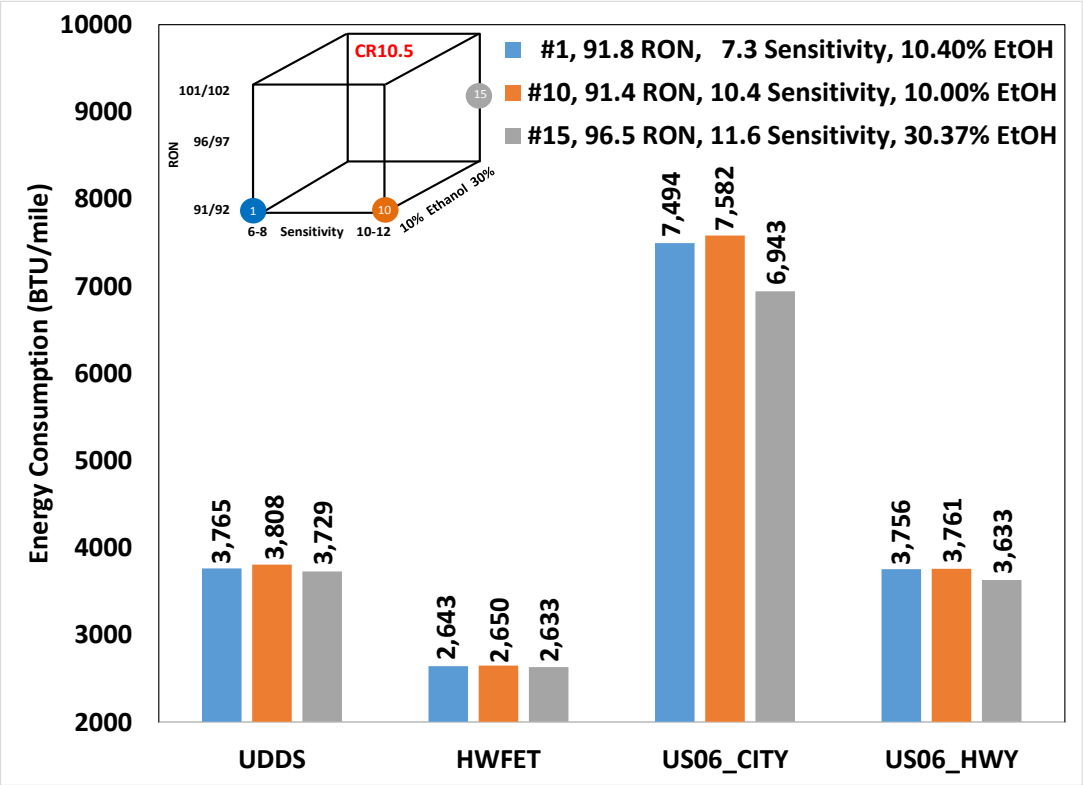

Figure 6.24. Energy consumption for the mid-size sedan at CR10.5.

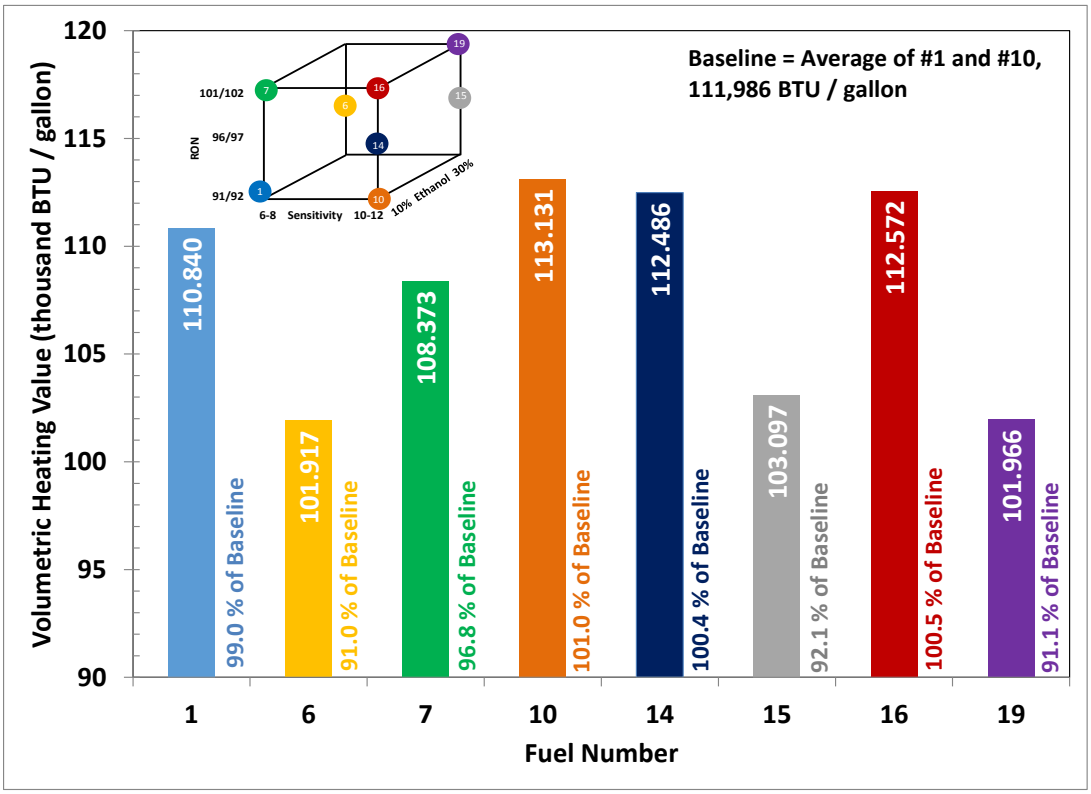

Figure 6.25. Volumetric net heating value for the Phase 3 fuel blends.

CO_2 emissions are another potential metric upon which to judge the performance of these fuels relative to one another. Hence, the results were re-cast using the analyses for each fuel to provide the CO_2 emissions rate for each fuel. As shown in figure 6.26, fuel #10 exhibited the highest CO_2 production on all cycles because of its higher carbon intensity (mgCO_2/BTU, Figure 6.27). Fuel #15 generally had similar or slightly lower CO_2 emissions than fuel #1. Figure 6.27 shows that fuel #7 (high RON, low S, E10) has the lowest CO_2 intensity of the fuels studied.

Table 6.2 includes the fuel economy, energy consumption, and CO_2 emissions results for the small SUV as well as for the mid-size sedan. The two vehicle platforms show directionally similar trends for each of the metrics across the fuels and driving cycles analyzed. The fuel economy for the SUV is lower than for the sedan, with the energy consumption and CO_2 emissions higher for the SUV than for the sedan, as expected due to larger target coefficients.

A baseline case was selected for use in evaluating the results from the AVFL-20 project vehicle modeling activity for different fuels at all CRs. The baseline case was defined as the average result for fuels #1 and #10 at CR10.5, for both the mid-size sedan and small SUV. The average value for fuels #1 and #10 was used since marketplace fuels tend to have sensitivities between those of fuels #1 and #10. That is, improvements are assessed for each vehicle independently. Table 6.3 shows the results for both the mid-size sedan and small SUV expressed as percentage changes from their respective baseline cases. The metrics are defined so that a positive numeric result is the desirable outcome.

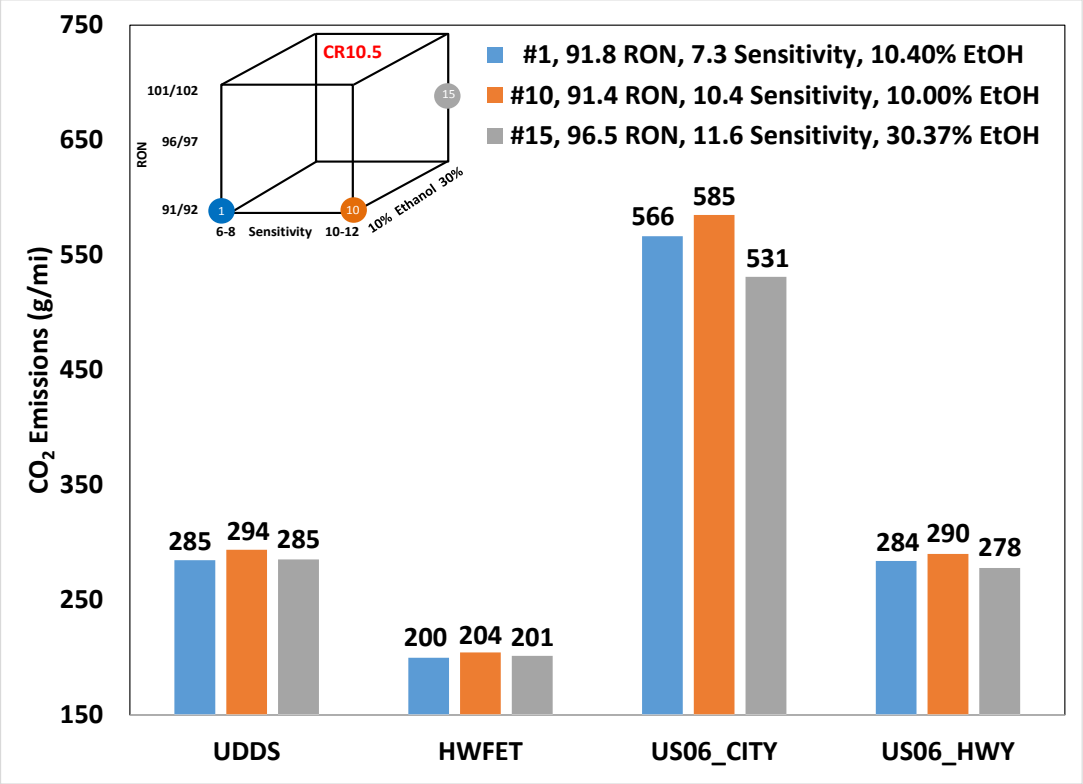

Figure 6.26. CO_2 emissions for the mid-size sedan with CR10.5 pistons.

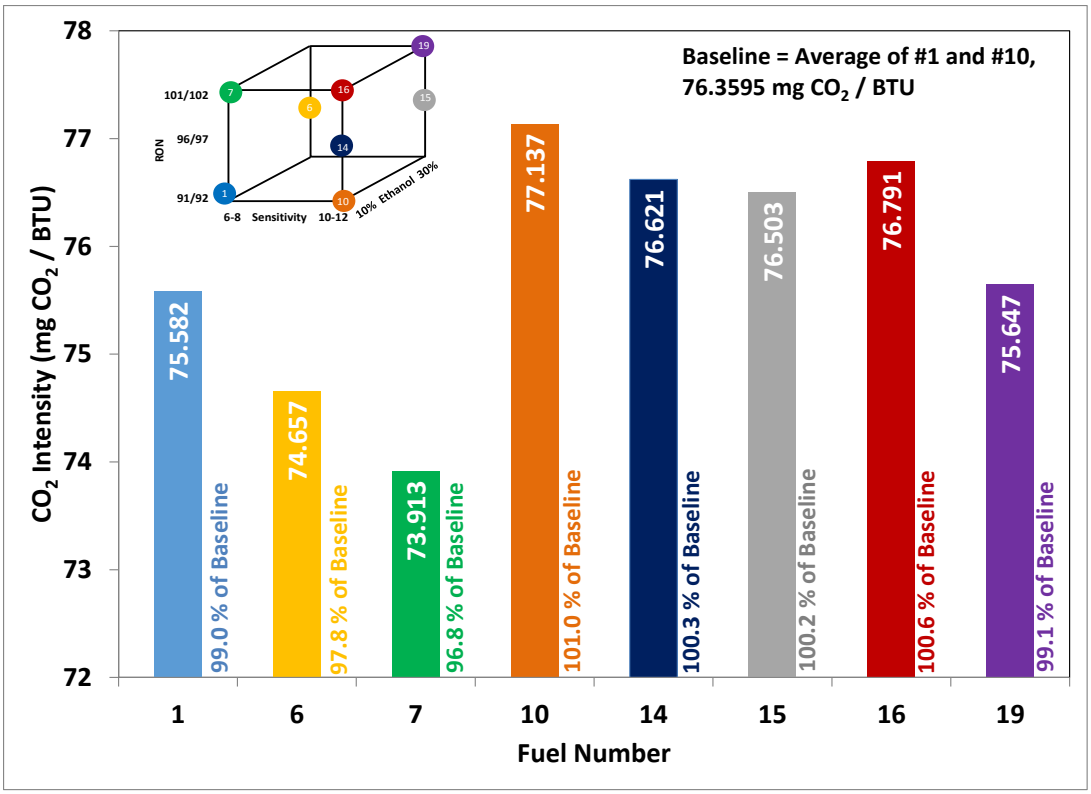

Figure 6.27. CO_2 intensity for the Phase 3 fuels.

Table 6.2. Volumetric fuel economy, energy consumption, and CO_2 emissions results for the mid-size sedan and small SUV at CR10.5.

Vehicle model results for the mid-size sedan and small SUV for CR10.5							
	Drive Cycle	Fuel #1 92 RON, 7 S, E10		Fuel #10 91 RON, 10 S, E10		Fuel #15 97 RON, 12 S, E30	
		Sedan	SUV	Sedan	SUV	Sedan	SUV
Energy Consumption (BTU/Mile)	UDDS	3,765	3,838	3,808	3,884	3,729	3,799
	HWFET	2,643	2,918	2,650	2,929	2,633	2,897
	US06 City	7,494	7,561	7,582	7,696	6,943	7,100
	US06 Hwy	3,756	4,200	3,761	4,232	3,633	4,001
Volumetric Fuel Economy (MPG)	UDDS	29.4	28.9	29.7	29.1	27.7	27.1
	HWFET	41.9	38.0	42.7	38.6	39.2	35.6
	US06 City	14.8	14.7	14.9	14.7	14.9	14.5
	US06 Hwy	29.5	26.4	30.1	26.7	28.4	25.8
Tailpipe CO_2 Emissions (g/mile)	UDDS	285	290	294	300	285	291
	HWFET	200	221	204	226	201	222
	US06 City	566	571	585	594	531	543
	US06 Hwy	284	317	290	326	278	306

Table 6.3. Improvements in volumetric fuel economy, energy use, and CO_2 emissions relative to baseline (average of E10 fuels #1 and #10) for fuels studied at CR10.5.

Changes with CR10.5 relative to baseline (avg. of fuels #1 and #10 at CR10.5)							
	Drive Cycle	Fuel #1 92 RON, 7 S, E10		Fuel #10 91 RON, 10 S, E10		Fuel #15 97 RON, 12 S, E30	
		Sedan	SUV	Sedan	SUV	Sedan	SUV
Energy Use Reduction	UDDS	0.6%	0.6%	-0.6%	-0.6%	1.5%	1.6%
	HWFET	0.1%	0.2%	-0.1%	-0.2%	0.5%	0.9%
	US06 City	0.6%	0.9%	-0.6%	-0.9%	7.9%	6.9%
	US06 Hwy	0.1%	0.4%	-0.1%	-0.4%	3.4%	5.1%
Fuel Economy Increase	UDDS	-0.5%	-0.4%	0.5%	0.4%	-6.5%	-6.4%
	HWFET	-0.9%	-0.8%	0.9%	0.8%	-7.5%	-7.1%
	US06 City	-0.4%	-0.1%	0.4%	0.1%	0.0%	-1.1%
	US06 Hwy	-1.0%	-0.6%	1.0%	0.6%	-4.8%	-3.0%
CO_2 Emissions Reduction	UDDS	1.6%	1.6%	-1.6%	-1.6%	1.4%	1.4%
	HWFET	1.1%	1.2%	-1.1%	-1.2%	0.3%	0.7%
	US06 City	1.6%	1.9%	-1.6%	-1.9%	7.7%	6.8%
	US06 Hwy	1.1%	1.4%	-1.1%	-1.4%	3.2%	4.9%

6.3.5 Vehicle Model Results – CR11.4

Figures 6.28 – 6.30 show the volumetric fuel economy, energy consumption, and CO_2 emissions for the mid-size sedan using CR11.4 and fuels #6 (mid RON, low S, E30), #7 (high RON, low S, E10), #14 (mid RON, high S, E10), and #15 (mid RON, high S, E30). The two vehicle platforms exhibit similar trends, as was observed for the CR10.5 results. Fuel #14 exhibits the best (highest) volumetric fuel economy on all cycles, with #6 showing the worst (lowest) fuel economy. Fuels #6 and #15 differ in sensitivity. In general, fuel #15 shows marginally improved fuel economy and similar or improved energy consumption compared with #6. The CO_2 emissions for fuel #15 compared to fuel #6 are similar or marginally higher. Fuels #7 and #14 are both E10 fuels and show improved volumetric fuel economy compared to the E30 fuels (5.2-7.9% better volumetric fuel economy for the E10 fuel #14 versus the E30 fuel #15, both fuels having nominally the same RON & octane sensitivity). Fuel #14 demonstrates improved energy consumption compared to fuel #7. This result is somewhat surprising, given that fuel #7 has a higher RON rating than fuel #14, although fuel #14 has the higher sensitivity of the two fuels. However, fuel #7 has the lowest volumetric heating value of all of the fuels, owing to the large fraction of saturated hydrocarbons in its makeup. This characteristic causes its volumetric fuel economy results to be low in spite of its octane number advantage. Table 6.4 shows the results for both the sedan and the small SUV at CR11.4. The trends for both vehicles are similar.

Table 6.5 shows the results for both the mid-size sedan and small SUV relative to their respective baseline cases (the average of fuels #1 and #10 at CR10.5). Fuel #14 is the only fuel at CR11.4 that has better volumetric fuel economy (1.4-3.8%) over all drive cycles than the baseline. Gasolines having properties similar to fuel #14 are available in the market today. For comparison, the fuel economies for fuel #15, which has the same nominal RON and sensitivity, but higher ethanol content than fuel #14 has poorer fuel

economies than the baseline on all drive cycles (2.1-6.6% lower). Fuel #6, also an E30 fuel, has the poorest fuel economies on all drive cycles (5.2-7.5% lower than baseline).

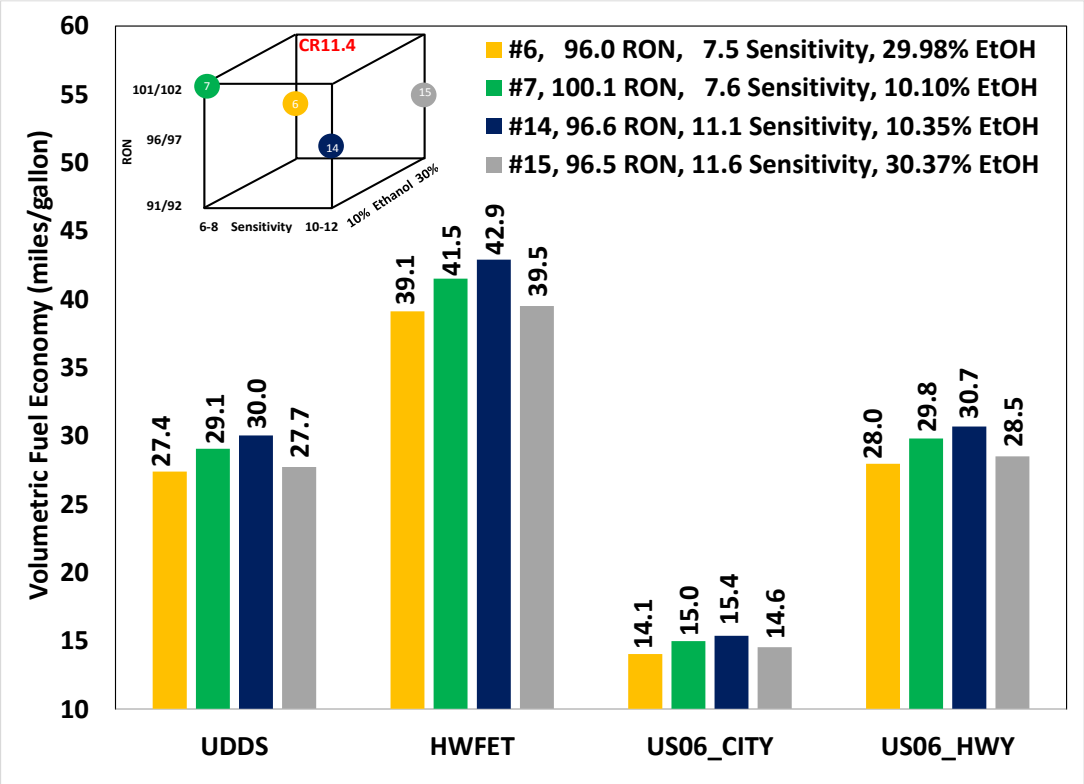

Figure 6.28. Fuel economy results for the mid-size sedan using CR11.4 and fuels #6, #7, #14, and #15.

