ORNL/TM-2017/357

An Engine and Modeling Study on Potential Fuel Efficiency Benefits of a High-Octane E25 Gasoline Blend

C. Scott Sluder
David E. Smith
Brian H. West

Approved for public release.
Distribution is unlimited.

August 2017

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

DOCUMENT AVAILABILITY

Reports produced after January 1, 1996, are generally available free via US Department of Energy (DOE) SciTech Connect.

Website http://www.osti.gov/scitech/

Reports produced before January 1, 1996, may be purchased by members of the public from the following source:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone 703-605-6000 (1-800-553-6847)
TDD 703-487-4639
Fax 703-605-6900
E-mail info@ntis.gov
Website http://classic.ntis.gov/

Reports are available to DOE employees, DOE contractors, Energy Technology Data Exchange representatives, and International Nuclear Information System representatives from the following source:

Office of Scientific and Technical Information
PO Box 62
Oak Ridge, TN 37831
Telephone 865-576-8401
Fax 865-576-5728
E-mail reports@osti.gov
Website http://www.osti.gov/contact.html

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

ORNL/TM-2017/357

Energy and Transportation Science Division

AN ENGINE AND MODELING STUDY ON POTENTIAL FUEL EFFICIENCY BENEFITS OF A HIGH-OCTANE E25 GASOLINE BLEND

C. Scott Sluder
David E. Smith
Brian H. West

Date Published: August 2017

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831-6283
managed by
UT-BATTELLE, LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Illinois Corn Marketing Board for their sponsorship of this study and report. This work has also benefited from input, direction, and support from numerous peers within industry and the DOE Vehicle Technologies Office, without whose support the facilities used for this study would not be available or relevant for this work. The authors also acknowledge and appreciate the thorough review from John Thomas at ORNL and V.J. Ewing for her help with preparation of the manuscript.

ACRONYMS

AKI	antiknock index
ATDC	after top dead center
BMEP	brake mean effective pressure
CA50	crank angle 50 (the crank angle at which 50% of the fuel has burned)
CAD	crank angle degree
CAFE	Corporate Average Fuel Economy (standards)
CR	compression ratio
DI	direct injection
E10	gasoline-ethanol blend with 10 vol % ethanol
E25	gasoline-ethanol blend with 25 vol % ethanol
FMEP	friction MEP
FTP	federal test procedure
HWFET	Highway Fuel Economy Test cycle
µDCAT	micro Drivven Combustion Analysis Tool
MBT	maximum brake torque
MEP	mean effective pressure (as in fuel MEP)
MON	motor octane number
ORNL	
RON	research octane number
SUV	sport-utility vehicle
UDDS	Urban Dynamometer Driving Schedule

1. INTRODUCTION

Corporate Average Fuel Economy (CAFE) standards are slated to rise sharply between now and 2025. The challenge posed by these rising standards has resulted in a resurgence of interest in potential fuel efficiency benefits that might be obtained through improving the antiknock performance of gasoline sold in the United States.[1] While the connection between fuel antiknock ratings, compression ratio (CR), and engine efficiency has been known for many years, the increased use of turbocharged direct-injection (DI) gasoline engines and the potential for biofuels, including ethanol, to provide increased antiknock performance have opened new possibilities that are deserving of consideration. Infrastructure compatibility and retail regulatory issues have resulted in a growing consensus that achieving greater than 25% by volume ethanol content in gasoline (E25) is quite challenging. While a number of ethanol and octane rating studies have been completed and others are ongoing, there is little if any experimental data available for the retail-limited case of E25.[2-9] This study is targeted at providing information to fill that gap.

To understand why antiknock performance in fuel is important, it is similarly important to have an appreciation for knock, why it occurs, and why avoiding it is important. A normal combustion event begins with the spark initiating combustion by forming a flame kernel. The flame kernel then expands smoothly, creating a flame front that moves outward to ideally consume all of the fuel in the cylinder. Knock occurs when a parcel of fuel experiences temperature and pressure conditions that are high enough to cause it to autoignite before the expanding flame front reaches it. When autoignition occurs, the pressure in the cylinder can rise rapidly, leading to an audible knocking condition. The audible indication of knock is undesirable, as it can lead to consumer dissatisfaction, but it is the sudden pressure rise that poses the risk of damage to the engine. Using a fuel with a higher knock resistance (or octane rating) can reduce the likelihood that knock will occur at a given engine condition.

The traditional antiknock metric for gasoline in the United States is the antiknock index (AKI). In most parts of the country, three AKI ratings are the most typical: 87 AKI or “regular grade,” 89 AKI or “mid-grade,” and 91-93 AKI or “premium grade.” In some areas of the country gasoline with other AKI ratings is also available. The AKI rating is the average of the research octane number (RON) and the motor octane number (MON). Both RON and MON are determined by using a specific engine designed for the purpose of examining and rating the knock resistance of gasoline blends. The details of these tests are specified in ASTM standards.[10,11]

Most, if not all, production gasoline engines have a CR that results in knock occurring during some operational conditions. Given this reality, it is important to develop engine control techniques for avoiding knock. Retarding combustion phasing by delaying spark timing relative to the crankshaft position is a common means of accomplishing knock avoidance. Figure 1 shows an example of the pressure versus volume relationship for three combustion phasing set points at the same output torque. In this example, the most advanced combustion phasing is shown in green, with increasing amounts of combustion phasing retard shown in blue and red. As combustion phasing is retarded, the peak pressure in the cylinder decreases. The peak temperature in the cylinder also declines—in proportion to the pressure. Since fuel autoignition is driven by temperature and pressure, reducing temperature and pressure reduces the occurrence of knock.

However, reducing in-cylinder pressure also has a deleterious effect on fuel efficiency. Moving the fresh air charge and exhaust through the engine requires the expenditure of pumping work, and is defined by the indicated pumping work region of the curve. The area of the gross indicated work output is the useful work produced by the engine. Net work output is the difference between indicated work output and indicated pumping work. As combustion phasing is retarded, it causes the maximum pressure to be reduced, which in turn decreases the indicated work output. Since the indicated pumping work doesn't change significantly as phasing is retarded, the net work output also decreases.

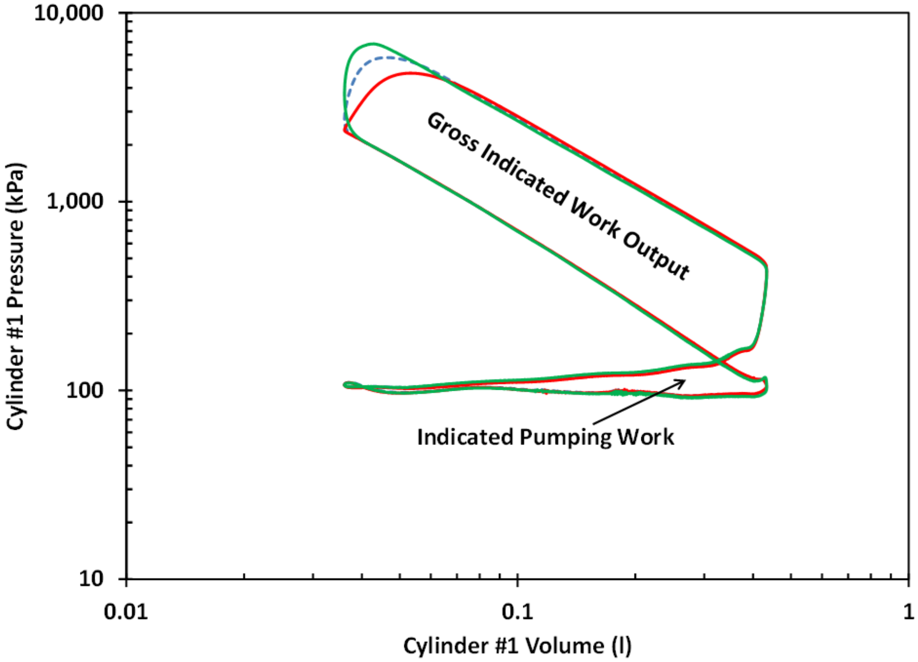


Figure 1. An example pressure versus volume diagram showing the impact of combustion phasing retard on work output.

It is useful at this point to introduce several terms that are used to describe engine performance. The first of these terms is brake mean effective pressure (BMEP). BMEP is measured in units of pressure, often kilopascals. It is a means of normalizing engine output torque per engine cycle by the displacement of the engine. Thus, when output torque is described as BMEP, results from engines with differing displacement can be directly compared. For example, most engines experience the onset of knock at very similar BMEP levels, though the output torque at the onset of knock can vary greatly as a result of the engine displacement. Similarly, the fuel energy input to the cylinders per cycle can also be normalized and expressed in units of pressure.[12-14] This quantity is called the fuel mean effective pressure (or fuel MEP). Fuel MEP expresses the energy input to the engine, regardless of the energy density of the fuel. Thus, the fuel energy input for fuels of differing energy content can be directly compared by examining fuel MEP. The ratio of BMEP to fuel MEP is equal to the brake thermal efficiency for the engine at a given condition. Friction MEP is traditionally abbreviated as FMEP. To avoid confusion, FMEP is not used to abbreviate fuel MEP. Finally, a metric that is frequently used to describe the phasing of the combustion event relative to piston position is the location in the engine cycle at which 50% of the fuel has burned. This metric is measured in crank angle degrees (CAD) and is termed CA50, for the crank angle at which 50% of the fuel has burned.

A key fuel property is net energy content or net heating value. The most fundamental measure of the heating value of a fuel is the gravimetric heating value, which expresses the energy content of a fixed mass of fuel. However, in most cases the gravimetric heating value is multiplied by the density of a fuel to obtain the volumetric heating value. It is the volumetric heating value, the amount of energy contained in a fixed volume of fuel, that is important in determining the familiar fuel economy metric in transportation applications. Figure 2 shows a comparison of the gravimetric and volumetric heating values for ethanol and three nonoxygenated hydrocarbons. Benzene is useful for a notional comparison because it has a H/C ratio of unity, meaning that it has the highest carbon content of any fuel-related hydrocarbon.

Pentane and isooctane are alkanes within the typical distillation range of gasoline and have higher H/C ratios, meaning that they derive less of their energy from their carbon content than does benzene. Ethanol is an alcohol, and because it has an oxygen atom in its molecular structure, it has a lower heating value than nonoxygenated hydrocarbons. This characteristic results in decreasing volumetric heating value when ethanol is blended into gasoline. Unless engine efficiency is increased, decreasing the volumetric heating value of a fuel decreases vehicle fuel economy in proportion to the decrease in heating value.

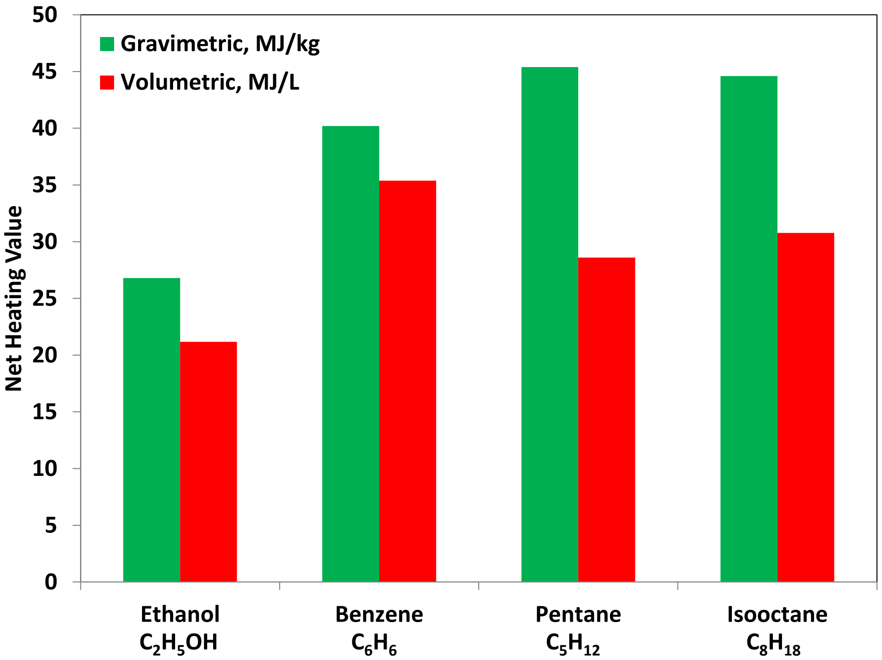


Figure 2. Comparison of net heating values of some fuel molecules.
(Data Source: *Bosch Automotive Handbook*, 2nd edition, Robert Bosch GmbH, 1986.)

2. FUELS

Two fuels were sourced from Gage Products of Ferndale, Michigan, and used for this study. The first was a Tier 3 emissions certification gasoline that contained 10% ethanol by volume (E10). The second fuel was E25 produced by blending additional denatured ethanol with the Tier 3 emissions certification fuel (commonly referred to as splash blending). Certificates of analysis are included in the appendix for both fuels. Table 1 summarizes attributes of these fuels that are relevant to the current study.

Table 1. Measured properties of the two study fuels

Property	Tier 3 Certification Gasoline	E25 Blend
Ethanol content (vol %)	9.93	25.27
Research octane number	92.3	98.9
Motor octane number	84.5	87.5
Antiknock index	88.4	93.2
Octane sensitivity	7.8	11.4
Density (g/cc)	0.7475	0.7545
Net heat of combustion (MJ/kg)	41.43	39.12
Net heat of combustion (MJ/l)	30.97	29.52

The E25 blend had increased RON, MON, AKI, and sensitivity associated with the higher level of ethanol in the fuel. These attributes can be used together with adjustments in ignition timing and CR to increase the efficiency of the engine. However, the net heat of combustion for the E25 blend is lower relative to the E10 blend, which results in decreased fuel economy (i.e., miles per gallon) unless the engine efficiency can be improved 4.7% to offset the difference in energy content.

3. ENGINE AND OPERATING CONDITIONS

A Ford EcoBoost 1.6 L 4-cylinder engine was used to support this study. This engine is a turbocharged gasoline DI engine equipped with variable cam phasing for both the intake and exhaust camshafts. Figure 3 shows the engine as it is installed in an engine research laboratory at Oak Ridge National Laboratory (ORNL). The production embodiment of this engine uses pistons that result in a 10.1 : 1 CR. Additional pistons were fabricated to produce higher CRs by reducing the piston bowl volume, which in turn reduces the total clearance volume of the cylinders. Pistons were designed to provide CR12, but measurements confirmed that the pistons provided CR11.4. While these new pistons would not satisfy all of the requirements that a car manufacturer would need to consider in a production application, they are appropriate for this study. Figure 4 shows the production and high-compression pistons. The OEM pistons and CR11.4 pistons were used for this study.