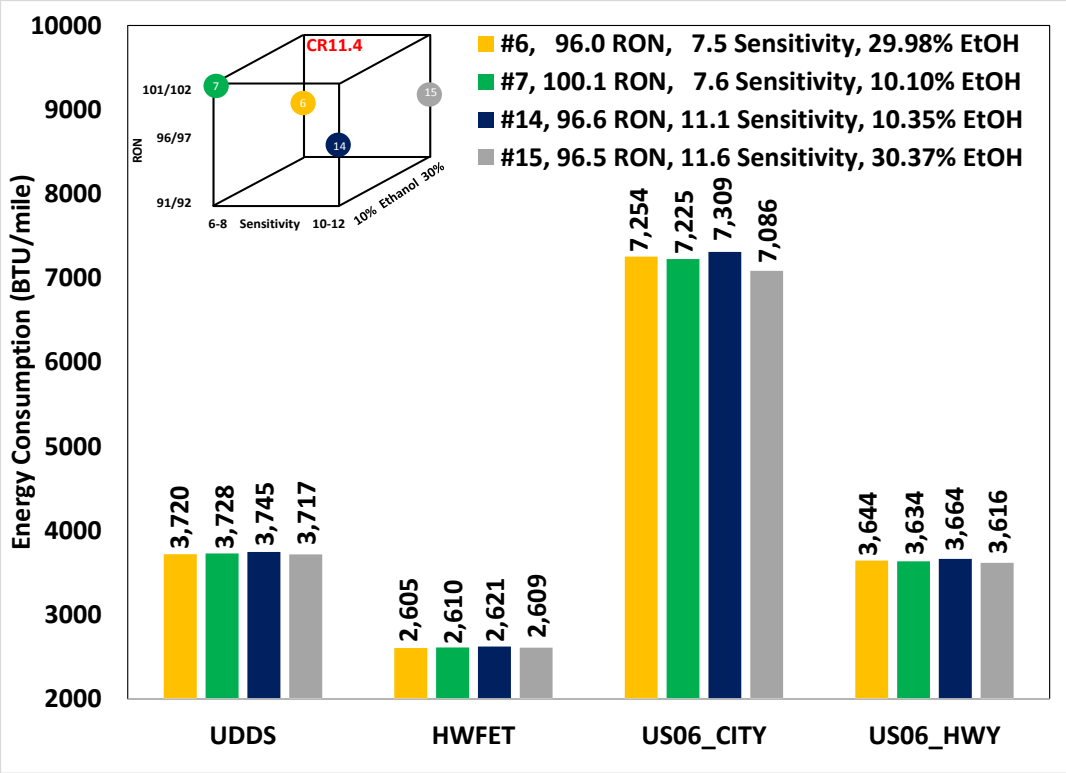

Figure 6.29. Energy consumption results for the mid-size sedan using CR11.4 and fuels #6, #7, #14, and #15.

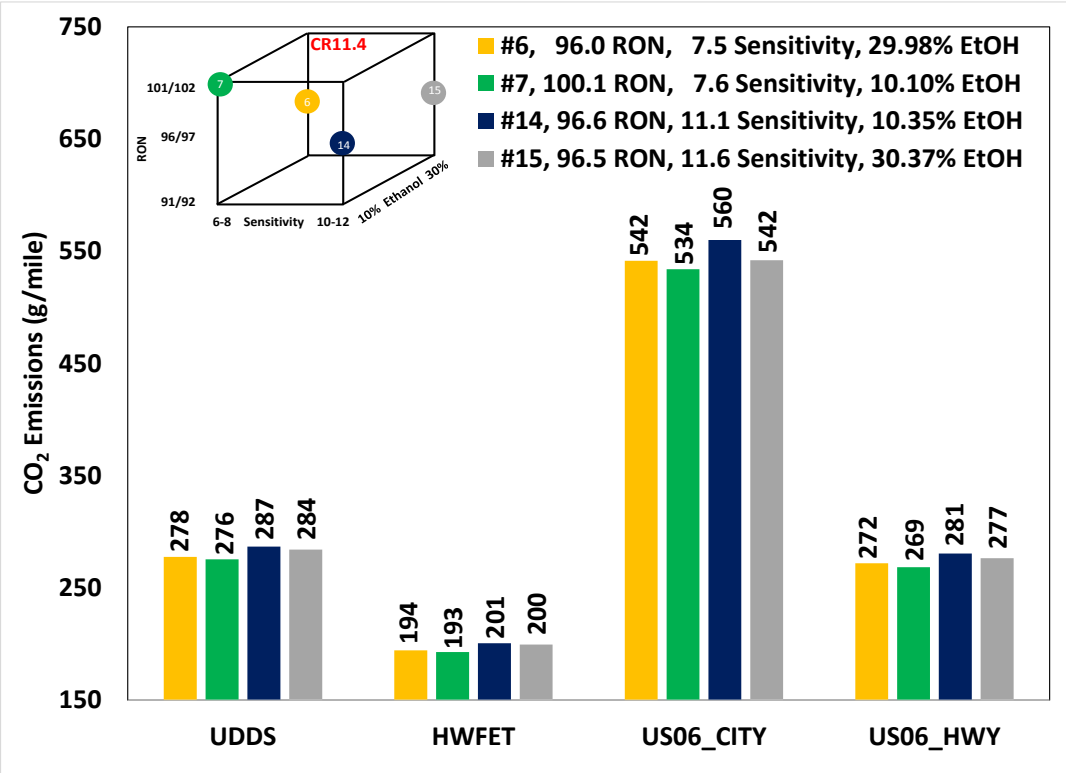

Figure 6.30. CO_2 emissions results for the mid-size sedan using CR11.4 and fuels #6, #7, #14, and #15.

Table 6.4. Volumetric fuel economy, energy consumption, and CO_2 emissions results for the mid-size sedan and small SUV at CR11.4.

Vehicle model results for the mid-size sedan and small SUV for CR11.4									
	Drive Cycle	Fuel #6 96 RON, 8 S, E30		Fuel #7 100 RON, 8 S, E10		Fuel #14 97 RON, 11 S, E10		Fuel #15 97 RON, 12 S, E30	
		Sedan	SUV	Sedan	SUV	Sedan	SUV	Sedan	SUV
Energy Consumption (BTU/Mile)	UDDS	3,720	3,787	3,728	3,789	3,745	3,813	3,717	3,782
	HWFET	2,605	2,863	2,610	2,860	2,621	2,882	2,609	2,859
	US06 City	7,254	7,322	7,225	7,259	7,309	7,381	7,086	7,230
	US06 Hwy	3,644	4,060	3,634	4,042	3,664	4,092	3,616	3,988
Volumetric Fuel Economy (MPG)	UDDS	27.4	26.9	29.1	28.6	30.0	29.5	27.7	27.3
	HWFET	39.1	35.6	41.5	37.9	42.9	39.0	39.5	36.1
	US06 City	14.1	13.9	15.0	14.9	15.4	15.2	14.6	14.3
	US06 Hwy	28.0	25.1	29.8	26.8	30.7	27.5	28.5	25.9
Tailpipe CO_2 Emissions (g/mile)	UDDS	278	283	276	280	287	292	284	289
	HWFET	194	214	193	211	201	221	200	219
	US06 City	542	547	534	537	560	566	542	553
	US06 Hwy	272	303	269	299	281	314	277	305

Table 6.5. Improvements in volumetric fuel economy, CO_2 emissions, and energy use relative to baseline (average of fuel #1 and #10 at CR10.5) for the mid-size sedan and small SUV.

Changes with CR11.4 relative to baseline (avg. of fuels #1 and #10 at CR10.5)									
	Drive Cycle	Fuel #6 96 RON, 8 S, E30		Fuel #7 100 RON, 8 S, E10		Fuel #14 97 RON, 11 S, E10		Fuel #15 97 RON, 12 S, E30	
		Sedan	SUV	Sedan	SUV	Sedan	SUV	Sedan	SUV
Energy Use Reduction	UDDS	1.8%	1.9%	1.5%	1.9%	1.1%	1.2%	1.8%	2.0%
	HWFET	1.6%	2.1%	1.4%	2.2%	1.0%	1.4%	1.4%	2.2%
	US06 City	3.8%	4.0%	4.2%	4.8%	3.0%	3.2%	6.0%	5.2%
	US06 Hwy	3.1%	3.7%	3.3%	4.1%	2.5%	2.9%	3.8%	5.4%
Fuel Economy Increase	UDDS	-7.4%	-7.2%	-1.7%	-1.4%	1.6%	1.7%	-6.2%	-6.0%
	HWFET	-7.5%	-7.0%	-1.9%	-1.1%	1.4%	1.9%	-6.6%	-5.8%
	US06 City	-5.4%	-5.2%	1.0%	1.7%	3.6%	3.8%	-2.1%	-2.9%
	US06 Hwy	-6.1%	-5.5%	0.0%	0.9%	3.0%	3.5%	-4.3%	-2.7%
CO_2 Emissions Reduction	UDDS	4.0%	4.1%	4.7%	5.0%	0.8%	0.9%	1.7%	1.9%
	HWFET	3.8%	4.3%	4.5%	5.3%	0.6%	1.1%	1.3%	2.0%
	US06 City	5.9%	6.2%	7.2%	7.9%	2.7%	2.9%	5.8%	5.1%
	US06 Hwy	5.2%	5.8%	6.4%	7.2%	2.2%	2.6%	3.6%	5.2%

As highlighted previously, the UDDS and HWFET cycles result in engine operation in the MBT region for most of the conditions in the cycle. At these conditions, the improvement in energy consumption should follow the improvement noted in fuel MEP for the increased compression ratio relative to baseline. However, some operation in these cycles does occur in the knock-limited region. Within the knock-limited region, changes in energy use will relate to the degree of CA50 retard needed to avoid knock with a particular fuel and compression ratio combination relative to the performance of the baseline fuel and compression ratio. Since the fuels studied at CR11.4 were selected based on their ability to produce combustion phasing that is similar to or better than the baseline case, additional improvements in energy use might be expected. Examination of the energy use improvements for both the mid-size sedan and small SUV shows that the improvements for the UDDS and HWFET are on the order of 1-2%. These improvements appear directionally correct and reasonable in magnitude given the average improvement in fuel MEP of 1.0% for the increased compression ratio in this comparison. Improvements in energy use for the city and highway portions of the US06 cycle are more dependent on the combustion phasing differences associated with knock avoidance for each fuel. For these cycles, greater improvements are noted than for the UDDS and HWFET.

6.3.6 Corporate Average Fuel Economy

In reporting the results of this study, it is important to highlight the fact that corporate average fuel economy (CAFE) values and volumetric fuel economy values are not the same. The fuel economy values that are used to demonstrate that manufacturers comply with CAFE standards are calculated as if the test fuel had the same volumetric energy content as certification gasoline that was in use in 1975, when the standards were first promulgated.[38,39,40] The R factor is a measure of the marginal difference in the volumetric energy content of the fuel that results in a marginal difference in volumetric fuel economy. The current value of the R factor of 0.6 was established in the late 1980s based on data from vehicles that used carburetors. EPA and the automotive manufacturers are working to develop an acceptable means of establishing CAFE fuel economy values with certification fuels that contain ethanol. While the details of current and potential future CAFE fuel economy calculations are beyond the scope of the current study, the fact that CAFE calculations include a means of adjusting for the volumetric heating value of the test fuel is important. For example, calculating the ratio of the CAFE fuel economy value to the volumetric fuel economy value for the 30% ethanol fuel #15 with an R factor of 0.6 gives a result of 1.058. Thus, if the volumetric fuel economy for this fuel is at least 94.5% of the fuel economy of an ethanol-free fuel with volumetric heating value equivalent to the 1975 certification fuel, the CAFE fuel economy for fuel #15 will be equal to or greater than that of the E0 fuel. This example demonstrates that even cases where the volumetric fuel economy declines marginally for a test fuel containing a low heating-value blending stream (such as ethanol), the CAFE fuel economy value can actually increase.

6.4 COMPARISON WITH PREVIOUSLY PUBLISHED DATA

The results from this study show that decreases in energy consumption and CO_2 emissions on the UDDS, HWFET, and US06 cycles are possible with higher-octane fuels when compression ratio is increased to take advantage of improved knock behavior. Volumetric energy content of the fuel remains as an important factor in whether decreases in energy consumption translate to increases in vehicle volumetric

[38] "Average Fuel Economy Standards," Title 49 U.S. Code, Sec. 32902 et seq, 2001 ed.
[39] Sluder, C., West, B., Butler, A., Mitcham, A., et al., "Determination of the R Factor for Fuel Economy Calculations Using Ethanol-Blended Fuels over Two Test Cycles," SAE Int. J. Fuels Lubr. 7(2):2014.
[40] Hochhauser, A., Benson, J., Burns, V., Gorse, R. et al., "Fuel Composition Effects on Automotive Fuel Economy – Auto/Oil Air Quality Improvement Research Program," SAE Technical Paper 930138, 1993.

fuel economy on given drive cycle. A recent review of previous studies have shown that efficiency gains for increasing from 10.5 to 11.5 compression ratio range from approximately 1.5% to just over 2%.[41] The ideal Otto Cycle establishes an upper limit on this improvement at just over 2.5%. The gains observed in engine efficiency in the MBT region in the AVFL20 study averaged 1%. Similarly, the UDDS and HWFET vehicle energy consumption improvements for fuels evaluated at CR11.4 fell between 1% and 2%. The improvements noted on the US06 cycle where knock-limited operation was more prevalent were larger, as expected. Thus, the observed improvements in this study compare reasonably well with those of other studies. Previous studies have also shown that 96-97 RON fuels typically enable compression ratios of 12 or higher.[40] The compression ratio used in this study with 97 RON fuels was 11.4. It is possible that additional benefits are possible for 96- 97 RON fuels that were not adequately captured with the CR11.4 pistons used in this study. Finally, this study focused on improving efficiency by increasing compression ratio and varying combustion phasing without changing other engine parameters, such as bore diameter, stroke length, valve timing, fuel injection pressure, fuel injection phasing, and so on.

[41] Leone, TG, Anderson, JE, Davis, RS, Iqbal, A, Reese, RA, Shelby, MH, and Studzinski, WM, "The Effect of Compression Ratio, Fuel Octane Rating, and Ethanol Content on Spark-Ignition Engine Efficiency," Environ. Sci. Tech. 49(18), 2015.

7. CONCLUSIONS

Based on the screening study:

- Knock behavior and the ability to increase CR were primarily affected by RON.
- Higher sensitivity (RON minus MON) also showed some knock benefit, especially for the ~101-102 RON fuels at the highest loads.
- At equal RON, there were no significant effects of differences in fuel ethanol content (between 10 vol% and 30 vol%) on knock behavior.
- The ~96-97 RON fuels at CR11.4 generally gave similar knock behavior to the baseline ~91-92 RON fuels at the baseline CR10.5. This indicates that +5 RON enabled +0.9 CR, i.e. 5.6 RON per CR.
- The ~101-102 RON fuels with high sensitivity at CR13.2 generally gave similar knock behavior to the baseline. This indicates that +10 RON enabled +2.7 CR, i.e. 3.7 RON per CR (however these results were not achieved with lower-sensitivity fuels).
- At similar RON (96-97) but lower sensitivity (7-8), fuel EEE (E0) offered knock resistance similar to fuel #15 (E30) at CR10.5, but more similar to fuel #5 (E10) at CR13.2.

Based on the vehicle modeling results:

<u>Comparing Compression Ratio 11.4 with the CR10.5 Baseline Condition (Average of Fuels #1 and #10)</u>

- On the UDDS and HWFET cycles, **increasing compression ratio from CR10.5 to CR11.4** provided vehicle energy consumption improvements (decreases) between 1-2.2% for both the mid-size sedan and small SUV depending upon the fuel used. Volumetric fuel economy changes ranged from a 7.5% detriment to a 1.9% improvement in volumetric fuel economy. Fuel #6 (96 RON, 7.5 sensitivity, E30) provided the poorest fuel economy result, with fuel #14 (96.6 RON, 11.1 sensitivity, E10) providing the highest volumetric fuel economy improvements, relative to the baseline. No ethanol levels between 10% and 30% were studied, so no data exists to directly indicate whether intermediate values of ethanol content might have achieved fuel economy parity with the baseline case. Tailpipe CO_2 emissions reductions ranged from 0.6-5.3%, with the largest improvements (reductions) achieved for fuels #6 (96.0 RON, 7.5 sensitivity, E30) and #7 (100.1 RON, 7.6 sensitivity, E10).
- On the higher load US06 cycle, **increasing compression ratio from CR10.5 to CR11.4** enabled decreases in vehicle energy consumption of 2.5-6.0% depending upon the fuel used. However, these improvements were not sufficient to enable the two E30 fuels (#6 and #15, both 96-97 RON and with varying sensitivity) to achieve volumetric fuel economy parity with the baseline case. No ethanol levels between 10% and 30% were studied, so no data exist to directly indicate whether intermediate values of ethanol content might have achieved fuel economy parity with the baseline case. Fuels #14 and #7 had better (higher) fuel economies over both portions of the US06 cycle compared to the baseline. Fuels #6, #7, and #15 showed significant tailpipe CO_2 emissions reductions, ranging from 3.6-7.9%, with fuel #7 showing the largest reductions.

<u>Compression Ratio 10.5</u>

- **Increasing sensitivity** from 7.3 (fuel #1) to 10.4 (fuel #10) at nominally fixed RON (91-92) and ethanol content (10%) caused vehicle energy consumption (BTU/mile) to increase on all cycles. Increases were in the range of 0-1.8%, and did not result in decreases in volumetric fuel economy (miles / gallon) because fuel #1 had a marginally lower volumetric heating value. Tailpipe CO_2 emissions trends followed energy consumption trends.

- **Increasing RON** from 91.4 (fuel #10) to 96.5 (fuel#15) by increasing ethanol content from 10% to 30% at nominally fixed sensitivity (11-12) caused vehicle energy consumption to decrease by 0.6 to 8.4%, depending on the drive cycle and vehicle. The largest decrease (8.4%) was sufficient to allow the E30 fuel to achieve volumetric fuel economy parity with the E10 fuel for the city portion of the US06 cycle for the sedan, but not for the SUV. On all other drive cycles the volumetric fuel economy of the E30 fuel was lower by 5.7 to 8.3% for the sedan and 1.2 to 7.9% for the SUV. Tailpipe CO_2 emissions trends followed energy consumption trends.

<u>Compression Ratio 11.4</u>

- All fuels mapped at CR11.4 produced similar energy consumption results on the UDDS and HWFET drive cycles. Since both of these cycles are dominated by operation in the MBT region, it is possible that CR11.4 did not provide enough knock propensity in the knock-limited region to enable effects to be differentiated as a function of fuel RON and sensitivity for these two cycles.
- **Increasing ethanol content** from 10% (fuel #14) to 30% (fuel#15) at nominally fixed sensitivity (11-12) and RON (96-97) caused vehicle energy consumption to decrease by 1-3% with the largest change occurring on the US06 cycle. This improvement was not large enough to offset the lower volumetric energy content of the E30 fuel relative to the E10 blend, and thus the volumetric fuel economy for fuel #15 was lower than for fuel #14 (5.5-7.9% lower). CO_2 emissions for fuel #15 were 1.4-3.0% lower than for fuel #14 on the US06 cycle. On the UDDS and HWFET cycles, the vehicle energy consumption for fuel #15 was 0.4 to 0.8% lower than fuel #14 while volumetric fuel economy was about 8% lower and tailpipe CO_2 emissions were about 1% lower.
- **Increasing sensitivity** from 7.5 (fuel #6) to 11.6 (fuel #15) at nominally fixed ethanol content (30%) and RON (96-97) caused vehicle energy consumption to improve (decline) in all but one case by 0.1-2.3%, with the greatest improvement on the city portion of the US06 cycle. Volumetric fuel economy was 1.0 to 3.6% higher (better) for fuel #15, partially due to the higher volumetric energy content of fuel #15. Tailpipe CO_2 emissions for fuel #15 were equal to or greater than those for fuel #6. On the UDDS and HWFET cycles, the vehicle energy consumption of the two fuels were comparable, although the volumetric fuel economy of the higher sensitivity fuel was about 1% better (higher). On those cycles, the tailpipe CO_2 emissions of the higher sensitivity fuel were about 2 to 3% higher.
- **Increasing RON** from 96.0 (fuel #6, E30) to 100.1 (fuel #7, E10) at nominally fixed sensitivity (6-7) and lower ethanol content resulted in less than 1% improvement in vehicle energy consumption on the city and highway portions of the US06 cycle. On both portions of the US06 cycle, volumetric fuel economy for fuel #7 was higher by about 7%. This difference was caused in part by to the higher volumetric energy content of fuel #7. Tailpipe CO_2 emissions were 0.5-1.8% lower for fuel #7 depending on the drive cycle and vehicle, caused in part by its lower CO_2 intensity. On the UDDS and HWFET cycles, the vehicle energy consumption was comparable for the two fuels, while the volumetric fuel economy was about 6% better for fuel #7 and tailpipe CO_2 emissions were about 1% better.
- Of the four fuels tested at CR11.4, fuel #14 (96.6 RON, 11.1 sensitivity, E10) had the highest (best) volumetric fuel economy while the two E30 fuels (#6 and #15, both 96-97 RON and with varying sensitivity) had the lowest (poorest) fuel economy on all drive cycles. The differences between fuel #14 and fuel #6 were consistently about 9% for all drive cycles and vehicles.
- Of the four fuels tested at CR11.4, fuel #15 (96.5 RON, 11.6 sensitivity, E30) had the lowest (best) vehicle energy consumption on all cycles, with one exception where fuel #6 (RON 96, sensitivity 7.5, E30) was marginally lower (by 0.2%). Fuel #14 had the highest (poorest) energy consumption results for all cycles and for both vehicles, by 0.5 to 3.1% compared with fuel #15.
- Of the four fuels tested at CR11.4, fuel #7 (100.1 RON, 7.6 sensitivity, E10) had the lowest (best) CO_2 emissions with fuel #14 (96.6 RON, 11.1 sensitivity, E10) resulting in the highest (poorest)

tailpipe CO_2 emissions for all cycles and both vehicles. The differences between these two fuels ranged from 4.1 to 5.4%.