The engine was equipped with an engine control unit that allowed modification of the spark timing and other parameters needed to support studies such as the one reported here. A DRIVVEN micro Drivven Combustion Analysis Tool (µDCAT) was used to monitor the in-cylinder pressures synchronously with the crankshaft position at increments of 0.2 CAD. These measurements allowed the µDCAT system to calculate combustion metrics such as the CA50 location. The signal from the pressure transducer in cylinder 1 was also monitored asynchronously to enable knock detection with the µDCAT system.

During experiments, the fuel system was flushed to remove the previous fuel before introduction of the fuel of interest to this study. The engine was then operated until it was fully warmed. At this point, the output torque was increased to increase the fuel consumption rate, and this condition was held for 15 minutes to ensure that all of the previous fuel had been removed from the fuel injector rail.

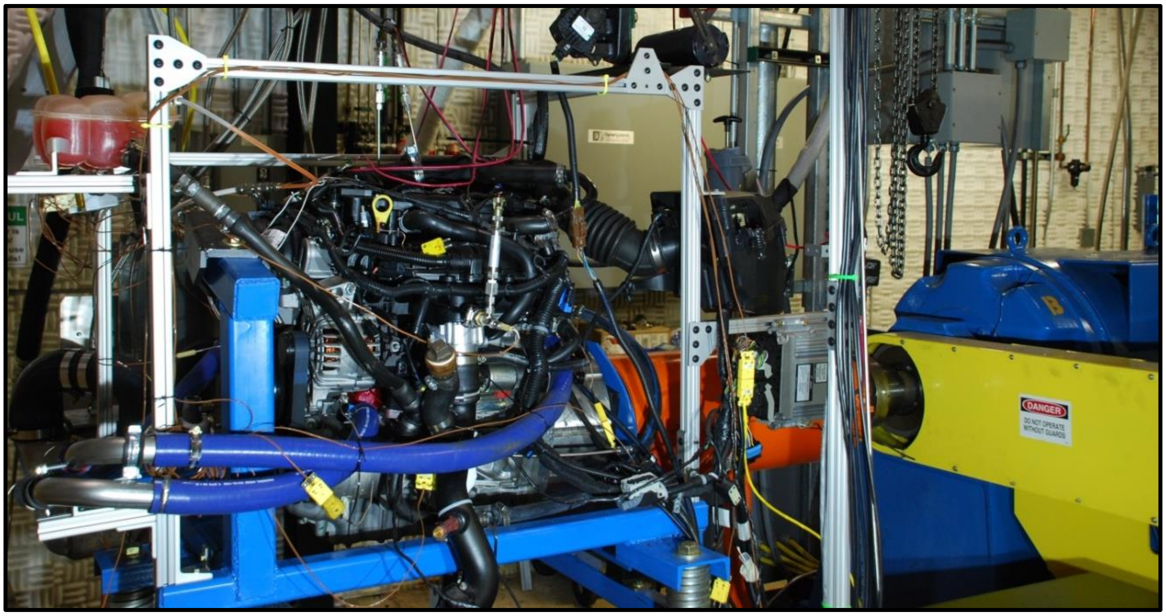


Figure 3. Ford EcoBoost engine installed in an engine research laboratory at Oak Ridge National Laboratory.

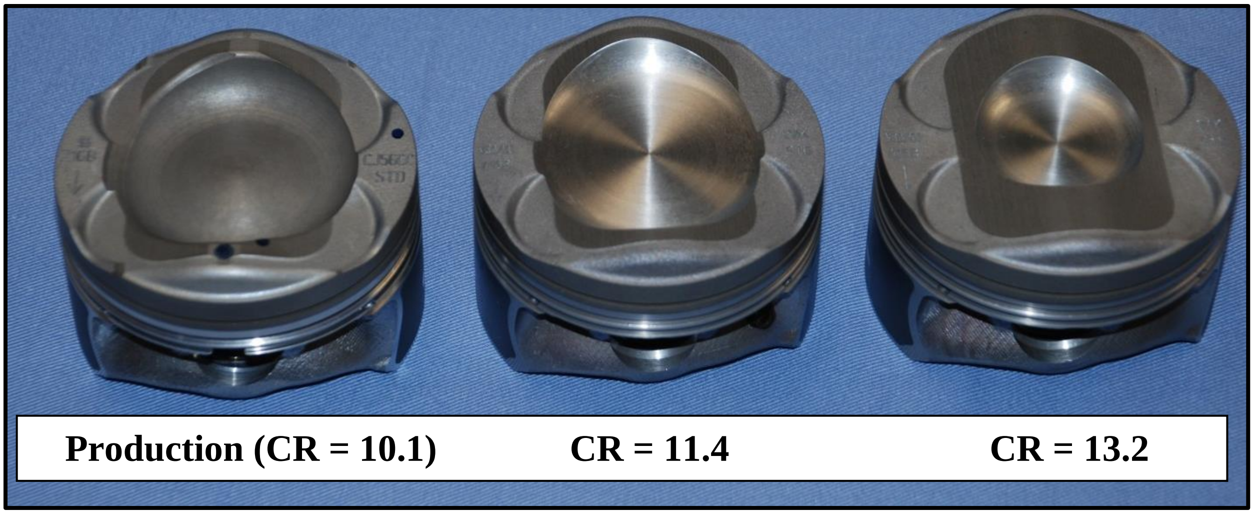


Figure 4. Production and high-compression pistons used with the 1.6 L engine.

Engine mapping began at low output torque and proceeded to higher torques until the maximum torque at a given engine speed was reached. Generally, this procedure resulted in data collection beginning at about 100 kPa BMEP and increasing to the maximum BMEP in increments of about 100 kPa BMEP. Data were collected at engine speeds of 1,000 RPM, 1,500 RPM, 2,000 RPM, 2,500 RPM, and 5,000 RPM. Additionally, the maximum torque curve between 3,000 and 5,000 RPM was determined. Figure 5 shows the points at which data were collected for the Tier 3 E10 fuel using the production pistons. This distribution of points is typical of the engine mapping procedure that is used when the resulting data will support vehicle modeling, as was the case with this study.

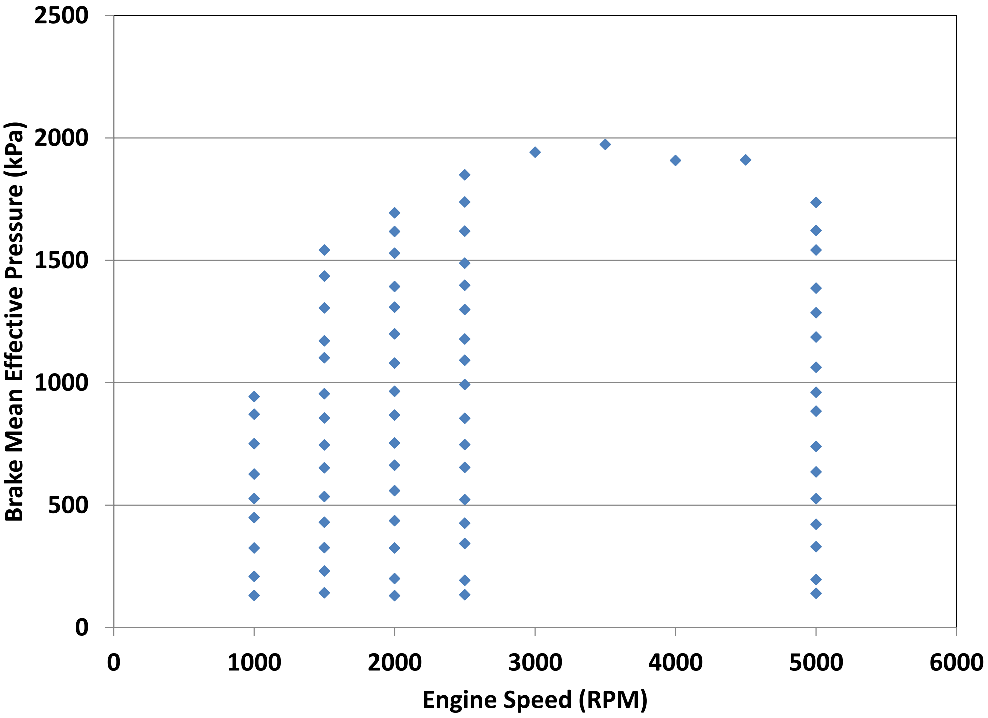


Figure 5. Points at which data were collected for the Tier 3 E10 fuel using the production pistons.

4. RESULTS FROM ENGINE EXPERIMENTS

Engine mapping studies were performed for the Tier 3 E10 fuel with the production pistons to serve as a baseline for comparisons. Once the baseline was completed, the pistons that produce a CR of 11.4 were installed and studies completed with both the E10 and E25 fuels.

4.1 E10 FUEL WITH PRODUCTION PISTONS

The first condition studied used the Tier 3 E10 fuel with the production pistons in the engine. Spark timing was manually adjusted to keep the CA50 location at 6 CAD after top dead center (ATDC) in the maximum brake torque (MBT) region. The BMEP region where CA50 is not retarded to avoid knock is known as the MBT region of operation. As the engine encountered the onset of knock, spark timing was manually adjusted to retard CA50 timing to avoid knock. Figure 6 shows the CA50 timing versus BMEP for several speeds. Intermediate speeds were omitted from this plot to enhance its legibility.

The 1,000 RPM curve shows that the CA50 timing increases sharply as the engine encounters knock at between 600 and 700 kPa BMEP. The maximum attainable BMEP at this speed is limited because of insufficient enthalpy in the exhaust to enable the turbocharger to produce boost at this low speed, thus limiting the quantity of air available to support combustion in the cylinders. As the engine speed increases, the BMEP at which the engine encounters knock also increases, though the difference grows smaller as speed continues to increase. At 5,000 RPM, the engine encounters knock at just over 900 kPa BMEP. As engine speed increases, less spark retard is needed at a given BMEP to avoid knock.

Within the MBT region, fuel MEP is linearly related to BMEP and is not a strong function of engine speed.[12-14] Figure 7 shows the fuel MEP results for the Tier 3 E10 fuel with the production pistons for engine speeds between 1,500 and 2,500 RPM.

The relationship shown in Figure 7 was used to calculate the fuel consumption rates in the MBT region. For conditions outside the MBT region, the measured fuel consumption rates were used. This approach reduces the impact of experimental noise in the MBT region on predicted fuel economy results from vehicle modeling. Figure 8 shows the fuel consumption results at all mapping conditions for the Tier 3 E10 fuel at CR 10.1.

4.2 91 RON E10 AND 99 RON E25 FUELS WITH 11.4 COMPRESSION RATIO

The 91 RON Tier 3 E10 fuel was also investigated at a CR of 11.4 by exchanging the production pistons for pistons with a modified crown that resulted in lower clearance volume in the cylinder at top dead center. During the piston change, the rings from each piston were removed and reinstalled on the new piston such that the piston rings remained in the same cylinder bore. This step was taken to reduce opportunities for differences in engine friction between experiments at different CRs. Experimental studies at this higher CR were conducted in the same way and at the same nominal conditions as with the production CR of 10.1.

Figure 9 shows the CA50 results for this fuel and CR combination. The same overall trends observed at CR 10.1 are still present. However, at a given BMEP, the greater knock propensity requires that CA50 timing is phased later than was the case at CR 10.1. For example, the maximum BMEP point at 1,000 RPM was attainable with CA50 of just less than 25 CAD ATDC at CR 10.1, but a CA50 of nearly 30 CAD ATDC is required at CR 11.4. As discussed previously, the increased knock propensity for this regular-grade fuel in combination with a higher CR is expected to reduce fuel efficiency in the knock-limited operating space.

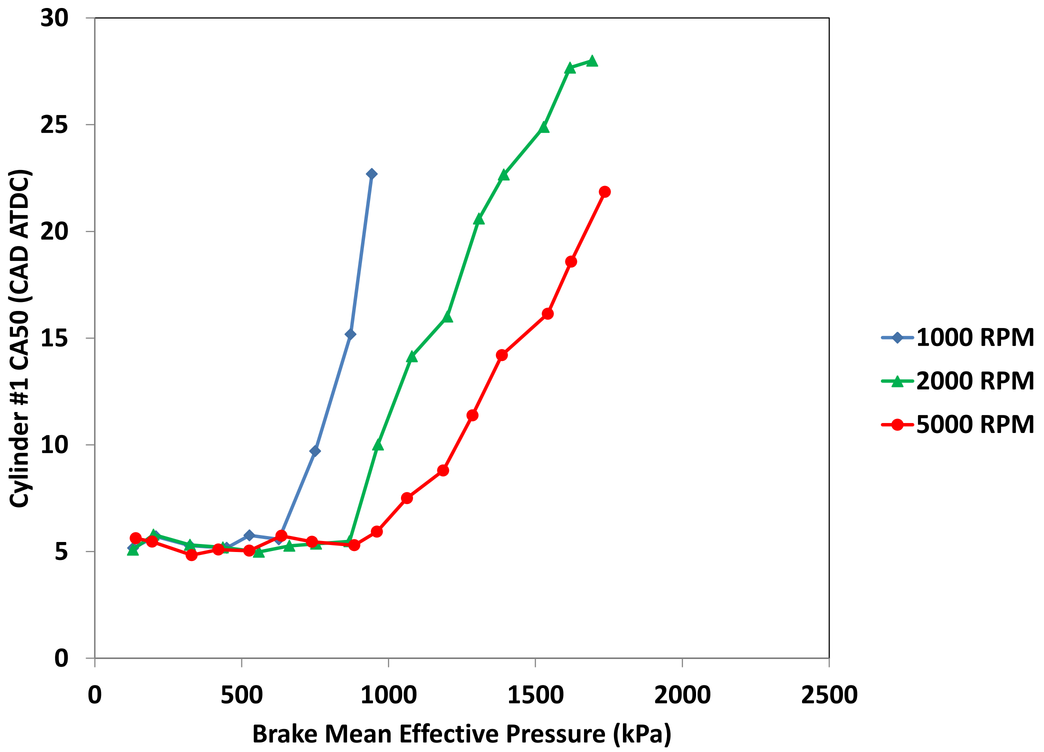


Figure 6. CA50 timing for the Tier 3 E10 fuel at a compression ratio of 10.1. (ATDC = after top dead center; CAD = crank angle degrees.)