Compression Ratio 13.2

- No vehicle models were produced for CR13.2 because of the engine failure and subsequent challenge in terms of data comparability with data at CR10.5 and CR11.4. Thus, no volumetric fuel economy, vehicle energy consumption, or tailpipe CO_2 emissions comparisons were established at CR13.2.

8. ACKNOWLEDGEMENTS

Many people and organizations contributed to the success of this study, which was funded by the Coordinating Research Council through the Advanced Vehicle/Fuel/Lubricants (AVFL) Committee. The authors would like to thank Ford Motor Company for providing the engine and controller used in this study, in addition to their valuable technical guidance and extensive computational fluid dynamics studies. Chevron contributed extensive fuel analyses to this study. Finally, the AVFL committee provided valuable technical guidance and extensive review or the project results.

APPENDIX A. Certificates of Analysis for Phase 2 Blends

GAGE PRODUCTS CO.
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Gage Products Company
Certificate of Analysis / QC Results

Customer: C00100 / CRC, Inc.

Sales Order # : 55123 Customer PO # : 769 Shipped Qty : 54

Packaged Product: 41771-55F
CRC AVFL-20 Fuel #1

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60 DEG. F	ASTM D4052		REPORT	0.7387
DENSITY AT 15.5 DEG. C	ASTM D4052	KG/L	REPORT	0.738
RESEARCH OCTANE NUMBER	ASTM D2699	RON	91.0 - 92.0	91.0
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	84.5
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	87.8
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	6.0 - 8.0	6.5
ETHANOL CONTENT	ASTM D4815	VOL.%	9.50 - 10.50	9.93
RVP @ 100 DEG. F	ASTM D5191	PSI (KPA)	REPORT	8.22(56.64)
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	102.0(38.9)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	125.4(51.9)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	133.4(56.3)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	143.6(62.0)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	150.9(66.1)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	162.7(72.6)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	REPORT	220.9(104.9)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	249.8(121.0)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	271.3(132.9)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	296.8(147.1)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	REPORT	329.0(165.0)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	348.7(175.9)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	REPORT	378.0(192.2)
RECOVERY	ASTM D86	VOL.%	REPORT	97.5
RESIDUE	ASTM D86	VOL.%	REPORT	1.0
LOSS	ASTM D86	VOL.%	REPORT	1.5
AROMATIC CONTENT	ASTM D1319	VOL.%	REPORT	9.7
OLEFIN CONTENT	ASTM D1319	VOL.%	REPORT	7.1
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	73.2

Lot # 7270700 **Made** 09/12/14

In sealed unopened containers this product is good until 09/05/15

Approved By: Robert Petzold

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Gage Products Company
Certificate of Analysis / QC Results

Customer: C00100 / CRC, Inc.

Sales Order # : 55519 Customer PO # : 769 Shipped Qty : 54

Packaged Product: 41772-55F
CRC AVFL-20 Fuel #2

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60 DEG. F	ASTM D4052		REPORT	0.7386
DENSITY AT 15.5 DEG. C	ASTM D4052	KG/L	REPORT	0.738
RESEARCH OCTANE NUMBER	ASTM D2699	RON	91.0 - 92.0	91.4
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	85.0
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	88.2
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	6.0 - 8.0	6.4
ETHANOL CONTENT	ASTM D4815	VOL.%	14.50 - 15.50	14.63
RVP @ 100 DEG. F	ASTM D5191	PSI (KPA)	REPORT	8.54(58.84)
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	103.3(39.6)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	121.8(49.9)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	129.6(54.2)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	140.7(60.4)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	149.2(65.1)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	156.0(68.9)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	REPORT	161.1(71.7)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	245.5(118.6)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	265.6(129.8)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	293.5(145.3)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	REPORT	329.9(165.5)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	357.5(180.8)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	REPORT	383.2(195.1)
RECOVERY	ASTM D86	VOL.%	REPORT	97.7
RESIDUE	ASTM D86	VOL.%	REPORT	0.9
LOSS	ASTM D86	VOL.%	REPORT	1.4
AROMATIC CONTENT	ASTM D1319	VOL.%	REPORT	8.4
OLEFIN CONTENT	ASTM D1319	VOL.%	REPORT	6.2
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	70.8

Lot # 7324000 **Made** 10/01/14

In sealed unopened containers this product is good until 09/19/15

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Customer: C00100 / CRC, Inc.

Sales Order # : 55519 Customer PO # : 769 Shipped Qty : 54

Packaged Product: 41773-55F
CRC AVFL-20 Fuel #3

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60 DEG. F	ASTM D4052		REPORT	0.7423
DENSITY AT 15.5 DEG. C	ASTM D4052	KG/L	REPORT	0.742
RESEARCH OCTANE NUMBER	ASTM D2699	RON	91.0 - 92.0	91.4
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	84.5
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	88.0
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	6.0 - 8.0	6.9
ETHANOL CONTENT	ASTM D4815	VOL.%	19.50 - 20.50	20.30
RVP @ 100 DEG. F	ASTM D5191	PSI (KPA)	REPORT	8.14(56.08)
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	104.9(40.5)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	124.0(51.1)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	131.7(55.4)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	143.4(61.9)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	152.2(66.8)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	159.6(70.9)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	REPORT	164.8(73.8)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	187.2(86.2)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	271.0(132.8)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	302.5(150.3)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	REPORT	338.4(170.2)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	355.3(179.6)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	REPORT	383.4(195.2)
RECOVERY	ASTM D86	VOL.%	REPORT	97.7
RESIDUE	ASTM D86	VOL.%	REPORT	0.8
LOSS	ASTM D86	VOL.%	REPORT	1.5
AROMATIC CONTENT	ASTM D1319	VOL.%	REPORT	7.0
OLEFIN CONTENT	ASTM D1319	VOL.%	REPORT	5.3
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	67.4

Lot # 7324400 **Made** 10/01/14

In sealed unopened containers this product is good until 09/19/15

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Customer: C00100 / CRC, Inc.

Sales Order # : 55123 Customer PO # : 769 Shipped Qty : 54

Packaged Product: 41774-55F
CRC AVFL-20 Fuel #4

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60 DEG. F	ASTM D4052		REPORT	0.7457
DENSITY AT 15.5 DEG. C	ASTM D4052	KG/L	REPORT	0.745
RESEARCH OCTANE NUMBER	ASTM D2699	RON	91.0 - 92.0	91.7
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	84.7
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	88.2
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	6.0 - 8.0	7.0
ETHANOL CONTENT	ASTM D4815	VOL.%	29.50 - 30.50	30.24
RVP @ 100 DEG. F	ASTM D5191	PSI (KPA)	REPORT	7.41(51.05)
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	108.7(42.6)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	128.5(53.6)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	136.2(57.9)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	148.8(64.9)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	158.4(70.2)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	164.5(73.6)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	REPORT	167.5(75.3)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	169.3(76.3)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	243.1(117.3)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	311.5(155.3)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	REPORT	341.4(171.9)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	356.7(180.4)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	REPORT	374.9(190.5)
RECOVERY	ASTM D86	VOL.%	REPORT	98.0
RESIDUE	ASTM D86	VOL.%	REPORT	1.0
LOSS	ASTM D86	VOL.%	REPORT	1.0
AROMATIC CONTENT	ASTM D1319	VOL.%	REPORT	4.5
OLEFIN CONTENT	ASTM D1319	VOL.%	REPORT	2.0
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	62.7

Lot # 7271100 **Made** 09/23/14

In sealed unopened containers this product is good until 09/05/15

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Customer: C00100 / CRC, Inc.

Sales Order # : 55519 Customer PO # : 769 Shipped Qty : 54

Packaged Product: 41775-55F
CRC AVFL-20 Fuel #5

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60 DEG. F	ASTM D4052		REPORT	0.7342
DENSITY AT 15.5 DEG. C	ASTM D4052	KG/L	REPORT	0.734
RESEARCH OCTANE NUMBER	ASTM D2699	RON	96.0 - 97.0	96.4
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	89.0
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	92.7
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	6.0 - 8.0	7.4
ETHANOL CONTENT	ASTM D4815	VOL.%	9.50 - 10.50	10.17
RVP @ 100 DEG. F	ASTM D5191	PSI (KPA)	REPORT	8.22(56.64)
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	100.3(37.9)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	127.1(52.8)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	136.0(57.8)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	148.1(64.5)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	155.4(68.6)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	186.5(85.8)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	REPORT	227.7(108.7)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	237.6(114.2)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	256.1(124.5)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	289.7(143.2)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	REPORT	330.8(166.0)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	344.6(173.7)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	REPORT	372.2(189.0)
RECOVERY	ASTM D86	VOL.%	REPORT	97.5
RESIDUE	ASTM D86	VOL.%	REPORT	1.0
LOSS	ASTM D86	VOL.%	REPORT	1.5
AROMATIC CONTENT	ASTM D1319	VOL.%	REPORT	8.8
OLEFIN CONTENT	ASTM D1319	VOL.%	REPORT	0.0
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	81.0

Lot # 7324800 **Made** 10/10/14

In sealed unopened containers this product is good until 09/19/15

Approved By: Robert Petzitt

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Gage Products Company
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Customer: C00100 / CRC, Inc.

Sales Order # : 55123 Customer PO # : 769 Shipped Qty : 54

Packaged Product: 41776-55F
CRC AVFL-20 Fuel #6

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60 DEG. F	ASTM D4052		REPORT	0.7386
DENSITY AT 15.5 DEG. C	ASTM D4052	KG/L	REPORT	0.738
RESEARCH OCTANE NUMBER	ASTM D2699	RON	96.0 - 97.0	96.3
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	88.4
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	92.4
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	6.0 - 8.0	7.9
ETHANOL CONTENT	ASTM D4815	VOL.%	29.50 - 30.50	30.03
RVP @ 100 DEG. F	ASTM D5191	PSI (KPA)	REPORT	7.59(52.30)
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	102.2(39.0)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	133.3(56.3)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	143.3(61.8)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	154.8(68.2)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	160.7(71.5)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	163.8(73.2)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	REPORT	165.6(74.2)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	167.1(75.1)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	190.1(87.8)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	281.3(138.5)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	REPORT	335.0(168.3)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	349.7(176.5)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	REPORT	368.4(186.9)
RECOVERY	ASTM D86	VOL.%	REPORT	97.7
RESIDUE	ASTM D86	VOL.%	REPORT	1.0
LOSS	ASTM D86	VOL.%	REPORT	1.3
AROMATIC CONTENT	ASTM D1319	VOL.%	REPORT	1.3
OLEFIN CONTENT	ASTM D1319	VOL.%	REPORT	2.1
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	66.4

Lot # 7271500 **Made** 10/02/14

In sealed unopened containers this product is good until 09/05/15

Approved By: Robert Petrillo

GAGE PRODUCTS CO.
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Gage Products Company
Certificate of Analysis / QC Results

Customer: C00100 / CRC, Inc.

Sales Order # : 55123 Customer PO # : 769 Shipped Qty : 54

Packaged Product: 41777-55F
CRC AVFL-20 Fuel #7

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60 DEG. F	ASTM D4052		REPORT	0.7142
DENSITY AT 15.5 DEG. C	ASTM D4052	KG/L	REPORT	0.714
RESEARCH OCTANE NUMBER	ASTM D2699	RON	100.0 - 102.0	100.0
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	92.4
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	96.2
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	6.0 - 8.0	7.2
ETHANOL CONTENT	ASTM D4815	VOL.%	9.50 - 10.50	10.28
RVP @ 100 DEG. F	ASTM D5191	PSI (KPA)	REPORT	7.88(54.29)
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	110.3(43.5)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	129.2(54.0)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	138.4(59.1)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	145.4(63.0)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	159.3(70.7)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	198.9(92.7)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	REPORT	219.4(104.1)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	222.8(106.0)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	228.4(109.1)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	240.1(115.6)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	REPORT	283.3(139.6)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	338.2(170.1)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	REPORT	388.4(198.0)
RECOVERY	ASTM D86	VOL.%	REPORT	97.5
RESIDUE	ASTM D86	VOL.%	REPORT	0.8
LOSS	ASTM D86	VOL.%	REPORT	1.7
AROMATIC CONTENT	ASTM D1319	VOL.%	REPORT	3.3
OLEFIN CONTENT	ASTM D1319	VOL.%	REPORT	0.5
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	85.6

Lot # 7271900 **Made** 09/12/14

In sealed unopened containers this product is good until 09/05/15

Approved By: Robert Petrillo

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Gage Products Company
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Customer: C00100 / CRC, Inc.

Sales Order # : 55519 Customer PO # : 769 Shipped Qty : 54

Packaged Product: 41791-55F
CRC AVFL-20 Fuel #7.5

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60 DEG. F	ASTM D4052		REPORT	0.7160
DENSITY AT 15.5 DEG. C	ASTM D4052	KG/L	REPORT	0.716
RESEARCH OCTANE NUMBER	ASTM D2699	RON	99.0 - 102.0	99.8
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	91.3
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	95.6
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	6.0 - 8.5	8.5
ETHANOL CONTENT	ASTM D4815	VOL.%	14.50 - 15.50	15.30
RVP @ 100 DEG. F	ASTM D5191	PSI (KPA)	REPORT	8.33(57.39)
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	101.8(38.8)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	130.3(54.6)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	138.5(59.2)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	150.0(65.6)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	156.8(69.3)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	160.7(71.5)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	REPORT	182.9(83.8)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	219.5(104.2)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	225.3(107.4)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	236.4(113.6)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	REPORT	290.4(143.6)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	337.6(169.8)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	REPORT	376.0(191.1)
RECOVERY	ASTM D86	VOL.%	REPORT	97.7
RESIDUE	ASTM D86	VOL.%	REPORT	1.1
LOSS	ASTM D86	VOL.%	REPORT	1.2
AROMATIC CONTENT	ASTM D1319	VOL.%	REPORT	2.1
OLEFIN CONTENT	ASTM D1319	VOL.%	REPORT	0.0
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	82.6

Lot # 7327600 **Made** 10/24/14

In sealed unopened containers this product is good until 09/19/15

Approved By: Robert Petzold

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Gage Products Company
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Customer: C00100 / CRC, Inc.

Sales Order # : 55519 Customer PO # : 769 Shipped Qty : 54

Packaged Product: 41778-55F
CRC AVFL-20 Fuel #8

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60 DEG. F	ASTM D4052		REPORT	0.7270
DENSITY AT 15.5 DEG. C	ASTM D4052	KG/L	REPORT	0.726
RESEARCH OCTANE NUMBER	ASTM D2699	RON	99.0 - 102.0	99.6
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	91.2
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	95.4
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	6.0 - 9.0	8.4
ETHANOL CONTENT	ASTM D4815	VOL.%	19.50 - 20.50	20.11
RVP @ 100 DEG. F	ASTM D5191	PSI (KPA)	REPORT	7.64(52.64)
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	115.2(46.2)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	139.1(59.5)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	149.5(65.3)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	158.9(70.5)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	162.0(72.2)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	163.0(72.8)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	REPORT	164.5(73.6)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	221.9(105.5)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	230.2(110.1)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	247.8(119.9)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	REPORT	320.5(160.3)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	338.5(170.3)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	REPORT	362.5(183.6)
RECOVERY	ASTM D86	VOL.%	REPORT	97.6
RESIDUE	ASTM D86	VOL.%	REPORT	0.7
LOSS	ASTM D86	VOL.%	REPORT	1.7
AROMATIC CONTENT	ASTM D1319	VOL.%	REPORT	1.7
OLEFIN CONTENT	ASTM D1319	VOL.%	REPORT	0.0
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	78.2

Lot # 7325200 **Made** 10/01/14

In sealed unopened containers this product is good until 09/19/15

Approved By: Robert Pabitt

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Gage Products Company
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Customer: C00100 / CRC, Inc.

Sales Order # : 55123 Customer PO # : 769 Shipped Qty : 54

Packaged Product: 41780-55F
CRC AVFL-20 Fuel #10

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60 DEG. F	ASTM D4052		REPORT	0.7593
DENSITY AT 15.5 DEG. C	ASTM D4052	KG/L	REPORT	0.759
RESEARCH OCTANE NUMBER	ASTM D2699	RON	91.0 - 92.0	91.1
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	80.7
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	85.9
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	10.0 - 12.0	10.4
ETHANOL CONTENT	ASTM D4815	VOL.%	9.50 - 10.50	10.00
RVP @ 100 DEG. F	ASTM D5191	PSI (KPA)	REPORT	7.59(52.30)
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	107.1(41.7)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	127.5(53.1)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	134.1(56.7)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	141.8(61.0)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	147.8(64.3)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	155.7(68.7)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	REPORT	207.2(97.3)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	262.3(127.9)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	287.4(141.9)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	302.8(150.4)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	REPORT	325.3(162.9)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	346.9(174.9)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	REPORT	375.1(190.6)
RECOVERY	ASTM D86	VOL.%	REPORT	98.0
RESIDUE	ASTM D86	VOL.%	REPORT	1.0
LOSS	ASTM D86	VOL.%	REPORT	1.0
AROMATIC CONTENT	ASTM D1319	VOL.%	REPORT	20.7
OLEFIN CONTENT	ASTM D1319	VOL.%	REPORT	19.6
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	49.7

Lot # 7272300 **Made** 09/23/14

In sealed unopened containers this product is good until 09/05/15

Approved By: Robert Petrillo

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Gage Products Company
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Customer: C00100 / CRC, Inc.

Sales Order # : 55519 Customer PO # : 769 Shipped Qty : 54

Packaged Product: 41781-55F
CRC AVFL-20 Fuel #11

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60 DEG. F	ASTM D4052		REPORT	0.7527
DENSITY AT 15.5 DEG. C	ASTM D4052	KG/L	REPORT	0.752
RESEARCH OCTANE NUMBER	ASTM D2699	RON	91.0 - 92.0	91.6
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	80.8
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	86.2
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	10.0 - 12.0	10.8
ETHANOL CONTENT	ASTM D4815	VOL.%	14.50 - 15.50	14.75
RVP @ 100 DEG. F	ASTM D5191	PSI (KPA)	REPORT	8.38(57.74)
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	103.9(39.9)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	120.6(49.2)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	128.4(53.6)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	136.0(57.8)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	141.8(61.0)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	147.2(64.0)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	REPORT	152.9(67.2)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	167.0(75.0)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	272.0(133.3)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	304.4(151.3)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	REPORT	340.4(171.3)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	363.4(184.1)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	REPORT	386.9(197.2)
RECOVERY	ASTM D86	VOL.%	REPORT	96.9
RESIDUE	ASTM D86	VOL.%	REPORT	1.1
LOSS	ASTM D86	VOL.%	REPORT	2.0
AROMATIC CONTENT	ASTM D1319	VOL.%	REPORT	13.8
OLEFIN CONTENT	ASTM D1319	VOL.%	REPORT	25.4
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	46.0

Lot # 7325600 **Made** 10/11/14

In sealed unopened containers this product is good until 09/19/15

Approved By: Robert Petrillo

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Gage Products Company
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Customer: C00100 / CRC, Inc.