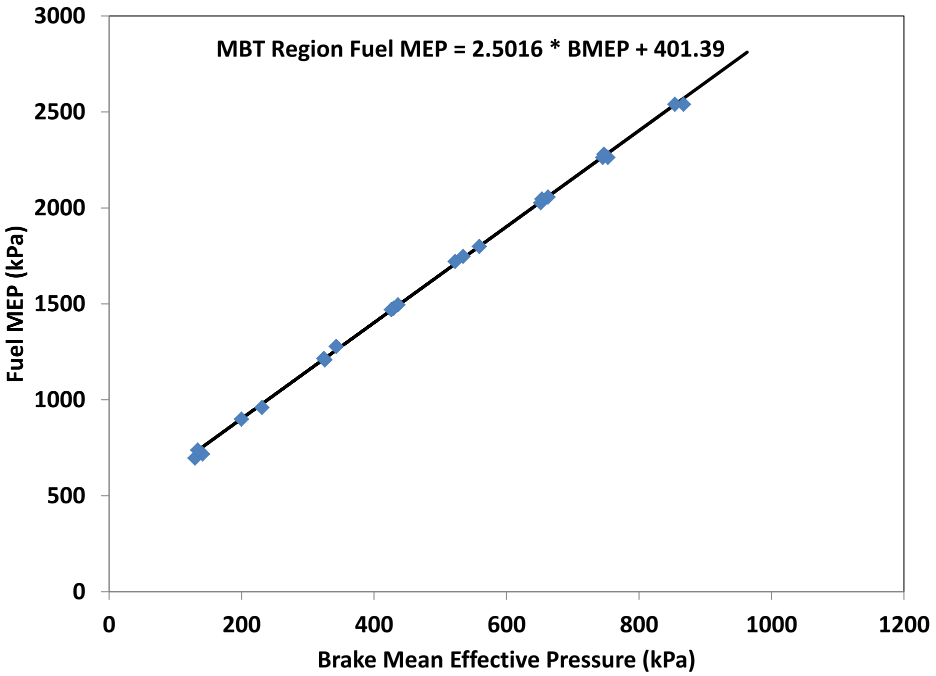


Figure 7. Fuel mean effective pressure (MEP) versus brake MEP (BMEP) in the maximum brake torque (MBT) region for the 91 research octane number Tier 3 E10 fuel and the production pistons.

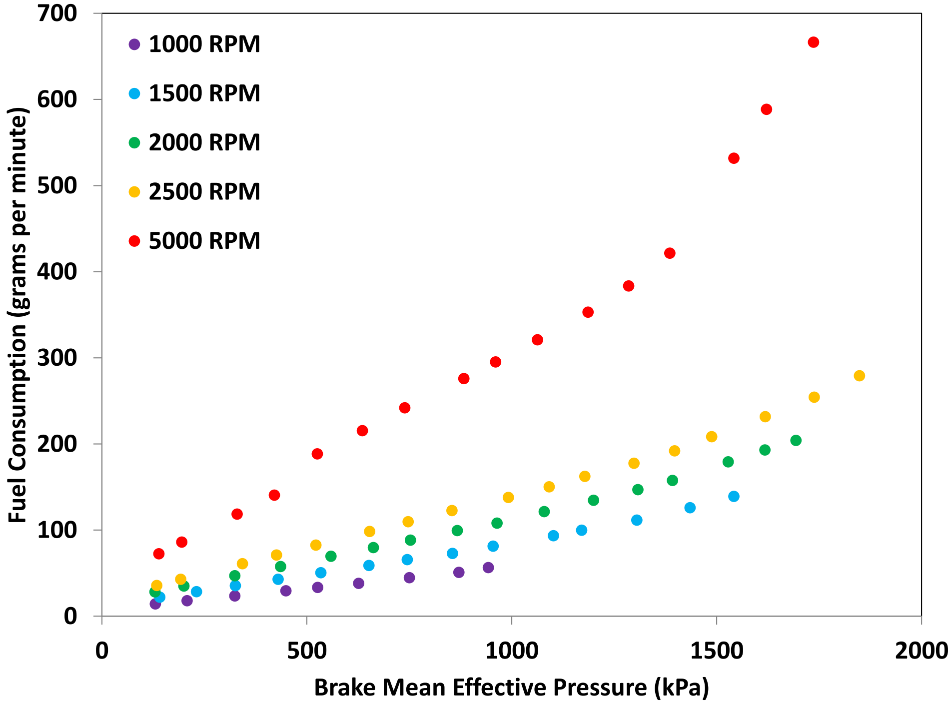


Figure 8. Fuel consumption results for the 91 research octane number Tier 3 E10 fuel with the production pistons.

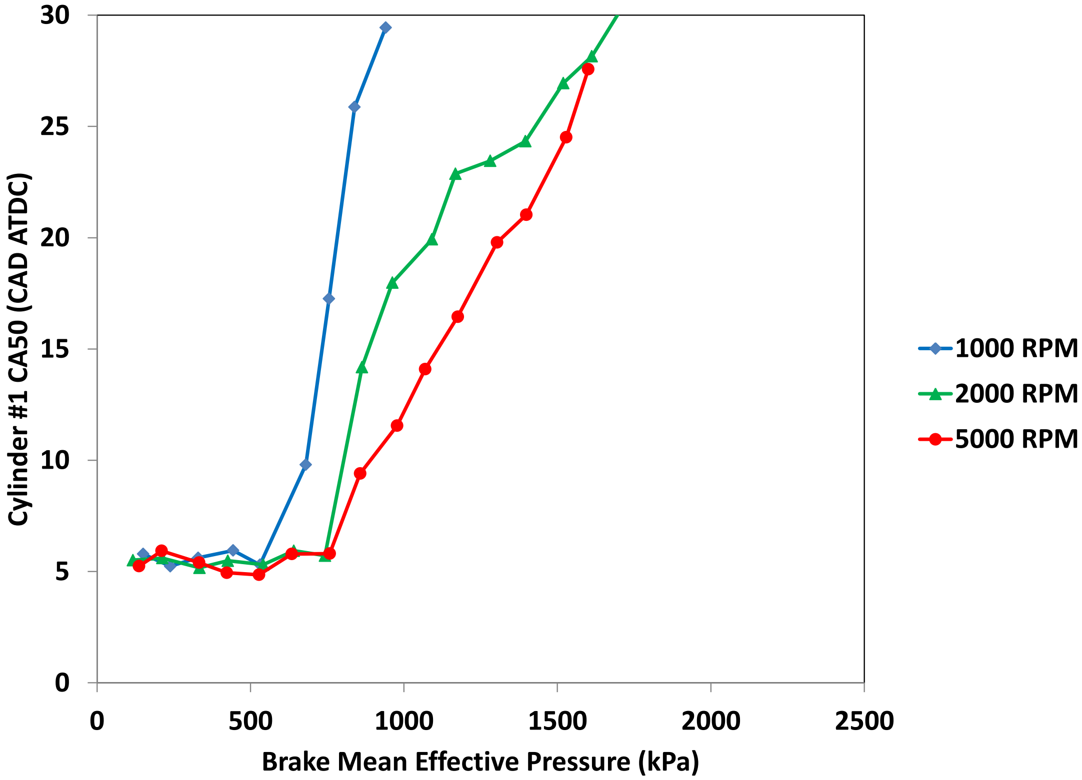


Figure 9. CA50 timing for the Tier 3 E10 fuel at a compression ratio of 11.4.

Figure 10 shows the fuel MEP results in the MBT operating space for the 91 RON E10 and the 99 RON E25 fuel at a CR of 11.4. As combustion phasing in the MBT region is not limited by knock, there is no advantage offered by the increased RON of the E25 fuel relative to the E10 fuel under these operating conditions. The results of both fuels fall on the same line. Linear regression of these data produces a best-fit line with lower slope and marginally higher intercept than was the case for the lower CR. The lower slope indicates an improvement in thermal efficiency, as expected for the use of a higher CR. The higher intercept indicates higher friction and pumping work, which is also typical for increasing CR. The fuel MEP for CRs of 11.4 and 10.1 is equal at a BMEP of 260 kPa, meaning that above this BMEP the lower slope of the CR 11.4 condition provides improved efficiency in the MBT region. As with the CR 10.1 condition, the regression of fuel MEP with BMEP was used to calculate fuel consumption values in the MBT region as a means of reducing the impact of experimental error on modeled fuel economy results.

CA50 results for the 99 RON E25 fuel at CR 11.4 are shown in Figure 11. As with the two previous cases, the combustion phasing is held at approximately 6 CAD ATDC in the MBT region. As the BMEP rises, knock onset occurs and the CA50 is retarded to avoid knock. The amount of spark retard needed at CR 11.4 for this high-RON fuel is less than that needed for the 91 RON E10 at the same CR and BMEP, as expected. The lower amount of CA50 retard for this high-RON fuel means that it will produce higher efficiency at a given knock-limited condition than the 91 RON E10 fuel. This efficiency gain also allows the engine to produce more output BMEP for the 2,000 and 5,000 RPM conditions. The 1,000 RPM maximum attainable BMEP is limited by the ability for the turbocharger to produce boost, and therefore does not increase significantly with higher CR or higher octane fuel.

Figure 12 shows a comparison of the fuel MEP for both of the fuels at a CR of 11.4 and engine speed of 2,000 RPM. The broken black line in this plot is the regression line established in the MBT region. Extrapolation of the regression line into the knock-limited region is a means of estimating the fuel MEP at a given BMEP if knock had not been present. That is, it represents a baseline for establishing the amount of fuel energy cost of knock avoidance at a given point in the knock-limited region. The results for all fuels will fall above this line. The results begin to diverge as the BMEP exceeds the maximum BMEP for the MBT region, though the change in slope is subtle. Results for the 99 RON E25 fuel fall just above the broken line, with the 91 RON E10 fuel results having a greater vertical displacement from the broken line due to the requirement for more severe spark retard. At a BMEP of 1,400 kPa, for example, the 99 RON E25 fuel requires just over 90 kPa of fuel MEP for knock avoidance, while the 91 RON E10 needs just under 300 kPa of fuel MEP to avoid knock. This difference allows the 99 RON E25 fuel to achieve a brake engine efficiency that is 1.9 efficiency points higher than the 91 RON E10 fuel at this engine condition. This value compares favorably with other values cited in the literature. Leone et al. established an equation to estimate efficiency gain from the data generated in a previous study by Smith et al.[15,16] Using this equation provides an estimate of efficiency gain for a CR of 11.4 relative to the 10.1 CR baseline of about 2.6% under typical engine conditions.

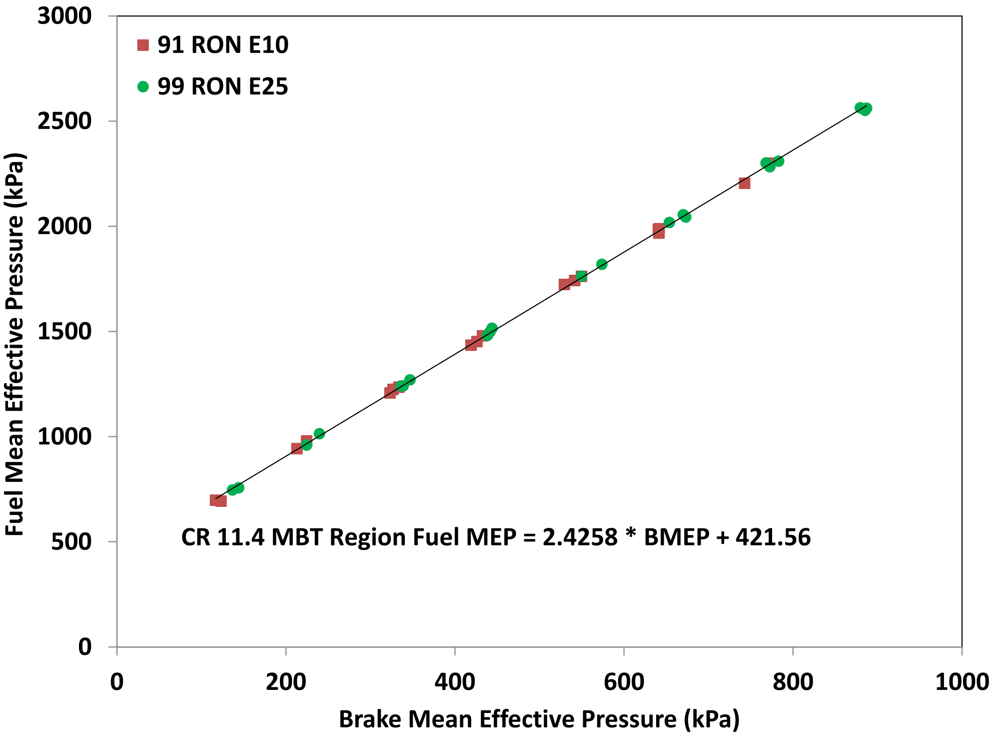


Figure 10. Fuel mean effective pressure (MEP) versus brake MEP (BMEP) at a compression ratio of 11.4. (MBT = maximum brake torque; RON = research octane number.)

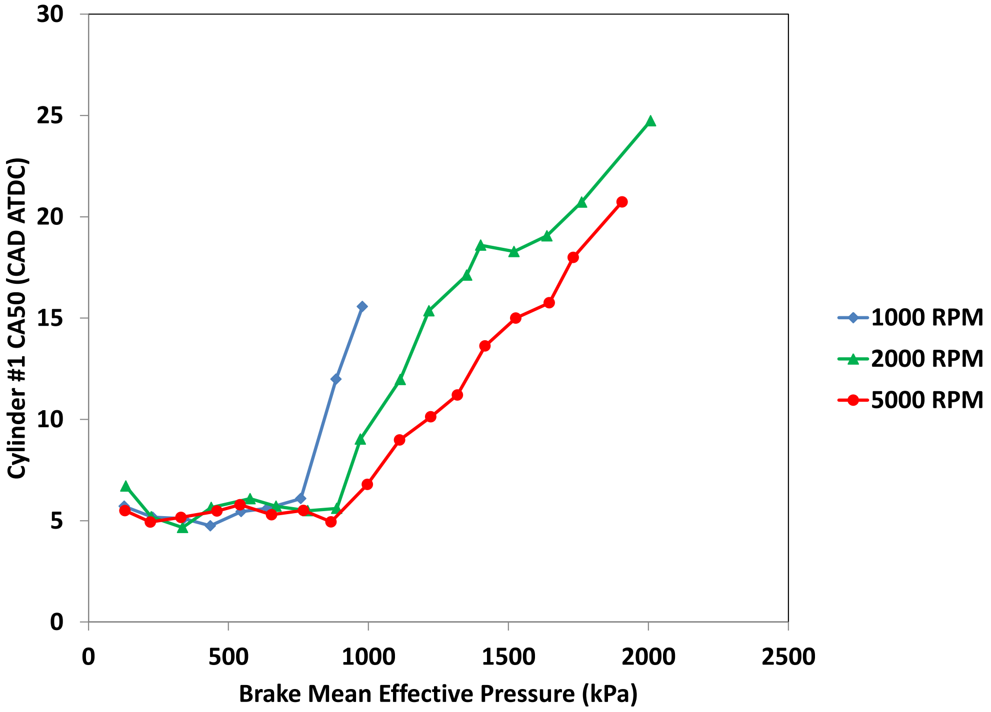


Figure 11. CA50 versus BMEP for the 99 RON E25 fuel at a compression ratio of 11.4. (ATDC = after top dead center; CAD = crank angle degrees.)