Sales Order # : 55519 Customer PO # : 769 Shipped Qty : 54

Packaged Product: 41782-55F
CRC AVFL-20 Fuel #12

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60 DEG. F	ASTM D4052		REPORT	0.7568
DENSITY AT 15.5 DEG. C	ASTM D4052	KG/L	REPORT	0.756
RESEARCH OCTANE NUMBER	ASTM D2699	RON	91.0 - 92.0	91.4
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	81.2
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	86.3
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	10.0 - 12.0	10.2
ETHANOL CONTENT	ASTM D4815	VOL.%	19.50 - 20.50	19.58
RVP @ 100 DEG. F	ASTM D5191	PSI (KPA)	REPORT	7.30(50.30)
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	108.3(42.4)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	124.7(51.5)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	131.5(55.3)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	140.4(60.2)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	146.3(63.5)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	151.7(66.5)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	REPORT	157.6(69.8)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	163.8(73.2)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	277.2(136.2)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	309.9(154.4)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	REPORT	351.7(177.6)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	373.1(189.5)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	REPORT	387.7(197.6)
RECOVERY	ASTM D86	VOL.%	REPORT	98.1
RESIDUE	ASTM D86	VOL.%	REPORT	0.9
LOSS	ASTM D86	VOL.%	REPORT	1.0
AROMATIC CONTENT	ASTM D1319	VOL.%	REPORT	15.1
OLEFIN CONTENT	ASTM D1319	VOL.%	REPORT	30.0
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	35.3

Lot # 7326000 **Made** 10/14/14

In sealed unopened containers this product is good until 09/19/15

Approved By: Robert Petzitt

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Gage Products Company
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Customer: C00100 / CRC, Inc.

Sales Order # : 55123 Customer PO # : 769 Shipped Qty : 54

Packaged Product: 41783-55F
CRC AVFL-20 Fuel #13

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60 DEG. F	ASTM D4052		REPORT	0.7543
DENSITY AT 15.5 DEG. C	ASTM D4052	KG/L	REPORT	0.754
RESEARCH OCTANE NUMBER	ASTM D2699	RON	91.0 - 92.0	91.9
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	81.2
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	86.6
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	10.0 - 12.0	10.7
ETHANOL CONTENT	ASTM D4815	VOL.%	29.50 - 30.50	29.90
RVP @ 100 DEG. F	ASTM D5191	PSI (KPA)	REPORT	7.34(50.57)
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	115.5(46.4)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	133.2(56.2)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	140.2(60.1)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	148.3(64.6)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	153.5(67.5)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	158.2(70.1)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	REPORT	163.2(72.9)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	167.2(75.1)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	170.2(76.8)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	297.9(147.7)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	REPORT	353.1(178.4)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	377.2(191.8)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	REPORT	400.5(204.7)
RECOVERY	ASTM D86	VOL.%	REPORT	98.3
RESIDUE	ASTM D86	VOL.%	REPORT	0.9
LOSS	ASTM D86	VOL.%	REPORT	0.8
AROMATIC CONTENT	ASTM D1319	VOL.%	REPORT	9.0
OLEFIN CONTENT	ASTM D1319	VOL.%	REPORT	24.8
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	36.3

Lot # 7272700 **Made** 09/23/14

In sealed unopened containers this product is good until 09/05/15

Approved By: Robert Petrillo

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Gage Products Company
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Customer: C00100 / CRC, Inc.

Sales Order # : 55123 Customer PO # : 769 Shipped Qty : 54

Packaged Product: 41784-55F
CRC AVFL-20 Fuel #14

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60 DEG. F	ASTM D4052		REPORT	0.7549
DENSITY AT 15.5 DEG. C	ASTM D4052	KG/L	REPORT	0.754
RESEARCH OCTANE NUMBER	ASTM D2699	RON	96.0 - 97.0	96.2
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	85.5
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	90.8
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	10.0 - 12.0	10.7
ETHANOL CONTENT	ASTM D4815	VOL.%	9.50 - 10.50	10.00
RVP @ 100 DEG. F	ASTM D5191	PSI (KPA)	REPORT	7.96(54.84)
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	100.1(37.8)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	121.1(49.5)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	127.4(53.0)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	135.2(57.3)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	143.1(61.7)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	150.2(65.7)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	REPORT	187.2(86.2)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	244.3(117.9)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	274.1(134.5)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	301.3(149.6)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	REPORT	333.7(167.6)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	356.6(180.3)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	REPORT	384.3(195.7)
RECOVERY	ASTM D86	VOL.%	REPORT	97.7
RESIDUE	ASTM D86	VOL.%	REPORT	1.1
LOSS	ASTM D86	VOL.%	REPORT	1.2
AROMATIC CONTENT	ASTM D1319	VOL.%	REPORT	20.1
OLEFIN CONTENT	ASTM D1319	VOL.%	REPORT	8.0
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	61.8

Lot # 7273100 **Made** 09/25/14

In sealed unopened containers this product is good until 09/05/15

Approved By: Robert Petrulli

GAGE PRODUCTS CO.
821 WANDA AVENUE
FERNDALE, MI 48220
(248) 541-3824

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Gage Products Company
Certificate of Analysis / QC Results

Customer: C00100 / CRC, Inc.

Sales Order # : 55519 Customer PO # : 769 Shipped Qty : 54

Packaged Product: 41785-55F
CRC AVFL-20 Fuel #15

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60 DEG. F	ASTM D4052		REPORT	0.7550
DENSITY AT 15.5 DEG. C	ASTM D4052	KG/L	REPORT	0.755
RESEARCH OCTANE NUMBER	ASTM D2699	RON	96.0 - 97.0	96.4
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	84.9
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	90.6
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	10.0 - 12.0	11.5
ETHANOL CONTENT	ASTM D4815	VOL.%	29.50 - 30.50	29.98
RVP @ 100 DEG. F	ASTM D5191	PSI (KPA)	REPORT	7.59(52.30)
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	104.9(40.5)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	132.9(56.1)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	141.4(60.8)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	151.0(66.1)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	156.7(69.3)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	160.7(71.5)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	REPORT	164.3(73.5)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	167.3(75.2)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	170.5(76.9)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	283.2(139.6)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	REPORT	346.0(174.4)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	370.5(188.1)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	REPORT	386.0(196.7)
RECOVERY	ASTM D86	VOL.%	REPORT	97.8
RESIDUE	ASTM D86	VOL.%	REPORT	1.1
LOSS	ASTM D86	VOL.%	REPORT	1.1
AROMATIC CONTENT	ASTM D1319	VOL.%	REPORT	11.2
OLEFIN CONTENT	ASTM D1319	VOL.%	REPORT	18.9
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	39.9

Lot # 7326400 **Made** 10/13/14

In sealed unopened containers this product is good until 09/19/15

Approved By: Robert Petrillo

GAGE PRODUCTS CO.
821 WANDA AVENUE
FERNDALE, MI 48220
(248) 541-3824

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Gage Products Company
Certificate of Analysis / QC Results

Customer: C00100 / CRC, Inc.

Sales Order # : 55123 Customer PO # : 769 Shipped Qty : 54

Packaged Product: 41786-55F
CRC AVFL-20 Fuel #16

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60 DEG. F	ASTM D4052		REPORT	0.7577
DENSITY AT 15.5 DEG. C	ASTM D4052	KG/L	REPORT	0.757
RESEARCH OCTANE NUMBER	ASTM D2699	RON	101.0 - 102.0	101.5
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	89.5
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	95.5
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	10.0 - 12.0	12.0
ETHANOL CONTENT	ASTM D4815	VOL.%	9.50 - 10.50	9.92
RVP @ 100 DEG. F	ASTM D5191	PSI (KPA)	REPORT	7.58(52.23)
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	102.6(39.2)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	128.6(53.7)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	136.4(58.0)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	147.0(63.9)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	155.0(68.3)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	185.4(85.2)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	REPORT	228.1(108.9)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	245.3(118.5)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	266.2(130.1)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	302.2(150.1)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	REPORT	337.0(169.4)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	354.0(178.9)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	REPORT	382.8(194.9)
RECOVERY	ASTM D86	VOL.%	REPORT	97.9
RESIDUE	ASTM D86	VOL.%	REPORT	1.1
LOSS	ASTM D86	VOL.%	REPORT	1.0
AROMATIC CONTENT	ASTM D1319	VOL.%	REPORT	25.6
OLEFIN CONTENT	ASTM D1319	VOL.%	REPORT	0.0
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	64.4

Lot # 7273500 **Made** 10/21/14

In sealed unopened containers this product is good until 09/05/15

Approved By: Robert Petrillo

GAGE PRODUCTS CO.
821 WANDA AVENUE
FERNDALE, MI 48220
(248) 541-3824

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Gage Products Company
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Customer: C00100 / CRC, Inc.

Sales Order # : 55519 Customer PO # : 769 Shipped Qty : 54

Packaged Product: 41787-55F
CRC AVFL-20 Fuel #17

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60 DEG. F	ASTM D4052		REPORT	0.7542
DENSITY AT 15.5 DEG. C	ASTM D4052	KG/L	REPORT	0.753
RESEARCH OCTANE NUMBER	ASTM D2699	RON	101.0 - 102.0	101.0
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	89.6
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	95.3
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	10.0 - 12.0	11.4
ETHANOL CONTENT	ASTM D4815	VOL.%	14.50 - 15.50	15.10
RVP @ 100 DEG. F	ASTM D5191	PSI (KPA)	REPORT	7.73(53.26)
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	110.3(43.5)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	130.1(54.5)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	139.5(59.7)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	151.5(66.4)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	157.6(69.8)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	161.6(72.0)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	REPORT	210.6(99.2)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	242.8(117.1)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	262.0(127.8)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	300.7(149.3)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	REPORT	337.5(169.7)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	354.7(179.3)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	REPORT	382.6(194.8)
RECOVERY	ASTM D86	VOL.%	REPORT	97.6
RESIDUE	ASTM D86	VOL.%	REPORT	1.0
LOSS	ASTM D86	VOL.%	REPORT	1.4
AROMATIC CONTENT	ASTM D1319	VOL.%	REPORT	17.2
OLEFIN CONTENT	ASTM D1319	VOL.%	REPORT	0.9
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	66.8

Lot # 7326800 **Made** 10/21/14

In sealed unopened containers this product is good until 09/19/15

Approved By: Robert Petitto

GAGE PRODUCTS CO.
821 WANDA AVENUE
FERNDALE, MI 48220
(248) 541-3824

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Gage Products Company
Certificate of Analysis / QC Results

Customer: C00100 / CRC, Inc.

Sales Order # : 55519 Customer PO # : 769 Shipped Qty : 54

Packaged Product: 41788-55F
CRC AVFL-20 Fuel #18

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60 DEG. F	ASTM D4052		REPORT	0.7591
DENSITY AT 15.5 DEG. C	ASTM D4052	KG/L	REPORT	0.758
RESEARCH OCTANE NUMBER	ASTM D2699	RON	101.0 - 102.0	101.1
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	89.1
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	95.1
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	10.0 - 12.0	12.0
ETHANOL CONTENT	ASTM D4815	VOL.%	19.50 - 20.50	20.32
RVP @ 100 DEG. F	ASTM D5191	PSI (KPA)	REPORT	7.36(50.71)
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	112.6(44.8)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	133.2(56.2)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	142.7(61.5)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	153.9(67.7)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	159.8(71.0)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	163.2(72.9)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	REPORT	166.3(74.6)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	247.5(119.7)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	270.7(132.6)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	311.2(155.1)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	REPORT	338.5(170.3)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	354.6(179.2)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	REPORT	384.4(195.8)
RECOVERY	ASTM D86	VOL.%	REPORT	98.0
RESIDUE	ASTM D86	VOL.%	REPORT	0.9
LOSS	ASTM D86	VOL.%	REPORT	1.1
AROMATIC CONTENT	ASTM D1319	VOL.%	REPORT	17.4
OLEFIN CONTENT	ASTM D1319	VOL.%	REPORT	0.5
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	61.8

Lot # 7327200 **Made** 10/21/14

In sealed unopened containers this product is good until 09/19/15

Approved By: Robert Petz, II

GAGE PRODUCTS CO.
821 WANDA AVENUE
FERNDALE, MI 48220
(248) 541-3824

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Gage Products Company
Certificate of Analysis / QC Results

Customer: C00100 / CRC, Inc.

Sales Order # : 55123 Customer PO # : 769 Shipped Qty : 54

Packaged Product: 41789-55F
CRC AVFL-20 Fuel #19

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60 DEG. F	ASTM D4052		REPORT	0.7495
DENSITY AT 15.5 DEG. C	ASTM D4052	KG/L	REPORT	0.749
RESEARCH OCTANE NUMBER	ASTM D2699	RON	101.0 - 102.0	101.0
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	89.0
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	95.0
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	10.0 - 12.0	12.0
ETHANOL CONTENT	ASTM D4815	VOL.%	29.50 - 30.50	29.85
RVP @ 100 DEG. F	ASTM D5191	PSI (KPA)	REPORT	7.25(49.95)
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	107.5(41.9)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	137.7(58.7)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	146.0(63.3)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	155.1(68.4)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	159.8(71.0)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	162.8(72.7)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	REPORT	165.0(73.9)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	167.0(75.0)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	174.5(79.2)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	277.2(136.2)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	REPORT	333.0(167.2)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	343.3(172.9)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	REPORT	365.4(185.2)
RECOVERY	ASTM D86	VOL.%	REPORT	98.0
RESIDUE	ASTM D86	VOL.%	REPORT	1.0
LOSS	ASTM D86	VOL.%	REPORT	1.0
AROMATIC CONTENT	ASTM D1319	VOL.%	REPORT	8.5
OLEFIN CONTENT	ASTM D1319	VOL.%	REPORT	2.4
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	59.2

Lot # 7273900 **Made** 10/01/14

In sealed unopened containers this product is good until 09/05/15

Approved By: Robert Petzold

haltermannsolutions

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Product Information

Telephone: (800) 969-2542

FAX: (281) 457-1469

Johann Haltermann Ltd.

PRODUCT: EPA TIER II EEE FEDERAL REGISTER

PRODUCT CODE: HF0437

Batch No.: CE2121LT10

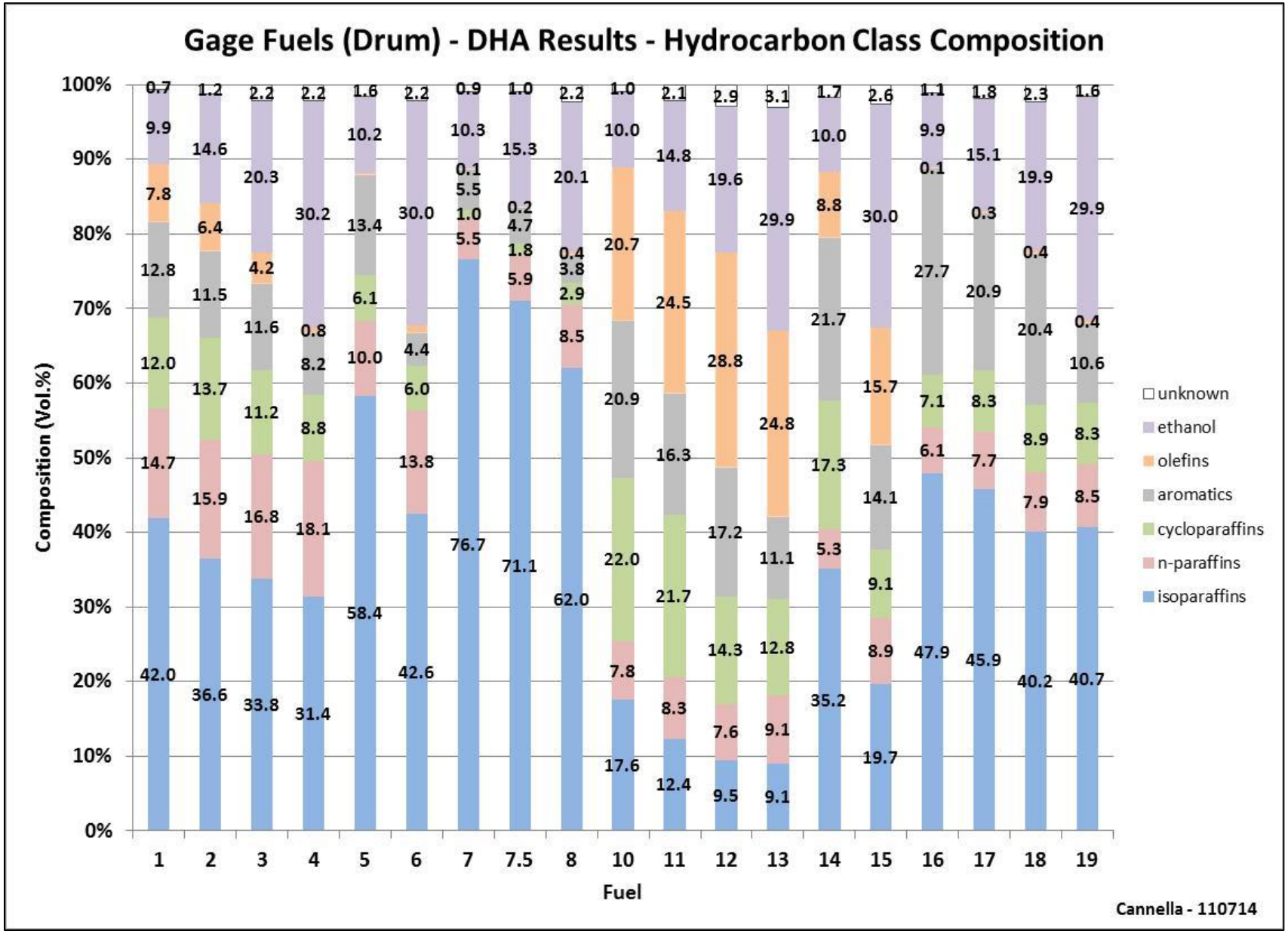
Tank No.: 105

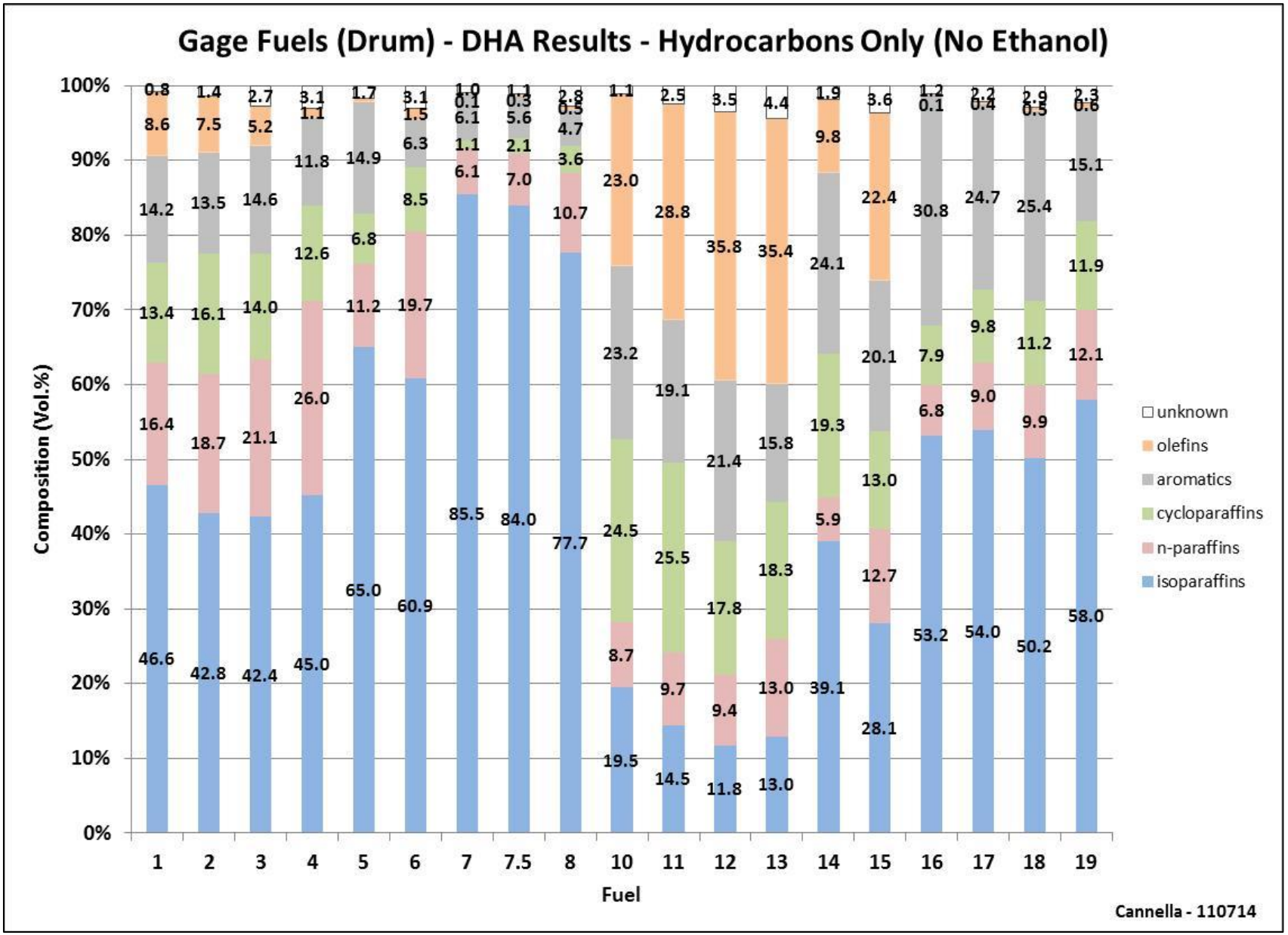
Date: 5/28/2014

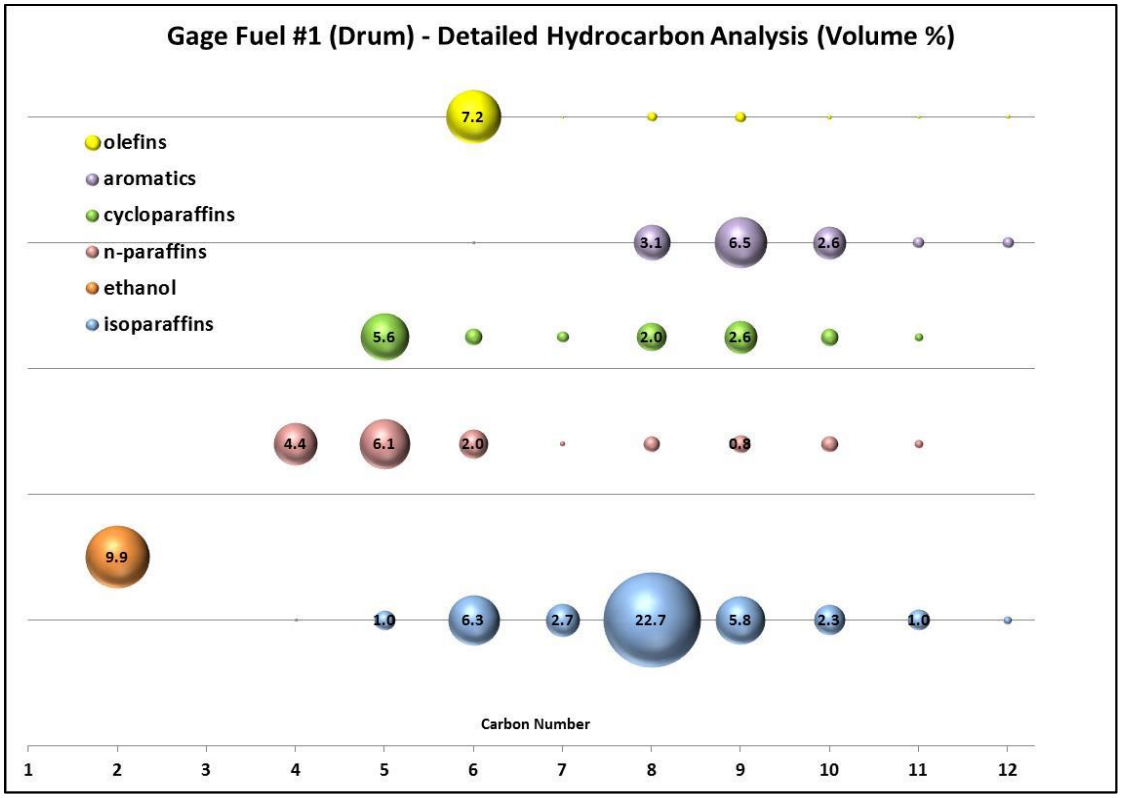
TEST	METHOD	UNITS	HALTERMANN Specs			RESULTS
			MIN	TARGET	MAX	
Distillation - IBP	ASTM D86	°F	75		95	90
5%		°F				105
10%		°F	120		135	121
20%		°F				144
30%		°F				168
40%		°F				198
50%		°F	200		230	219
60%		°F				230
70%		°F				240
80%		°F				257
90%		°F	305		325	312
95%		°F				337
Distillation - EP		°F			415	396
Recovery		vol %		Report		95.4
Residue		vol %		Report		1.1
Loss		vol %		Report		3.5
Gravity	ASTM D4052	°API	58.7		61.2	59.0
Density	ASTM D4052	kg/l	0.734		0.744	0.743
Reid Vapor Pressure	ASTM D5191	psi	8.7		9.2	9.2
Carbon	ASTM D3343	wt fraction		Report		0.8650
Carbon	ASTM D5291	wt fraction		Report		0.8644
Hydrogen	ASTM D5291	wt fraction		Report		0.1355
Hydrogen/Carbon ratio	ASTM D5291	mole/mole		Report		1.867
Stoichiometric Air/Fuel Ratio				Report		14.607
Oxygen	ASTM D4815	wt %			0.05	None Detected
Sulfur	ASTM D5453	wt %	0.0025		0.0035	0.0033
Lead	ASTM D3237	g/gal			0.01	None Detected
Phosphorous	ASTM D3231	g/gal			0.005	None Detected
Silicon	ASTM 5184	mg/kg			4	None Detected
Composition, aromatics	ASTM D1319	vol %			35	28
Composition, olefins	ASTM D1319	vol %			10	1
Composition, saturates	ASTM D1319	vol %		Report		71
Particulate matter	ASTM D5452	mg/l			1	0.4
Oxidation Stability	ASTM D525	minutes	240			1000+
Copper Corrosion	ASTM D130				1	1a
Gum content, washed	ASTM D381	mg/100mls			5	<0.5
Fuel Economy Numerator/C Density	ASTM D5291		2401		2441	2425
C Factor	ASTM D5291			Report		1.0088
Research Octane Number	ASTM D2699		96.0			97.4
Motor Octane Number	ASTM D2700			Report		89.0
Sensitivity			7.5			8.4
Net Heating Value, btu/lb	ASTM D3338	btu/lb		Report		18479
Net Heating Value, btu/lb	ASTM D240	btu/lb		Report		18241
Color	VISUAL			Report		Undyed

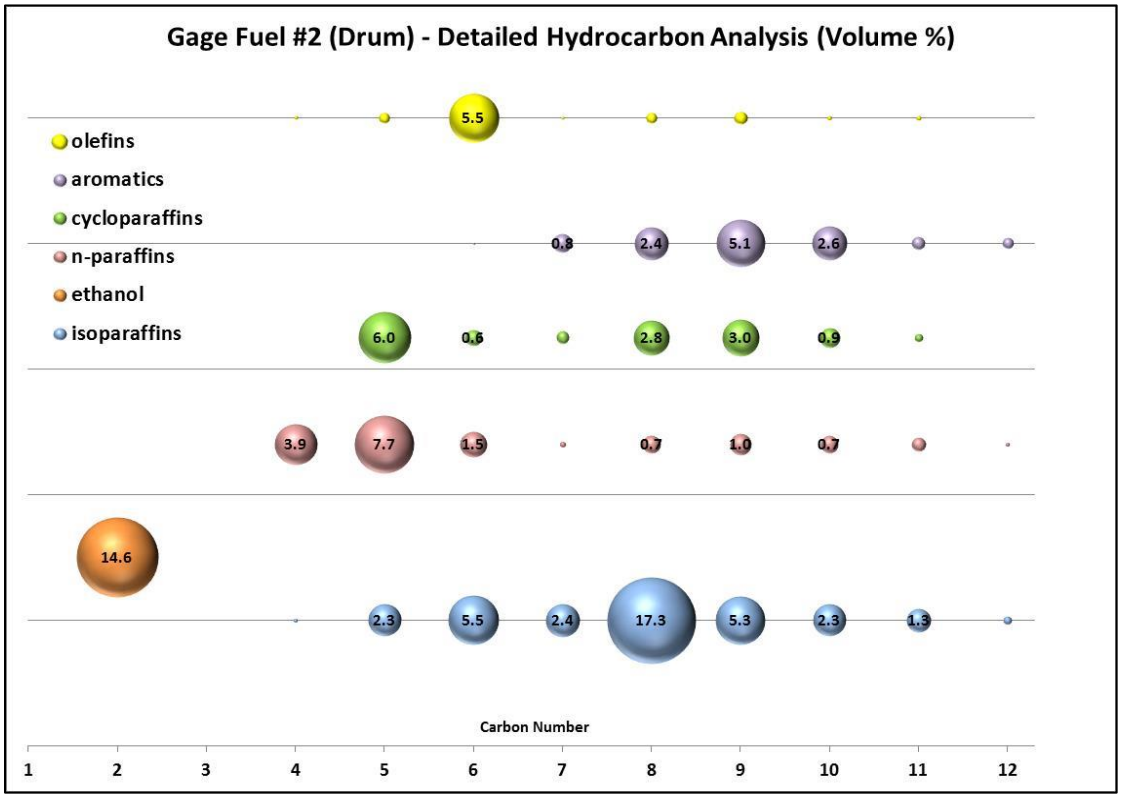
APPROVED BY:

APPENDIX B. Chevron DHA Results for Phase 2 Blends


Gage Fuels (Drum) - DHA Results - Hydrocarbon Class Composition
Composition (Vol.%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
1 2 3 4 5 6 7 7.5 8 10 11 12 13 14 15 16 17 18 19
Fuel
unknown
ethanol
olefins
aromatics
cycloparaffins
n-paraffins
isoparaffins
Cannella - 110714


Gage Fuels (Drum) - DHA Results - Hydrocarbons Only (No Ethanol)
Composition (Vol.%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
1 2 3 4 5 6 7 7.5 8 10 11 12 13 14 15 16 17 18 19
Fuel
unknown
olefins
aromatics
cycloparaffins
n-paraffins
isoparaffins
Cannella - 110714


Gage Fuel #1 (Drum) - Detailed Hydrocarbon Analysis (Volume %)
olefins
aromatics
cycloparaffins
n-paraffins
ethanol
isoparaffins
7.2
3.1
6.5
2.6
5.6
2.0
2.6
4.4
6.1
2.0
0.8
9.9
1.0
6.3
2.7
22.7
5.8
2.3
1.0
Carbon Number
1
2
3
4
5
6
7
8
9
10
11
12


Gage Fuel #2 (Drum) - Detailed Hydrocarbon Analysis (Volume %)
olefins
aromatics
cycloparaffins
n-paraffins
ethanol
isoparaffins
5.5
0.8
2.4
5.1
2.6
6.0
0.6
2.8
3.0
0.9
3.9
7.7
1.5
0.7
1.0
0.7
14.6
2.3
5.5
2.4
17.3
5.3
2.3
1.3
Carbon Number
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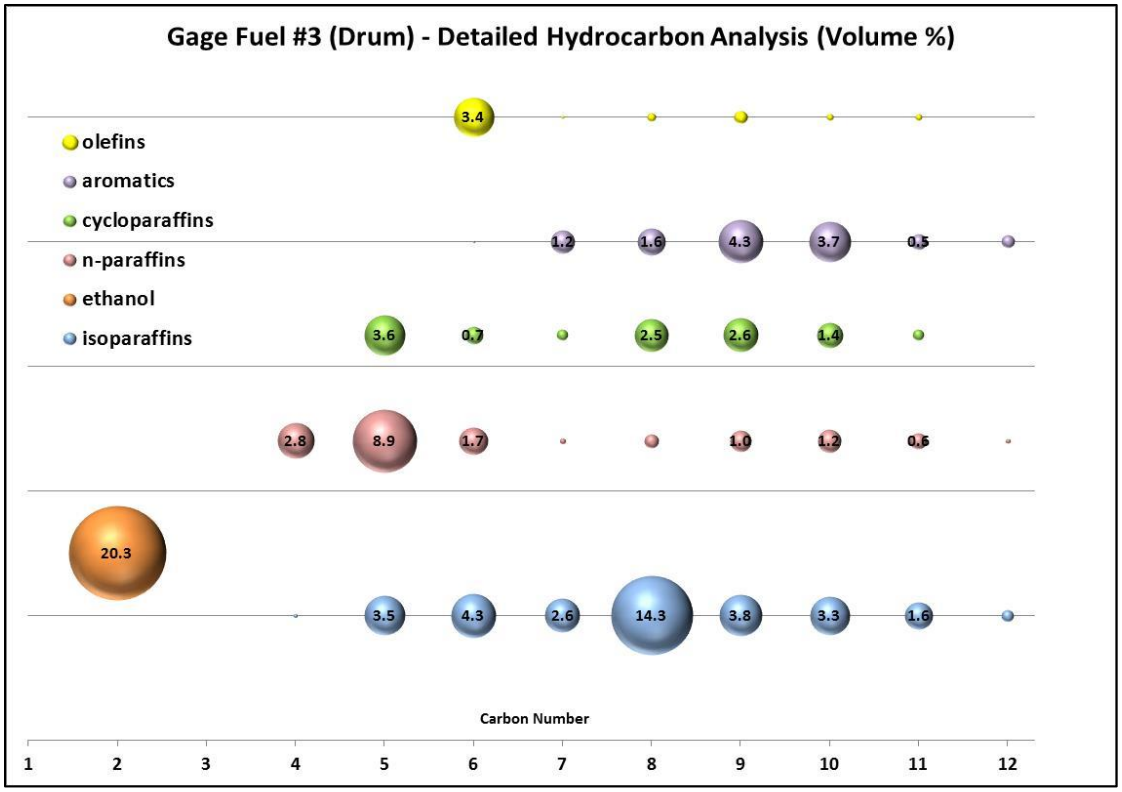
2
3
4
5
6
7
8
9
10
11
12


Gage Fuel #3 (Drum) - Detailed Hydrocarbon Analysis (Volume %)
olefins
aromatics
cycloparaffins
n-paraffins
ethanol
isoparaffins
3.4
1.2
1.6
4.3
3.7
0.5
3.6
0.7
2.5
2.6
1.4
2.8
8.9
1.7
1.0
1.2
0.6
20.3
3.5
4.3
2.6
14.3
3.8
3.3
1.6
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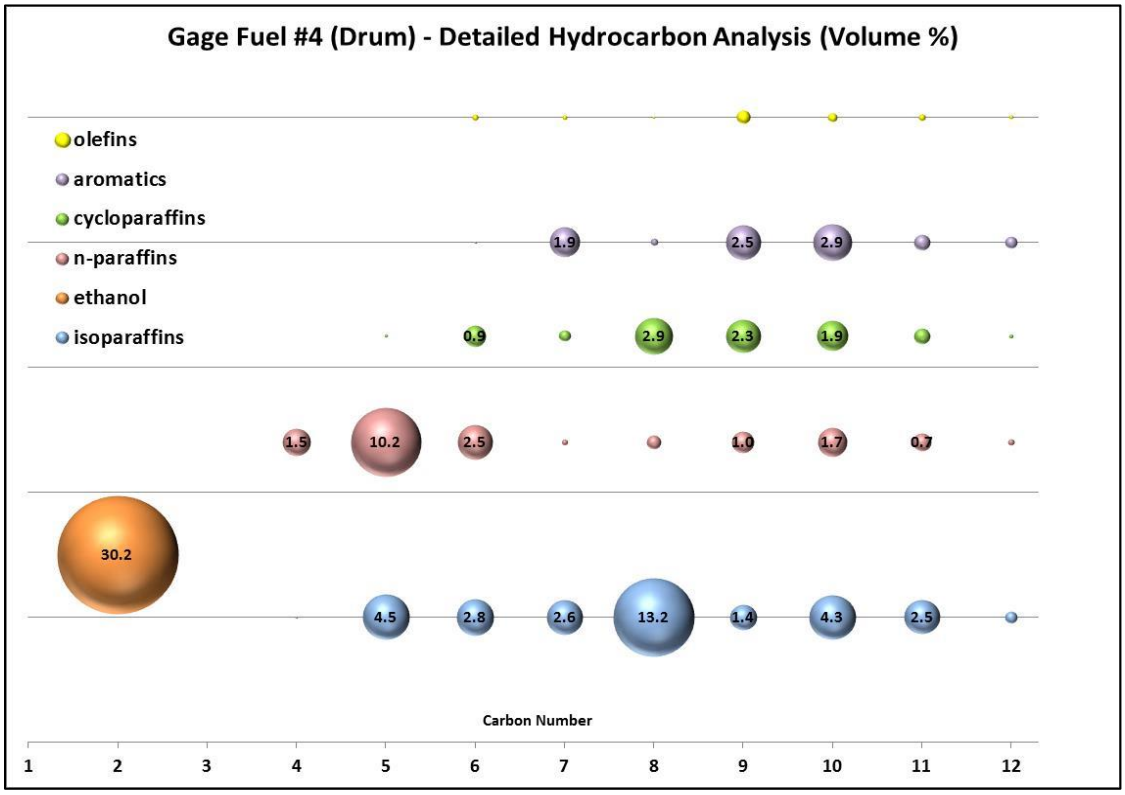
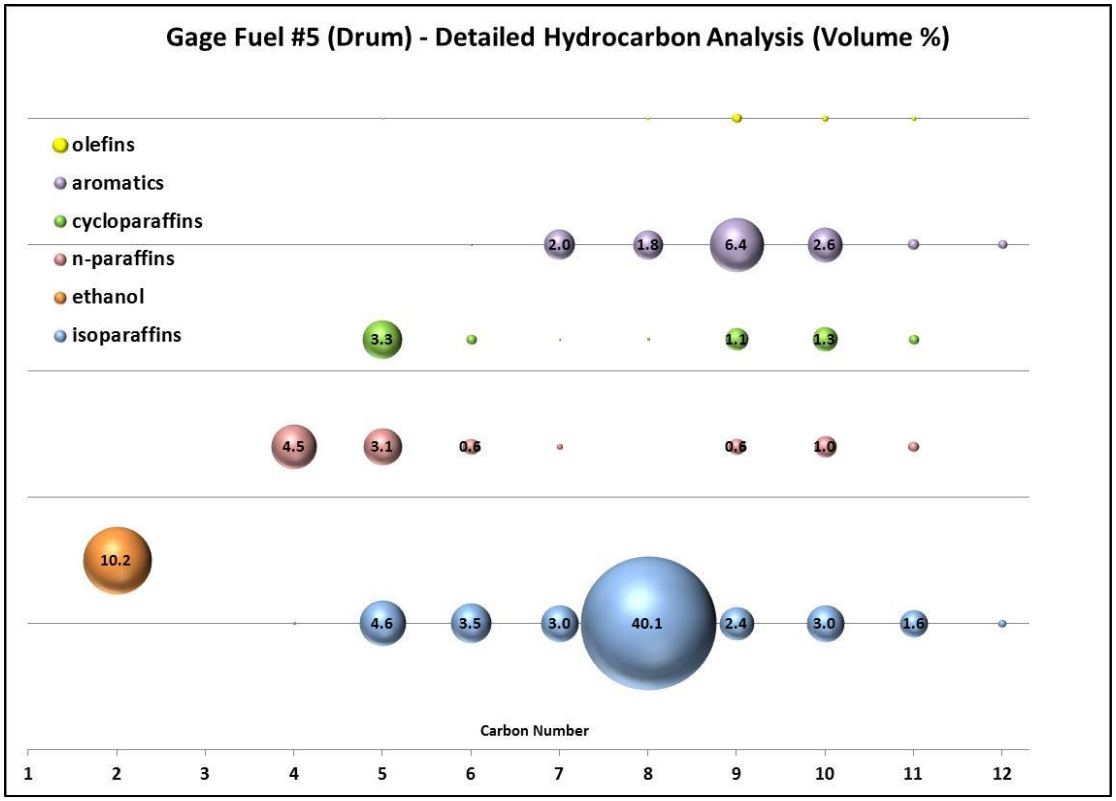
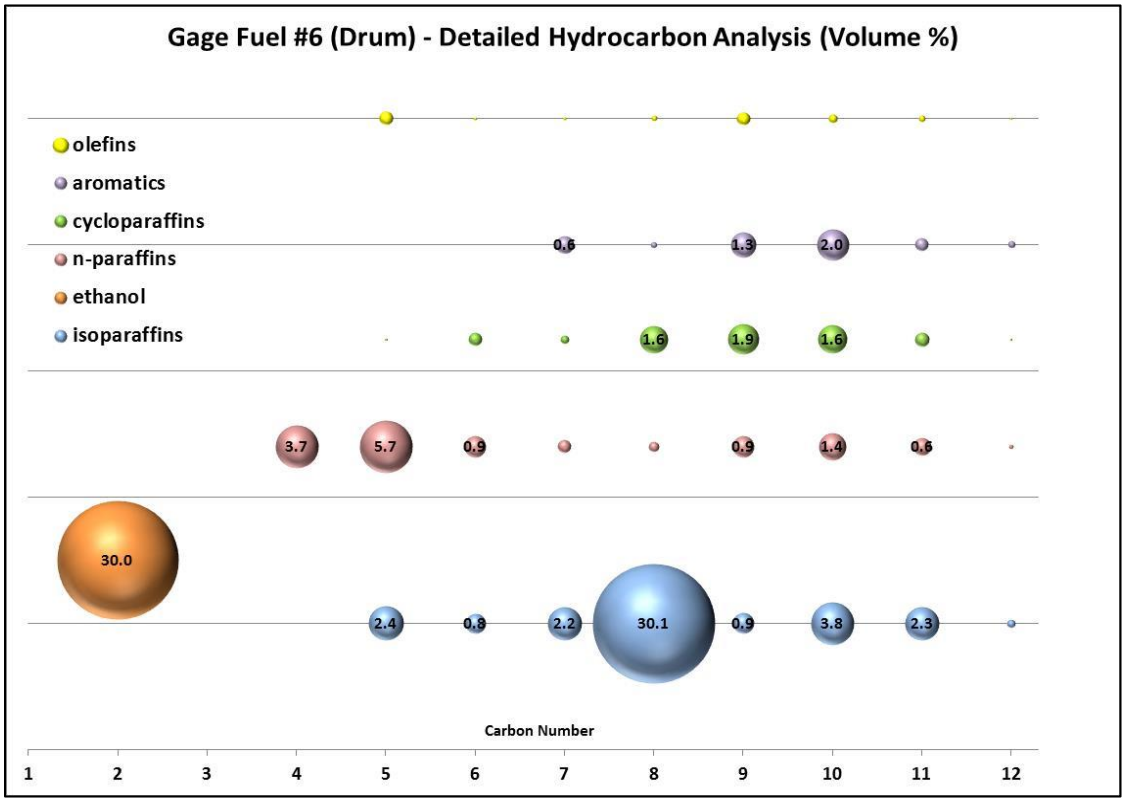
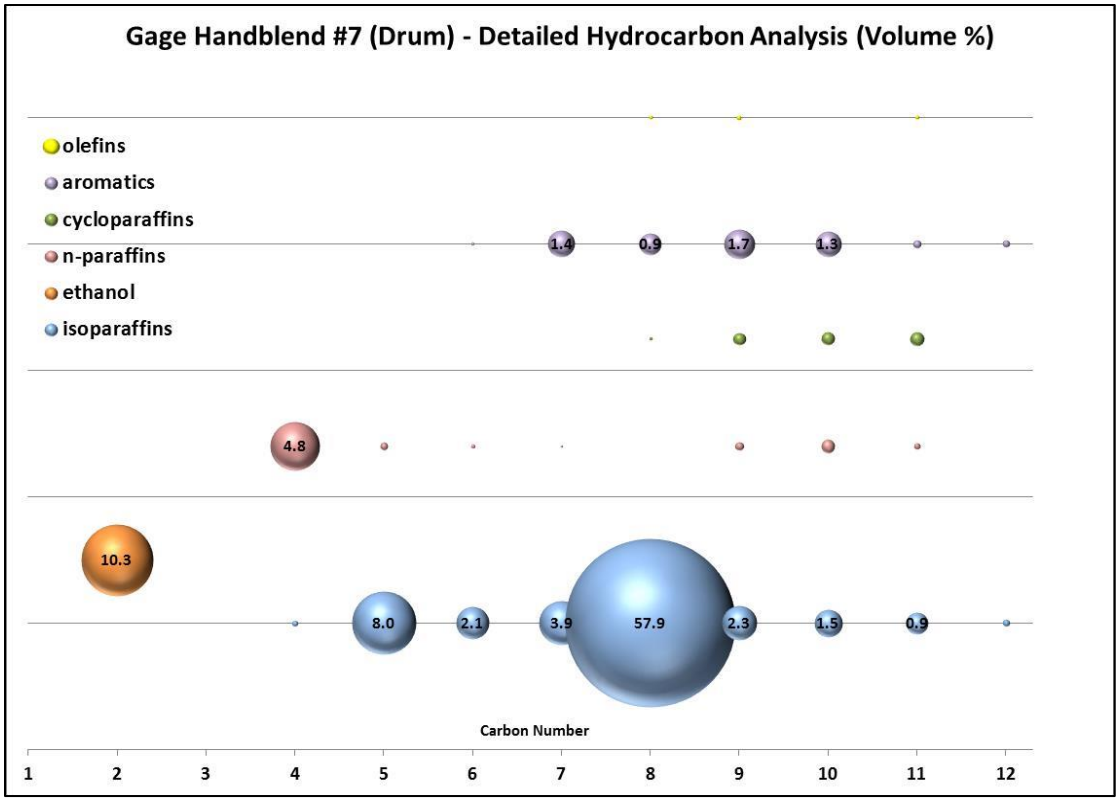
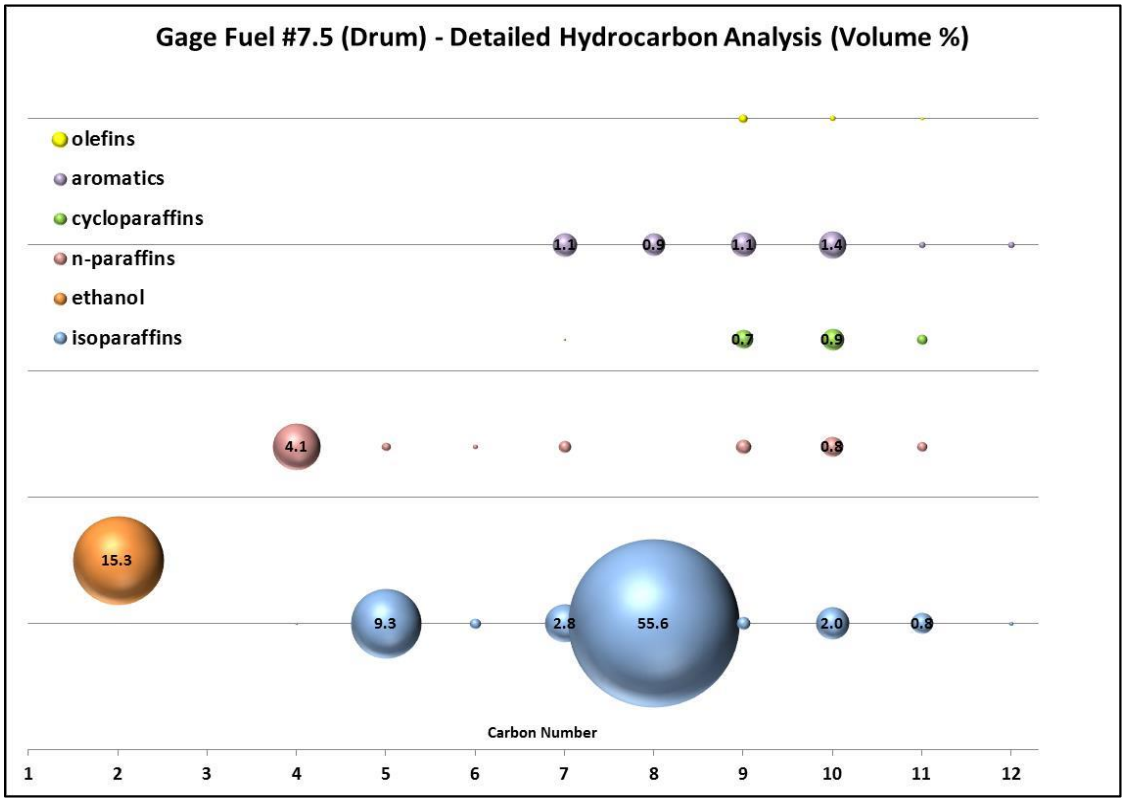
3
4
5
6
7
8
9
10
11
12