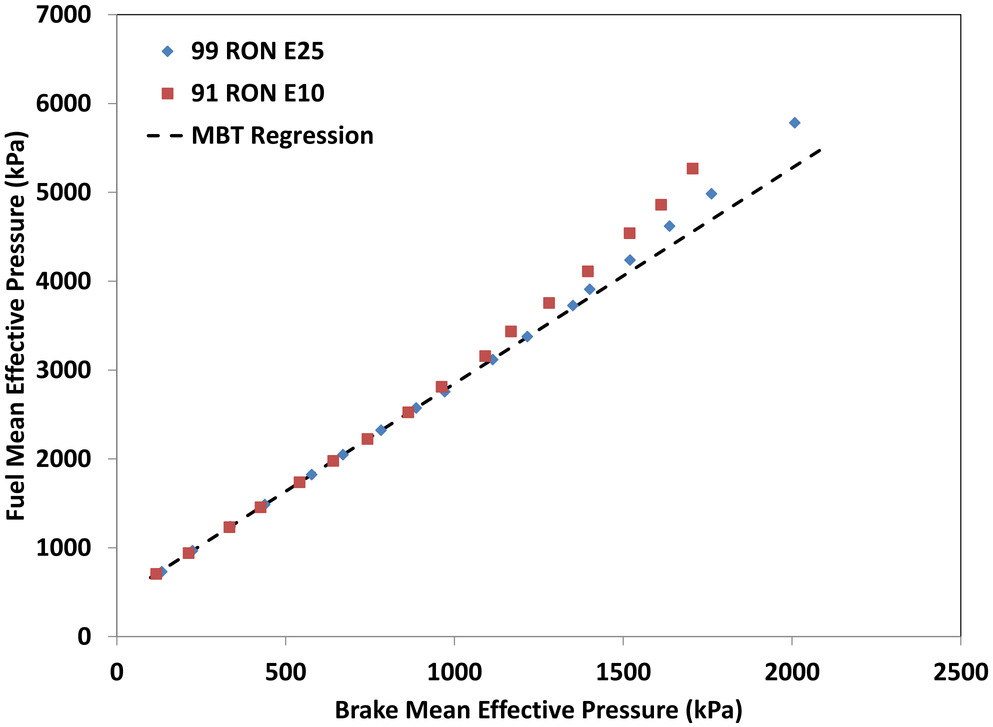


Figure 12. Comparison of fuel mean effective pressure (MEP) versus brake MEP for the two study fuels at a compression ratio of 11.4 and 2,000 RPM. (MBT = maximum brake torque; RON = research octane number.)

5. VEHICLE MODELING

Once the engine data for this project were developed, they were used to support vehicle modeling. The vehicle modeling activity allows the efficiency changes that were observed in the engine data to be projected into the vehicle space as changes in fuel economy. Two vehicles were studied: an industry-average midsize sedan and an industry-average small sport-utility vehicle (SUV). Both vehicles were studied as conventional vehicles without hybridization.

5.1 VEHICLE MODEL SETUP

The vehicle modeling task for this study was carried out using the Autonomie model.[17] In addition to the engine maps developed to support the modeling effort, the vehicle model requires parameters that describe the aerodynamic and mass characteristics of the vehicle and the diameter of its tires and relevant gear ratios for the transmission and final drive. Once these parameters are established, the model can project the engine conditions needed to "drive" the model vehicle through any number of test cycles. Vehicle model parameters for this study are shown in Table 2; these parameters are typical of an industry-average midsize sedan and small SUV and are being used for a number of related modeling studies at ORNL that also use maps from this EcoBoost engine. For this project, the vehicles were studied using the Urban Dynamometer Driving Schedule (UDDS), the Highway Fuel Economy Test cycle (HWFET), and both the city and highway portions of the US06 cycle (US06_City and US06_Highway, respectively). UDDS is the driving schedule that is used for the first two phases or "bags" of the federal test procedure (FTP), and the FTP is used for both fuel economy and emissions certification. HWFET is used for fuel economy certification, and US06 is used for emissions certification and also contributes to adjustments in the "label" fuel economy.[18,19] For each instant in each driving cycle, a target vehicle speed is specified. The speed versus time traces for all three cycles are shown in Figures 13–15. Figure 15 shows how the highway portion of the US06 is a 365-second segment in the middle, while the city portion is made up of the first 130 seconds and the last 105 seconds. Autonomie calculates the required engine output speed and torque to meet the necessary speed and acceleration at each instant in the cycle. These quantities then allow Autonomie to calculate the fuel consumption for each instant in the cycle from the engine map that is provided for each fuel and CR. The distance travelled and the fuel consumed at each instant are summed over the drive cycle and used to calculate the overall fuel economy.

Table 2. Vehicle model parameters

Parameter	Midsize sedan	Small SUV
Target coefficient A (lb_f)	34.0501	31.3622
Target coefficient B (lb_f/MPH)	0.2061	0.3408
Target coefficient C (lb_f/MPH^2)	0.0178	0.0235
Equivalent Test Weight (lb)	4,000	4,000
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

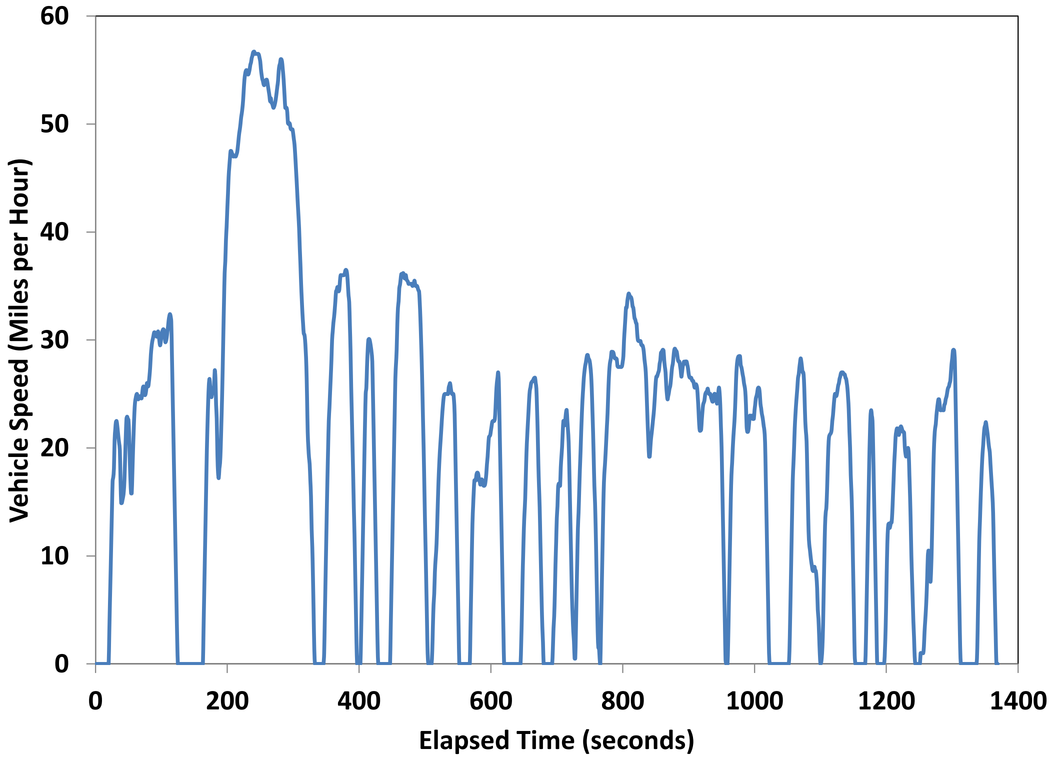


Figure 13. The Urban Dynamometer Driving Schedule speed versus time trace.