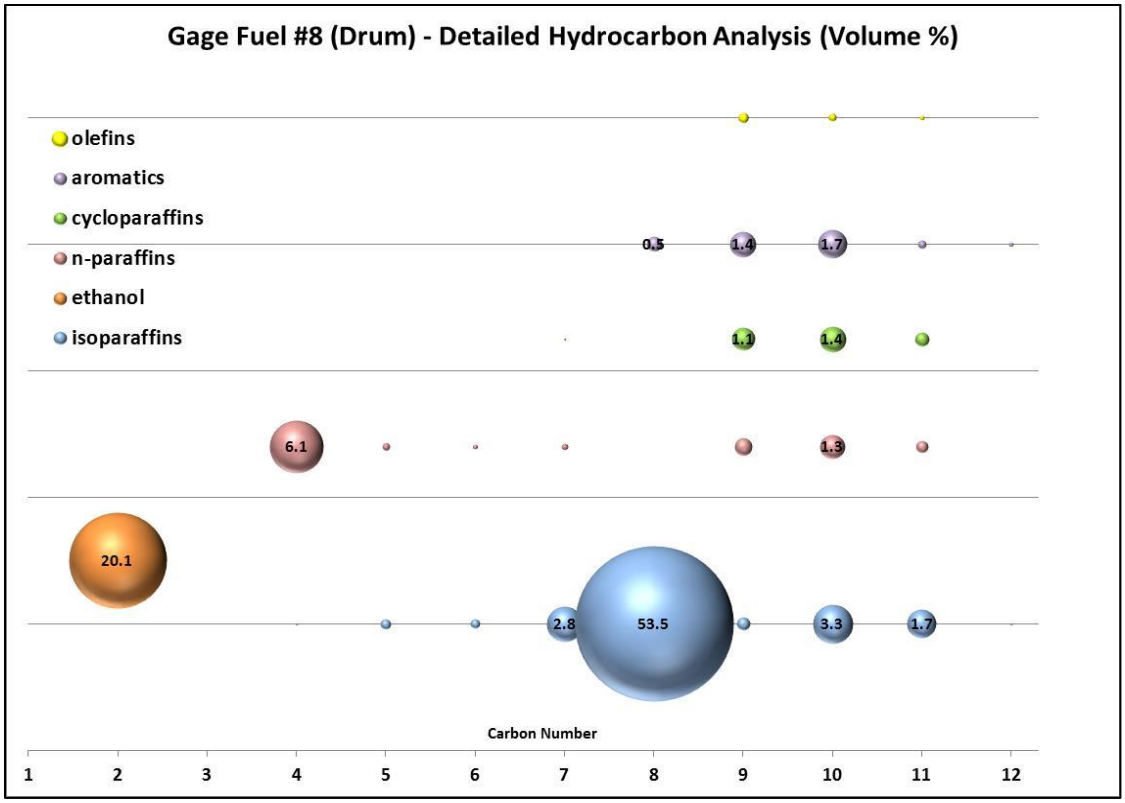

Gage Fuel #4 (Drum) - Detailed Hydrocarbon Analysis (Volume %)
olefins
aromatics
cycloparaffins
n-paraffins
ethanol
isoparaffins
1.9
2.5
2.9
0.9
2.9
2.3
1.9
1.5
10.2
2.5
1.0
1.7
0.7
30.2
4.5
2.8
2.6
13.2
1.4
4.3
2.5
Carbon Number
1
2
3
4
5
6
7
8
9
10
11
12

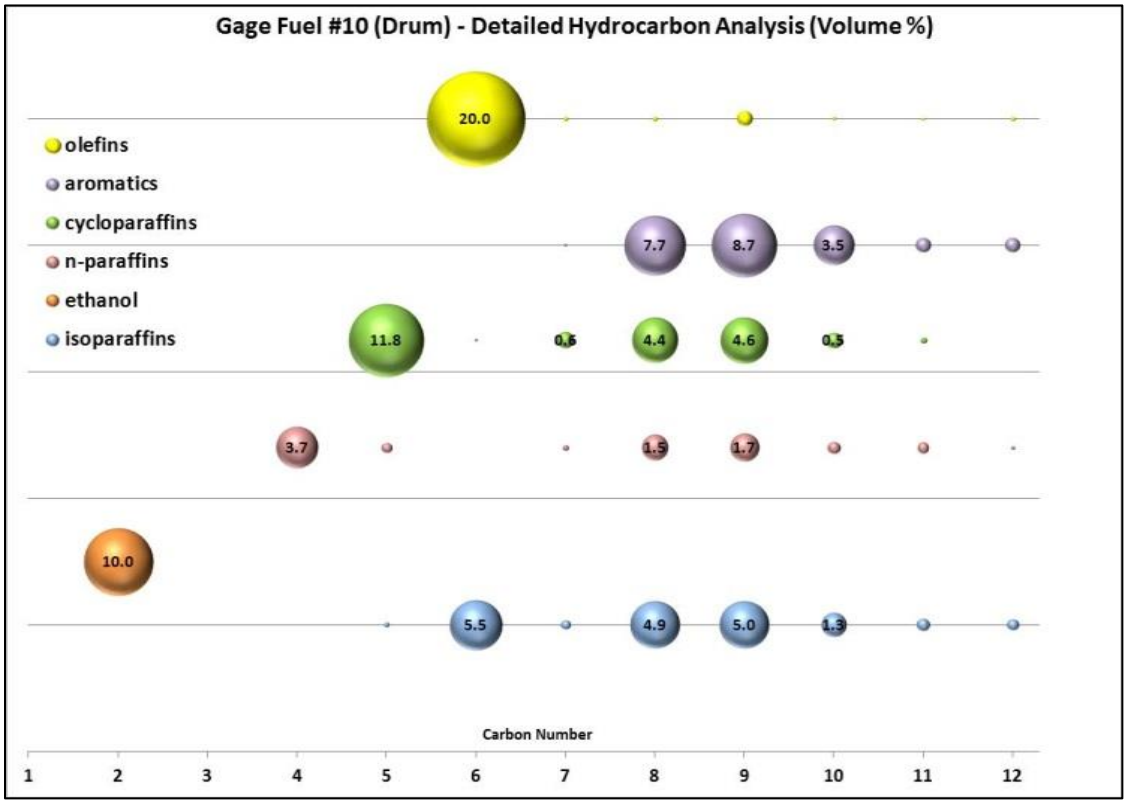

Gage Fuel #5 (Drum) - Detailed Hydrocarbon Analysis (Volume %)
olefins
aromatics
cycloparaffins
n-paraffins
ethanol
isoparaffins
2.0
1.8
6.4
2.6
3.3
1.1
1.3
4.5
3.1
0.6
0.6
1.0
10.2
4.6
3.5
3.0
40.1
2.4
3.0
1.6
Carbon Number
1
2
3
4
5
6
7
8
9
10
11
12

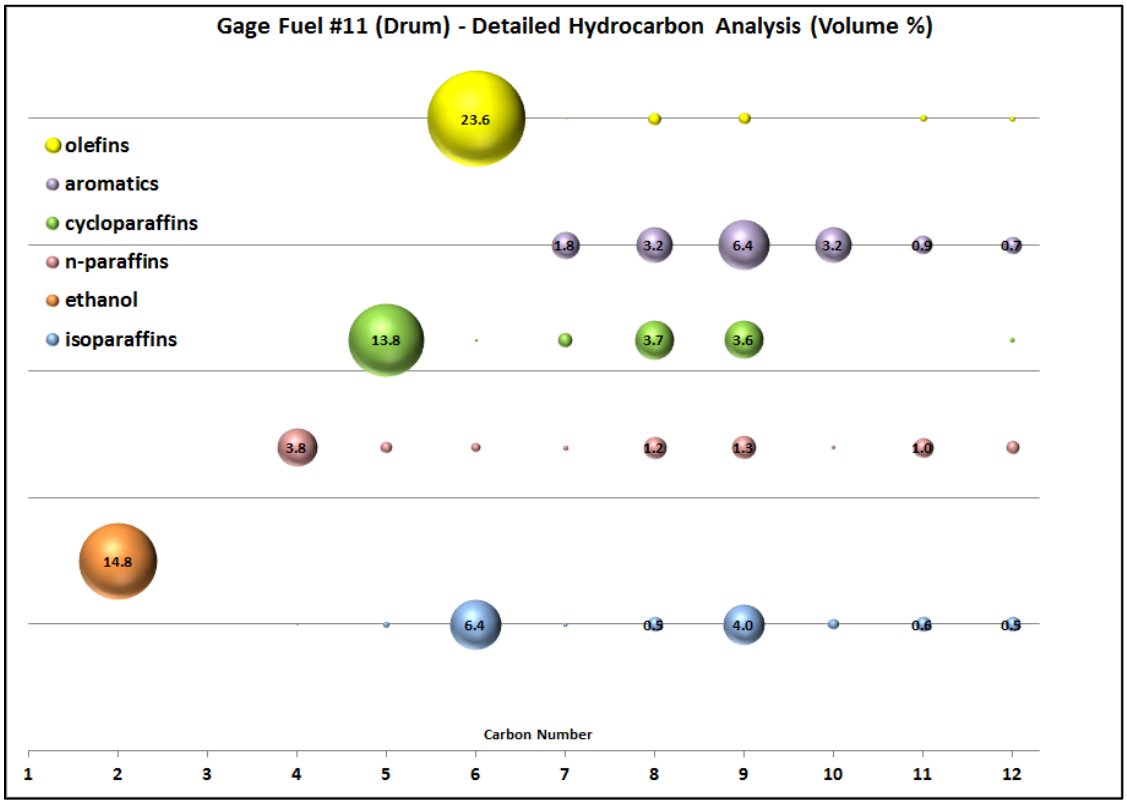

Gage Fuel #6 (Drum) - Detailed Hydrocarbon Analysis (Volume %)
olefins
aromatics
cycloparaffins
n-paraffins
ethanol
isoparaffins
0.6
1.3
2.0
1.6
1.9
1.6
3.7
5.7
0.9
0.9
1.4
0.6
30.0
2.4
0.8
2.2
30.1
0.9
3.8
2.3
Carbon Number
1
2
3
4
5
6
7
8
9
10
11
12

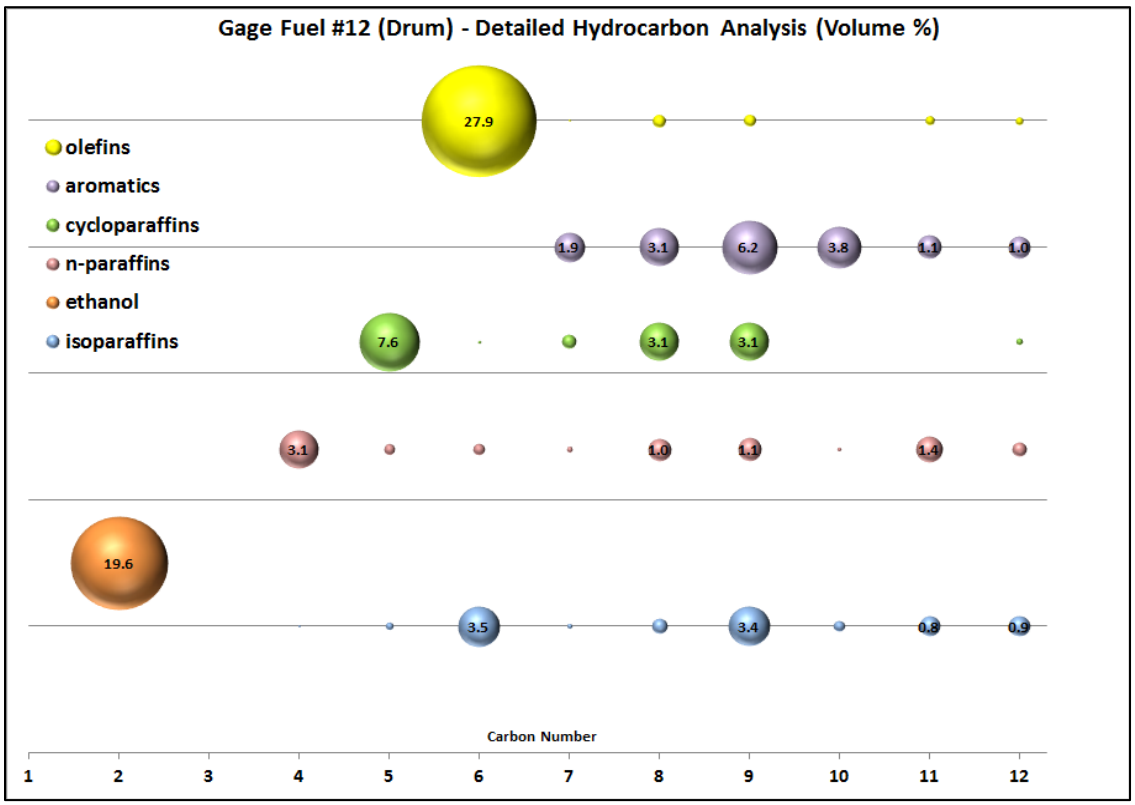

Gage Handblend #7 (Drum) - Detailed Hydrocarbon Analysis (Volume %)
olefins
aromatics
cycloparaffins
n-paraffins
ethanol
isoparaffins
1.4
0.9
1.7
1.3
4.8
10.3
8.0
2.1
3.9
57.9
2.3
1.5
0.9
Carbon Number
1
2
3
4
5
6
7
8
9
10
11
12

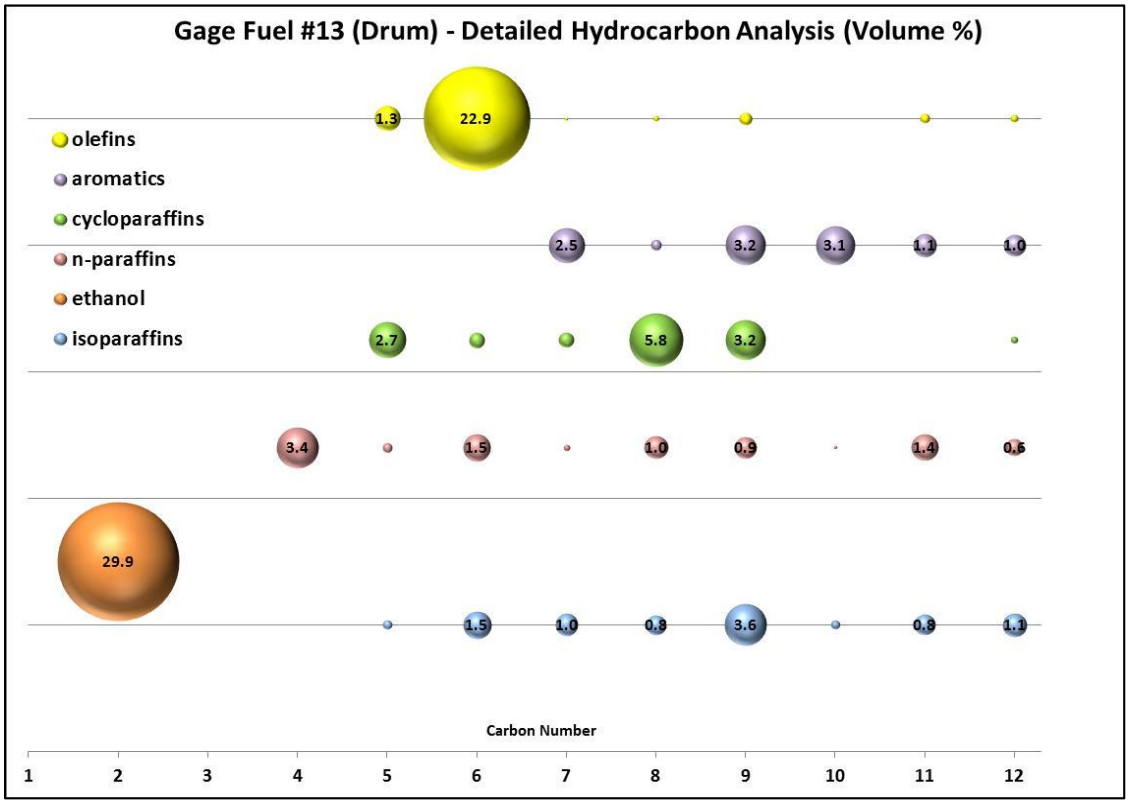

Gage Fuel #7.5 (Drum) - Detailed Hydrocarbon Analysis (Volume %)
olefins
aromatics
cycloparaffins
n-paraffins
ethanol
isoparaffins
1.1
0.9
1.1
1.4
0.7
0.9
4.1
0.8
15.3
9.3
2.8
55.6
2.0
0.8
Carbon Number
1
2
3
4
5
6
7
8
9
10
11
12

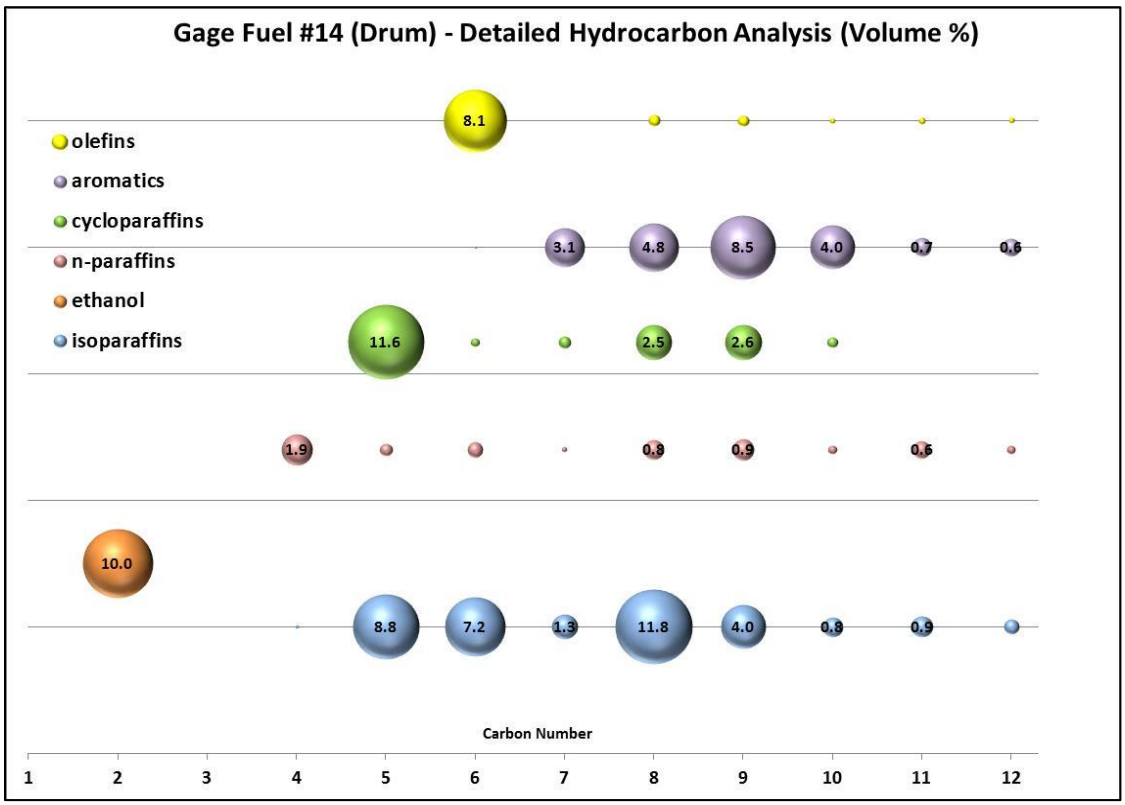

Gage Fuel #8 (Drum) - Detailed Hydrocarbon Analysis (Volume %)
olefins
aromatics
cycloparaffins
n-paraffins
ethanol
isoparaffins
0.5
1.4
1.7
1.1
1.4
6.1
1.3
20.1
2.8
53.5
3.3
1.7
Carbon Number
1
2
3
4
5
6
7
8
9
10
11
12

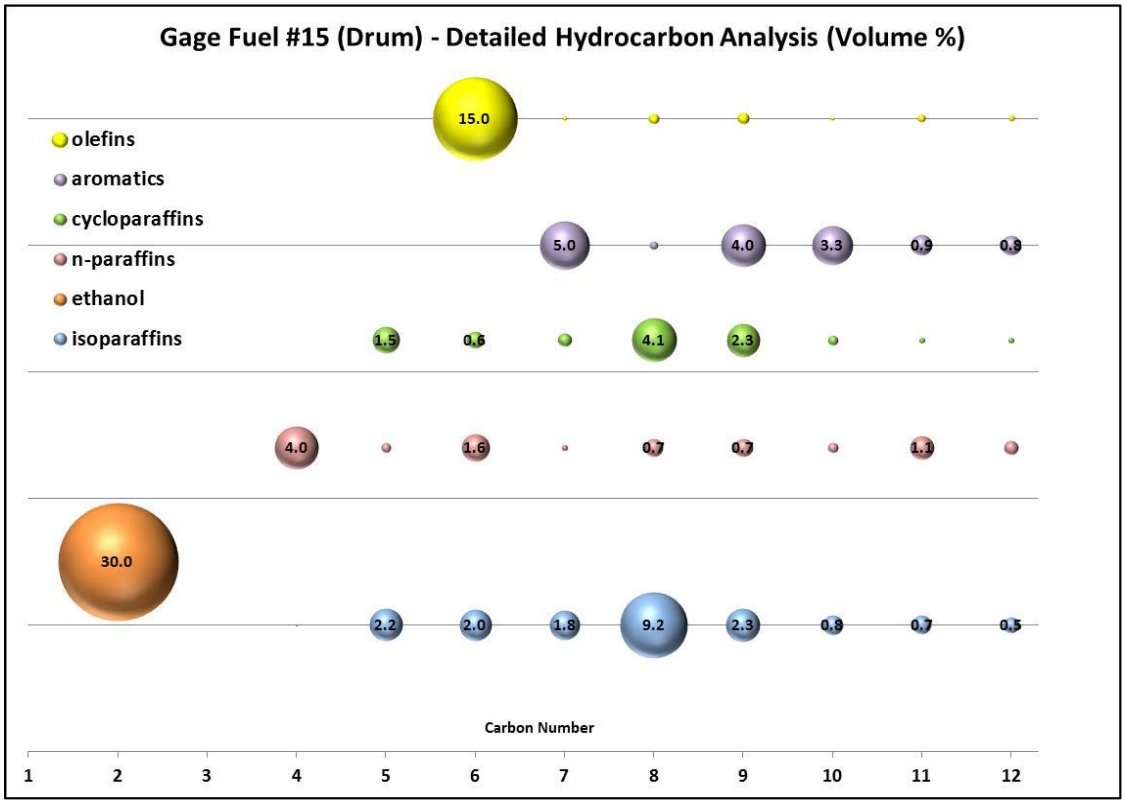

Gage Fuel #10 (Drum) - Detailed Hydrocarbon Analysis (Volume %)
olefins
aromatics
cycloparaffins
n-paraffins
ethanol
isoparaffins
20.0
7.7
8.7
3.5
11.8
0.6
4.4
4.6
0.5
3.7
1.5
1.7
10.0
5.5
4.9
5.0
1.3
Carbon Number
1
2
3
4
5
6
7
8
9
10
11
12

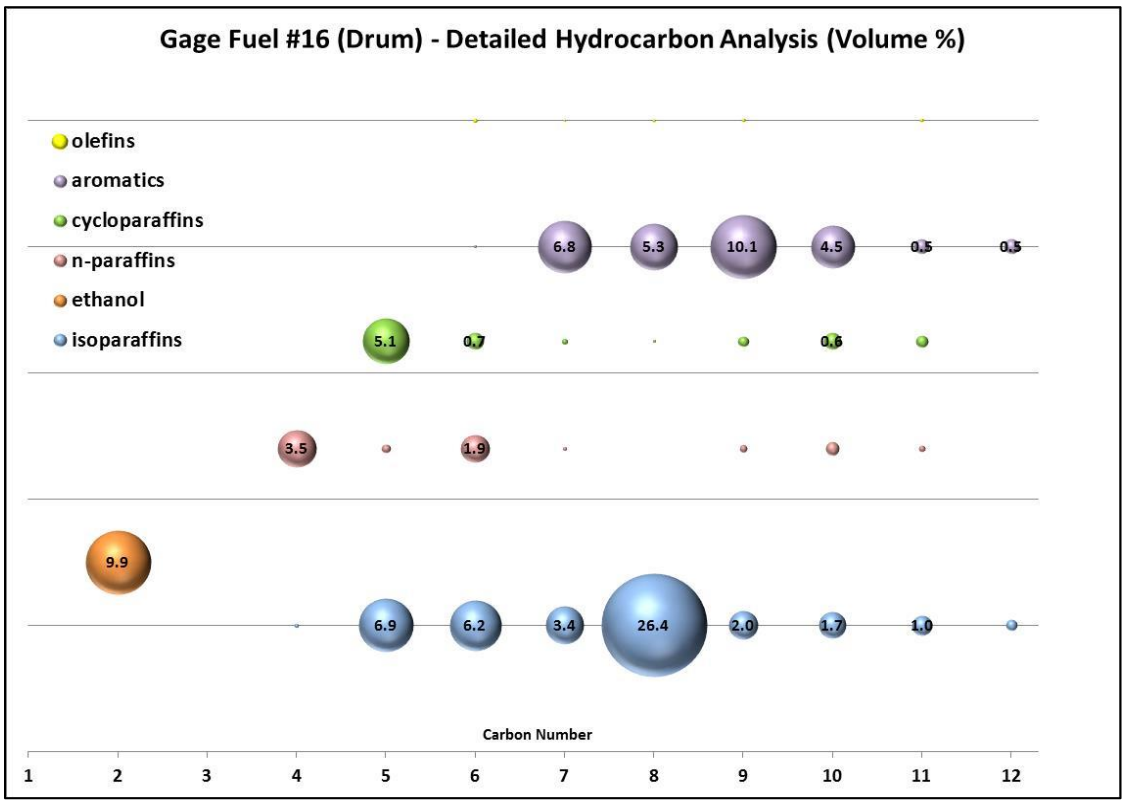

Gage Fuel #11 (Drum) - Detailed Hydrocarbon Analysis (Volume %)
olefins
aromatics
cycloparaffins
n-paraffins
ethanol
isoparaffins
23.6
1.8
3.2
6.4
3.2
0.9
0.7
13.8
3.7
3.6
3.8
1.2
1.3
1.0
14.8
6.4
0.5
4.0
0.6
0.5
Carbon Number
1
2
3
4
5
6
7
8
9
10
11
12

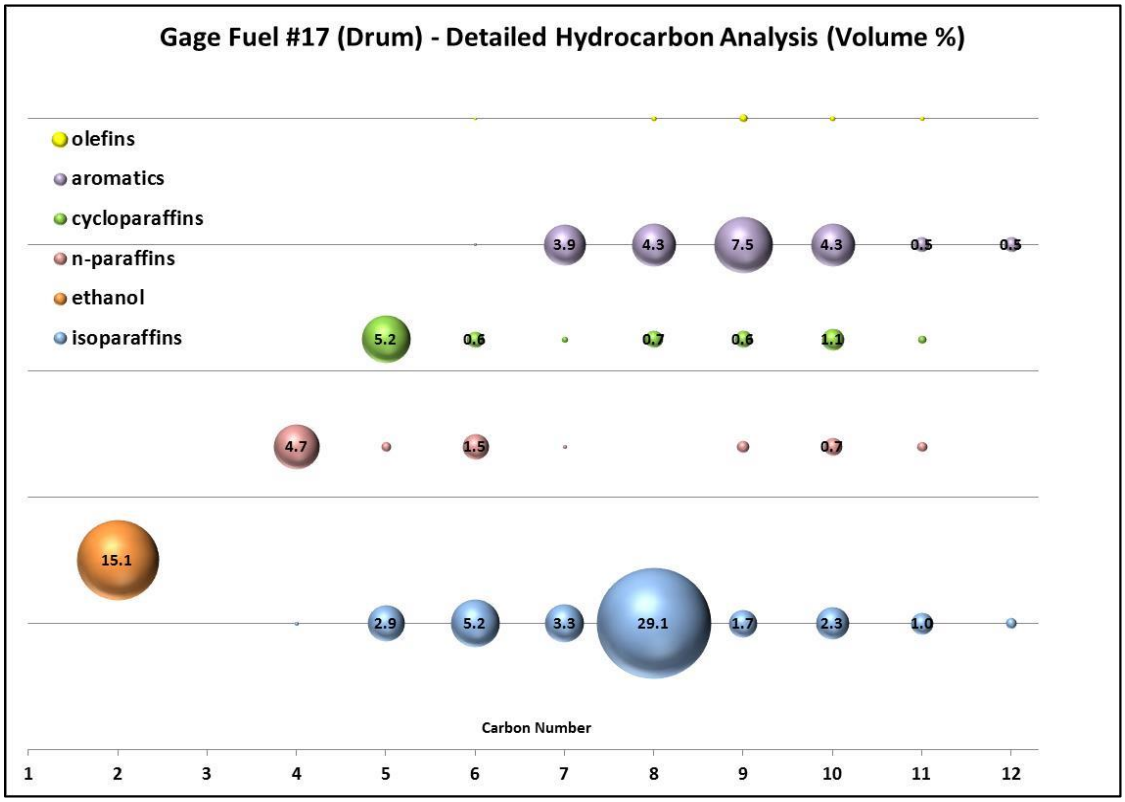

Gage Fuel #12 (Drum) - Detailed Hydrocarbon Analysis (Volume %)
olefins
aromatics
cycloparaffins
n-paraffins
ethanol
isoparaffins
27.9
1.9
3.1
6.2
3.8
1.1
1.0
7.6
3.1
3.1
3.1
1.0
1.1
1.4
19.6
3.5
3.4
0.8
0.9
Carbon Number
1
2
3
4
5
6
7
8
9
10
11
12

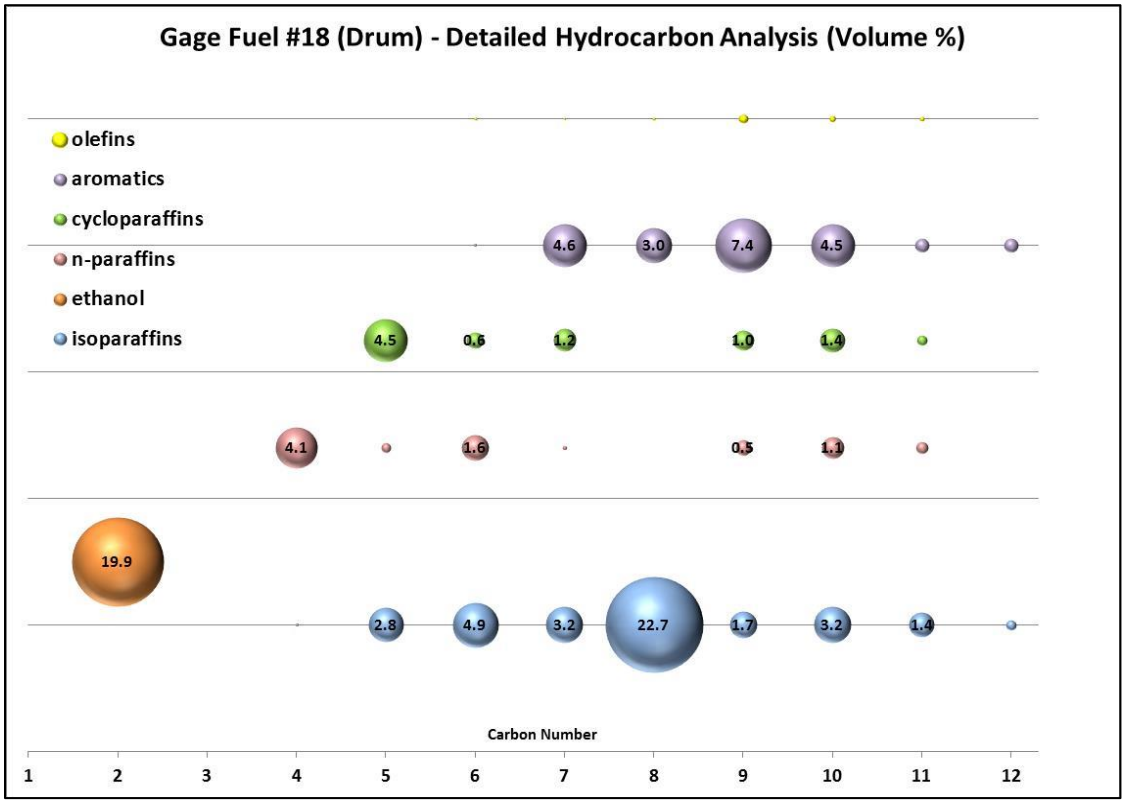

Gage Fuel #13 (Drum) - Detailed Hydrocarbon Analysis (Volume %)
olefins
aromatics
cycloparaffins
n-paraffins
ethanol
isoparaffins
1.3
22.9
2.5
3.2
3.1
1.1
1.0
2.7
5.8
3.2
3.4
1.5
1.0
0.9
1.4
0.6
29.9
1.5
1.0
0.8
3.6
0.8
1.1
Carbon Number
1
2
3
4
5
6
7
8
9
10
11
12

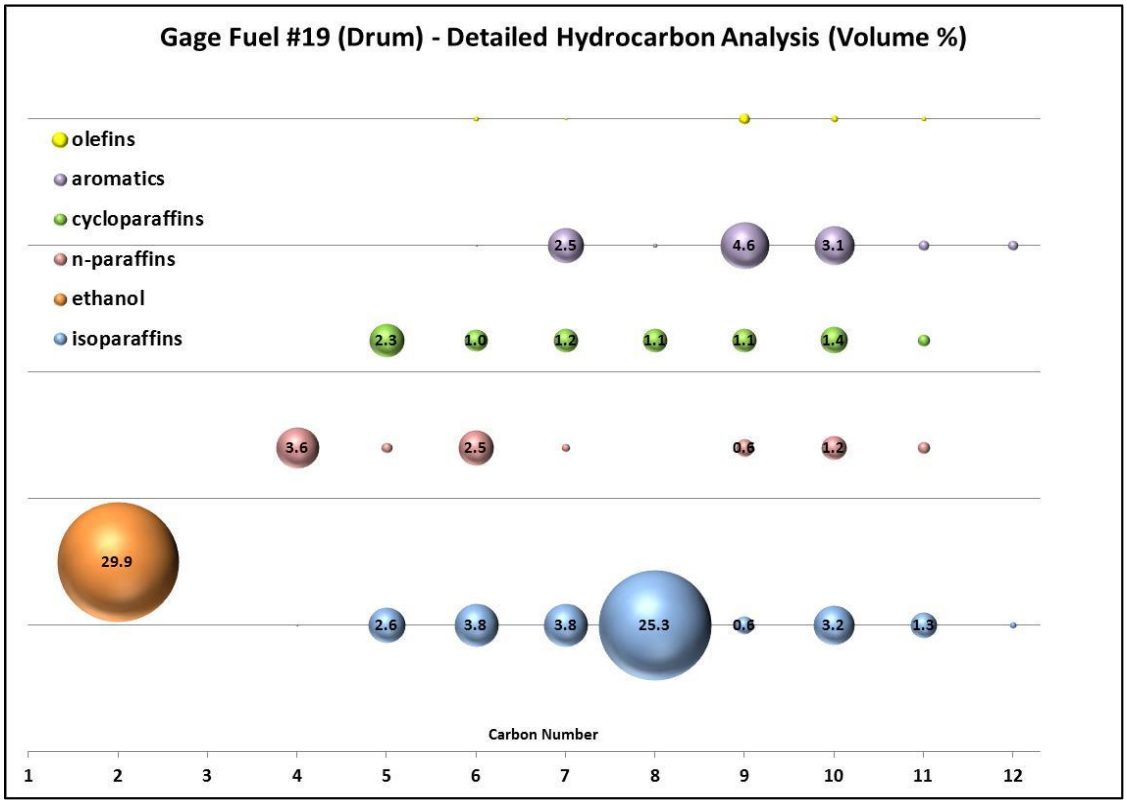

Gage Fuel #14 (Drum) - Detailed Hydrocarbon Analysis (Volume %)
olefins
aromatics
cycloparaffins
n-paraffins
ethanol
isoparaffins
8.1
3.1
4.8
8.5
4.0
0.7
0.6
11.6
2.5
2.6
1.9
0.8
0.9
0.6
10.0
8.8
7.2
1.3
11.8
4.0
0.8
0.9
Carbon Number
1
2
3
4
5
6
7
8
9
10
11
12


Gage Fuel #15 (Drum) - Detailed Hydrocarbon Analysis (Volume %)
olefins
aromatics
cycloparaffins
n-paraffins
ethanol
isoparaffins
15.0
5.0
4.0
3.3
0.9
0.8
1.5
0.6
4.1
2.3
4.0
1.6
0.7
0.7
1.1
30.0
2.2
2.0
1.8
9.2
2.3
0.8
0.7
0.5
Carbon Number
1
2
3
4
5
6
7
8
9
10
11
12


Gage Fuel #16 (Drum) - Detailed Hydrocarbon Analysis (Volume %)
olefins
aromatics
cycloparaffins
n-paraffins
ethanol
isoparaffins
6.8
5.3
10.1
4.5
0.5
0.5
5.1
0.7
0.6
3.5
1.9
9.9
6.9
6.2
3.4
26.4
2.0
1.7
1.0
Carbon Number
1
2
3
4
5
6
7
8
9
10
11
12


Gage Fuel #17 (Drum) - Detailed Hydrocarbon Analysis (Volume %)
olefins
aromatics
cycloparaffins
n-paraffins
ethanol
isoparaffins
3.9
4.3
7.5
4.3
0.5
0.5
5.2
0.6
0.7
0.6
1.1
4.7
1.5
0.7
15.1
2.9
5.2
3.3
29.1
1.7
2.3
1.0
Carbon Number
1
2
3
4
5
6
7
8
9
10
11
12


Gage Fuel #18 (Drum) - Detailed Hydrocarbon Analysis (Volume %)
olefins
aromatics
cycloparaffins
n-paraffins
ethanol
isoparaffins
4.6
3.0
7.4
4.5
4.5
0.6
1.2
1.0
1.4
4.1
1.6
0.5
1.1
19.9
2.8
4.9
3.2
22.7
1.7
3.2
1.4
Carbon Number
1
2
3
4
5
6
7
8
9
10
11
12


Gage Fuel #19 (Drum) - Detailed Hydrocarbon Analysis (Volume %)
olefins
aromatics
cycloparaffins
n-paraffins
ethanol
isoparaffins
2.5
4.6
3.1
2.3
1.0
1.2
1.1
1.1
1.4
3.6
2.5
0.6
1.2
29.9
2.6
3.8
3.8
25.3
0.6
3.2
1.3
Carbon Number
1
2
3
4
5
6
7
8
9
10
11
12

APPENDIX C. Southwest Research Institute Fuel Analysis Results For Phase 2 Blends

	D4809 Net			D5291		D5453	
				Carbon	Hydrogen	Sulfur	
Fuel Number	BTU/lb	MJ/kg	cal/g	mass %	mass %	ppm	mass %
1	18007	41.884	10004	82.3	14.39	1.5	0.00015
2	17678	41.118	9820.8	80.22	14.41	1.5	0.00015
3	17172	39.941	9539.7	77.41	14.36	1.2	0.00012
4	16400	38.148	9111.4	74.31	14.4	1.4	0.00014
5	18028	41.933	10016	82.11	14.51	1.5	0.00015
6	16504	38.387	9168.6	73.12	14.34	1	0.0001
7	18163	42.247	10091	79.81	14.98	1.6	0.00016
7.5	17740	41.263	9855.6	78.84	15.1	1	0.0001
8	17304	40.248	9613.1	77.04	14.92	1	0.0001
10	17844	41.505	9913.3	82.58	13.5	1.1	0.00011
11	17482	40.664	9712.5	81.06	13.55	1.4	0.00014
12	17080	39.727	9488.6	78.98	13.57	1	0.0001
13	16368	38.071	9093.1	75.16	13.6	1	0.0001
14	17870	41.567	9928.1	83	13.72	1.6	0.00016
15	16310	37.937	9061.1	75.57	13.61	1	0.0001
16	17806	41.417	9892.2	83.84	13.96	1.9	0.00019
17	17445	40.577	9691.7	81.32	14.07	1.3	0.00013
18	17088	39.748	9493.6	79.38	14.14	1.4	0.00014
19	16381	38.102	9100.6	75.03	14.51	0.9	0.00009

APPENDIX D. Results of Analyses for Phase 3 Blends

GAGE PRODUCTS CO.
821 WANDA AVENUE
FERNDALE, MI 48220
(248) 541-3824

Gage Products Company
Certificate of Analysis / QC Results

Page: 1
Date: 06/16/15 at 3:01 PM

Customer: C00100 / CRC, Inc.

Sales Order # : 63180 Customer PO # : 769 REVISED Shipped Qty : 150

Packaged Product: 41771-55F
CRC AVFL-20 Fuel #1

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60 DEG. F	ASTM D4052		REPORT	0.7383
DENSITY AT 15.5 DEG. C	ASTM D4052	KG/L	REPORT	0.737
RESEARCH OCTANE NUMBER	ASTM D2699	RON	91.0 - 92.0	91.8
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	84.5
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	88.2
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	6.0 - 8.0	7.3
ETHANOL CONTENT	ASTM D4815	VOL.%	9.50 - 10.50	10.40
RVP @ 100 DEG. F	ASTM D5191	PSI (KPA)	REPORT	8.33(57.39)
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	103.6(39.8)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	126.3(52.4)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	133.4(56.3)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	143.1(61.7)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	149.9(65.5)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	156.9(69.4)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	REPORT	215.9(102.2)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	248.0(120.0)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	272.2(133.4)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	297.5(147.5)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	REPORT	327.3(164.1)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	345.6(174.2)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	REPORT	372.3(189.1)
RECOVERY	ASTM D86	VOL.%	REPORT	97.7
RESIDUE	ASTM D86	VOL.%	REPORT	1.0
LOSS	ASTM D86	VOL.%	REPORT	1.3
AROMATIC CONTENT	ASTM D1319	VOL.%	REPORT	11.6
OLEFIN CONTENT	ASTM D1319	VOL.%	REPORT	6.0
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	72.0

Lot # 8240400 Made 06/15/15

In sealed unopened containers this product is good until 06/15/16

Approved By: Robert Pitzitt

GAGE PRODUCTS CO.
821 WANDA AVENUE
FERNDALE, MI 48220
(248) 541-3824

Gage Products Company
Certificate of Analysis / QC Results

Page: 1
Date: 09/02/15 at 2:35 PM

Customer: C00100 / CRC, Inc.

Sales Order # : 64719 Customer PO # : 769 REVISED Shipped Qty : 150

Packaged Product: 41776-55F
CRC AVFL-20 Fuel #6

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60 DEG. F	ASTM D4052		REPORT	0.7390
DENSITY AT 15.5 DEG. C	ASTM D4052	KG/L	REPORT	0.738
RESEARCH OCTANE NUMBER	ASTM D2699	RON	96.0 - 97.0	96.0
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	88.5
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	92.2
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	6.0 - 8.0	7.5
ETHANOL CONTENT	ASTM D4815	VOL.%	29.50 - 30.50	29.98
RVP @ 100 DEG. F	ASTM D5191	PSI (KPA)	REPORT	6.81(46.92)
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	113.1(45.1)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	138.8(59.3)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	147.1(63.9)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	156.4(69.1)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	161.4(71.9)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	164.1(73.4)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	REPORT	165.8(74.3)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	167.2(75.1)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	226.4(108.0)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	282.4(139.1)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	REPORT	337.0(169.4)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	348.4(175.8)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	REPORT	365.4(185.2)
RECOVERY	ASTM D86	VOL.%	REPORT	97.0
RESIDUE	ASTM D86	VOL.%	REPORT	1.0
LOSS	ASTM D86	VOL.%	REPORT	2.0
AROMATIC CONTENT	ASTM D1319	VOL.%	REPORT	1.4
OLEFIN CONTENT	ASTM D1319	VOL.%	REPORT	1.4
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	67.2

Lot # 8423800 **Made** 08/29/15

In sealed unopened containers this product is good until 07/24/16

Approved By: Robert Petzitt

GAGE PRODUCTS CO.
821 WANDA AVENUE
FERNDALE, MI 48220
(248) 541-3824

Gage Products Company
Certificate of Analysis / QC Results

Page: 1
Date: 09/02/15 at 2:35 PM

Customer: C00100 / CRC, Inc.

Sales Order # : 64719 Customer PO # : 769 REVISED Shipped Qty : 150

Packaged Product: 41777-55F
CRC AVFL-20 Fuel #7

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60 DEG. F	ASTM D4052		REPORT	0.7145
DENSITY AT 15.5 DEG. C	ASTM D4052	KG/L	REPORT	0.714
RESEARCH OCTANE NUMBER	ASTM D2699	RON	100.0 - 102.0	100.1
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	92.5
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	96.3
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	6.0 - 8.0	7.6
ETHANOL CONTENT	ASTM D4815	VOL.%	9.50 - 10.50	10.10
RVP @ 100 DEG. F	ASTM D5191	PSI (KPA)	REPORT	7.69(52.98)
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	105.1(40.6)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	135.3(57.4)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	143.0(61.7)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	153.4(67.4)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	161.0(71.7)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	208.3(97.9)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	REPORT	217.7(103.2)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	222.4(105.8)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	227.7(108.7)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	237.1(113.9)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	REPORT	275.5(135.3)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	337.2(169.6)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	REPORT	377.9(192.2)
RECOVERY	ASTM D86	VOL.%	REPORT	97.5
RESIDUE	ASTM D86	VOL.%	REPORT	1.1
LOSS	ASTM D86	VOL.%	REPORT	1.4
AROMATIC CONTENT	ASTM D1319	VOL.%	REPORT	3.7
OLEFIN CONTENT	ASTM D1319	VOL.%	REPORT	0.7
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	85.5

Lot # 8424000 **Made** 08/21/15

In sealed unopened containers this product is good until 07/24/16

Approved By: Robert Petrillo

GAGE PRODUCTS CO.
821 WANDA AVENUE
FERNDALE, MI 48220
(248) 541-3824

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Customer: C00100 / CRC, Inc.

Sales Order # : 63180 Customer PO # : 769 REVISED Shipped Qty : 150

Packaged Product: 41780-55F
CRC AVFL-20 Fuel #10

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60 DEG. F	ASTM D4052		REPORT	0.7591
DENSITY AT 15.5 DEG. C	ASTM D4052	KG/L	REPORT	0.758
RESEARCH OCTANE NUMBER	ASTM D2699	RON	91.0 - 92.0	91.4
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	81.0
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	86.2
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	10.0 - 12.0	10.4
ETHANOL CONTENT	ASTM D4815	VOL.%	9.50 - 10.50	10.00
RVP @ 100 DEG. F	ASTM D5191	PSI (KPA)	REPORT	7.72(53.19)
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	105.7(40.9)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	128.4(53.6)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	134.4(56.9)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	141.9(61.1)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	147.3(64.1)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	154.9(68.3)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	REPORT	211.0(99.4)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	270.8(132.7)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	293.4(145.2)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	302.0(150.0)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	REPORT	323.9(162.2)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	343.8(173.2)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	REPORT	367.6(186.4)
RECOVERY	ASTM D86	VOL.%	REPORT	98.4
RESIDUE	ASTM D86	VOL.%	REPORT	1.0
LOSS	ASTM D86	VOL.%	REPORT	0.6
AROMATIC CONTENT	ASTM D1319	VOL.%	REPORT	20.5
OLEFIN CONTENT	ASTM D1319	VOL.%	REPORT	20.9
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	48.5

Lot # 8240100 **Made** 06/15/15

In sealed unopened containers this product is good until 06/15/16

Approved By: Robert Petzitt

GAGE PRODUCTS CO.
821 WANDA AVENUE
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(248) 541-3824

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Customer: C00100 / CRC, Inc.

Sales Order # : 64717 Customer PO # : 775 Shipped Qty : 150

Packaged Product: 41784-55F
CRC AVFL-20 Fuel #14

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60 DEG. F	ASTM D4052		REPORT	0.7532
DENSITY AT 15.5 DEG. C	ASTM D4052	KG/L	REPORT	0.752
RESEARCH OCTANE NUMBER	ASTM D2699	RON	96.0 - 97.0	96.6
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	85.5
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	91.0
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	10.0 - 12.0	11.1
ETHANOL CONTENT	ASTM D4815	VOL.%	9.50 - 10.50	10.35
RVP @ 100 DEG. F	ASTM D5191	PSI (KPA)	REPORT	8.31(57.26)
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	104.0(40.0)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	118.9(48.3)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	125.8(52.1)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	135.3(57.4)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	143.4(61.9)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	150.3(65.7)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	REPORT	184.3(84.6)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	245.7(118.7)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	277.2(136.2)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	302.0(150.0)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	REPORT	330.3(165.7)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	352.4(178.0)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	REPORT	381.0(193.9)
RECOVERY	ASTM D86	VOL.%	REPORT	98.3
RESIDUE	ASTM D86	VOL.%	REPORT	0.9
LOSS	ASTM D86	VOL.%	REPORT	0.8
AROMATIC CONTENT	ASTM D1319	VOL.%	REPORT	19.9
OLEFIN CONTENT	ASTM D1319	VOL.%	REPORT	8.1
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	61.6

Lot # 8424200 Made 08/17/15

In sealed unopened containers this product is good until 07/24/16

Approved By: Robert Petrillo

GAGE PRODUCTS CO.
821 WANDA AVENUE
FERNDALE, MI 48220
(248) 541-3824

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Customer: C00100 / CRC, Inc.

Sales Order # : 63180 Customer PO # : 769 REVISED Shipped Qty : 150

Packaged Product: 41785-55F
CRC AVFL-20 Fuel #15

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60 DEG. F	ASTM D4052		REPORT	0.7559
DENSITY AT 15.5 DEG. C	ASTM D4052	KG/L	REPORT	0.755
RESEARCH OCTANE NUMBER	ASTM D2699	RON	96.0 - 97.0	96.5
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	84.9
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	90.7
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	10.0 - 12.0	11.6
ETHANOL CONTENT	ASTM D4815	VOL.%	29.50 - 30.50	30.37
RVP @ 100 DEG. F	ASTM D5191	PSI (KPA)	REPORT	7.65(52.71)
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	109.3(42.9)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	134.8(57.1)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	142.4(61.3)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	151.4(66.3)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	156.9(69.4)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	160.9(71.6)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	REPORT	164.4(73.6)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	167.7(75.4)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	170.5(76.9)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	291.0(143.9)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	REPORT	345.0(173.9)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	368.7(187.1)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	REPORT	383.7(195.4)
RECOVERY	ASTM D86	VOL.%	REPORT	98.0
RESIDUE	ASTM D86	VOL.%	REPORT	1.1
LOSS	ASTM D86	VOL.%	REPORT	0.9
AROMATIC CONTENT	ASTM D1319	VOL.%	REPORT	12.8
OLEFIN CONTENT	ASTM D1319	VOL.%	REPORT	16.5
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	40.3

Lot # 8239800 **Made** 06/09/15

In sealed unopened containers this product is good until 06/09/16

Approved By: Robert Petrillo

GAGE PRODUCTS CO.
821 WANDA AVENUE
FERNDALE, MI 48220
(248) 541-3824

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Customer: C00100 / CRC, Inc.

Sales Order # : 64717 Customer PO # : 775 Shipped Qty : 150

Packaged Product: 41786-55F
CRC AVFL-20 Fuel #16

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60 DEG. F	ASTM D4052		REPORT	0.7539
DENSITY AT 15.5 DEG. C	ASTM D4052	KG/L	REPORT	0.753
RESEARCH OCTANE NUMBER	ASTM D2699	RON	101.0 - 102.0	101.1
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	89.3
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	95.2
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	10.0 - 12.0	11.8
ETHANOL CONTENT	ASTM D4815	VOL.%	9.50 - 10.50	10.21
RVP @ 100 DEG. F	ASTM D5191	PSI (KPA)	REPORT	7.75(53.40)
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	100.6(38.1)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	129.4(54.1)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	137.1(58.4)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	147.2(64.0)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	154.7(68.2)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	182.8(83.8)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	REPORT	227.0(108.3)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	243.6(117.6)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	261.2(127.3)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	299.7(148.7)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	REPORT	333.9(167.7)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	348.2(175.7)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	REPORT	375.9(191.1)
RECOVERY	ASTM D86	VOL.%	REPORT	98.0
RESIDUE	ASTM D86	VOL.%	REPORT	1.0
LOSS	ASTM D86	VOL.%	REPORT	1.0
AROMATIC CONTENT	ASTM D1319	VOL.%	REPORT	23.4
OLEFIN CONTENT	ASTM D1319	VOL.%	REPORT	0.7
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	65.7

Lot # 8420700 **Made** 08/19/15

In sealed unopened containers this product is good until 07/23/16

Approved By: Robert Petzitt

GAGE PRODUCTS CO.
821 WANDA AVENUE
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(248) 541-3824

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Gage Products Company
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Customer: C00100 / CRC, Inc.

Sales Order # : 64717 Customer PO # : 775 Shipped Qty : 150

Packaged Product: 41789-55F
CRC AVFL-20 Fuel #19

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60 DEG. F	ASTM D4052		REPORT	0.7493
DENSITY AT 15.5 DEG. C	ASTM D4052	KG/L	REPORT	0.748
RESEARCH OCTANE NUMBER	ASTM D2699	RON	101.0 - 102.0	101.2
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	89.2
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	95.2
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	10.0 - 12.0	12.0
ETHANOL CONTENT	ASTM D4815	VOL.%	29.50 - 30.50	30.34
RVP @ 100 DEG. F	ASTM D5191	PSI (KPA)	REPORT	7.17(49.40)
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	110.5(43.6)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	136.5(58.1)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	145.2(62.9)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	154.7(68.2)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	159.6(70.9)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	162.6(72.6)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	REPORT	164.9(73.8)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	167.1(75.1)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	169.0(76.1)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	281.9(138.8)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	REPORT	333.5(167.5)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	342.4(172.4)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	REPORT	360.8(182.7)
RECOVERY	ASTM D86	VOL.%	REPORT	97.6
RESIDUE	ASTM D86	VOL.%	REPORT	1.0
LOSS	ASTM D86	VOL.%	REPORT	1.4
AROMATIC CONTENT	ASTM D1319	VOL.%	REPORT	7.8
OLEFIN CONTENT	ASTM D1319	VOL.%	REPORT	2.2
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	59.5

Lot # 8421000 **Made** 08/17/15

In sealed unopened containers this product is good until 07/23/16

Approved By: Robert Petzelt

Southwest Research Institute Analyses of Phase 3 Fuel Blends			
Fuel Number	ASTM D4809	ASTM D5291	ASTM D5291
	Net Heating Value (kJ/kg)	Carbon Content (wt%)*	Hydrogen Content (wt%)*
1	41861	80.91	14.12
6	38491	73.67	14.46
7	42305	80.77	15.34
10	41544	82.78	13.47
14	41581	83.60	13.88
15	38060	75.07	13.67
16	41448	83.32	13.73
19	37944	75.05	14.73

*In cases where the carbon, hydrogen, and oxygen content summed to less than 100%, the oxygen content (calculated from measured ethanol content) was taken as correct and the carbon and hydrogen results were scaled up to close the mass balance. In cases where the sum was greater than 100%, the carbon and hydrogen results were taken as correct and the oxygen results scaled down to close the mass balance.