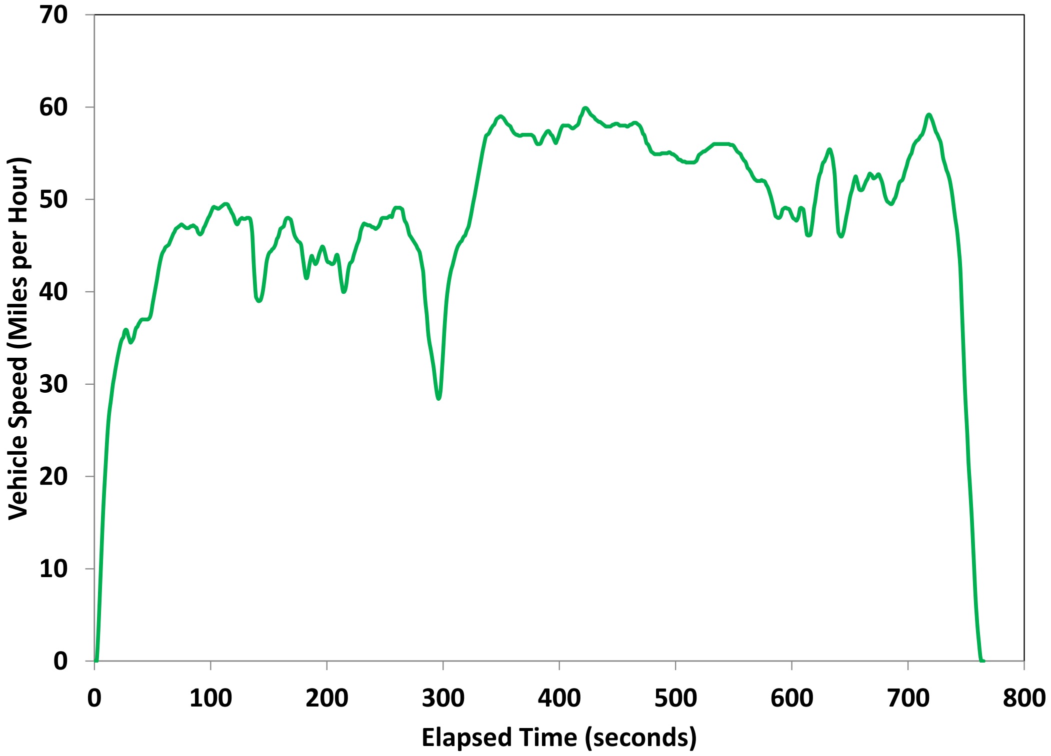


Figure 14. The Highway Fuel Economy Test cycle speed versus time trace.

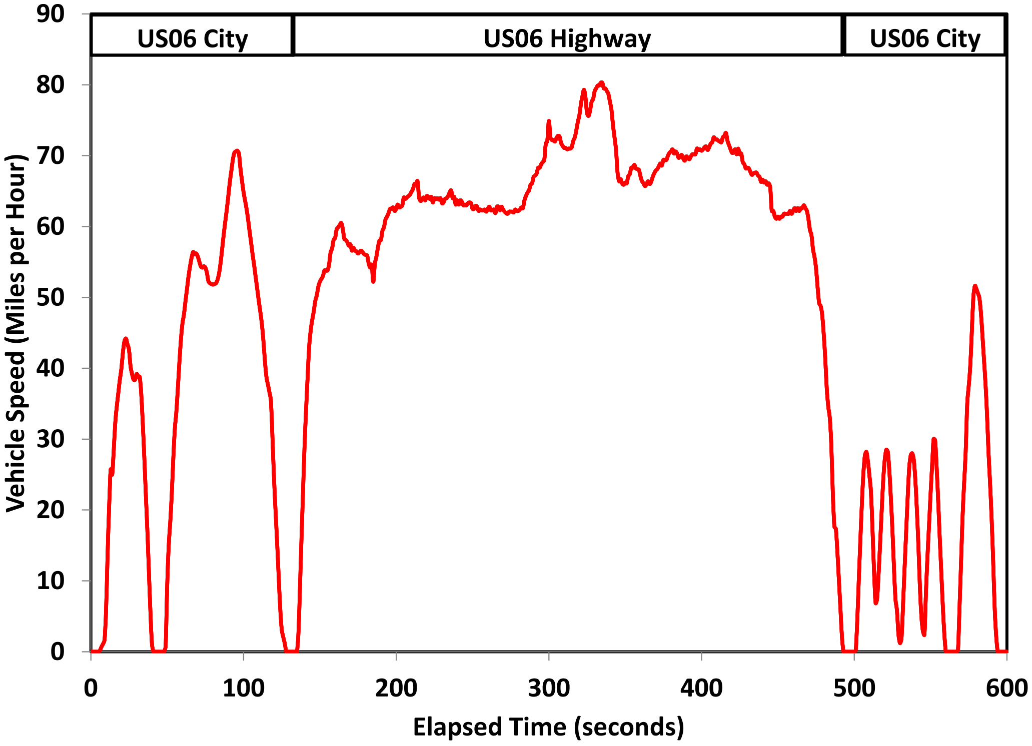


Figure 15. The US06 cycle speed versus time trace.

5.2 VEHICLE MODEL RESULTS FOR MIDSIZE SEDAN

The Autonomie model predicts the engine speed and torque conditions needed to allow the vehicle to complete the target drive cycle. For example, Figure 16 shows the speed and BMEP conditions predicted for UDDS for the midsize sedan. The blue dots show the second-by-second engine conditions, with the broken red line indicating the approximate location of the onset of knock at each speed. Negative values of the engine BMEP occur during deceleration events on the cycle. The engine speed during this drive cycle is most frequently less than 2,000 RPM, with some operation to just over 3,000 RPM. BMEP remains less than 1,600 kPa, with most operation occurring at 800 kPa or less. About 7% of the conditions on this cycle cause knock-limited operation when the 91 RON fuel is used, so UDDS fuel economy is dominated by fuel consumption in the MBT region of the engine operating map. HWFET is similar to UDDS in terms of speed and load condition. Just over 11% of vehicle operation on HWFET occurs in the knock-limited space when the 91 RON fuel is used. Thus, HWFET fuel economy is also dominated by fuel consumption in the MBT region of the engine operating map.

In the absence of differences in transmission shift point or powertrain hardware modifications, the operating conditions for each drive cycle are independent of the fuel and CR being used. The Autonomie model uses an algorithm to calculate transmission shift points that mimic the behavior of production vehicles.[20] Increasing the CR in the 1.6 L engine increased the brake thermal efficiency of the engine but did not change the speed at which the peak efficiency was observed. Hence, the general shape of the engine efficiency map was similar for both CRs. This similarity resulted in transmission shift points that were nearly constant when the CR was increased. An example plot of the engine speed versus time for UDDS is shown in Figure 17. In general, the results for the three cases lay on top of one another. However, the RON 91, E10 CR 11.4 condition shows higher engine speed peaks. These peaks are consistent with deviations in the shift points needed to offset torque losses caused by knock avoidance. Because the 91 RON CR 10.1 and 99 RON CR 11.4 conditions provided similar maximum torque values at each speed, the shift points for these conditions are almost identical. Similar trends were observed for the HWFET and both the city and highway portions of the US06 cycle.

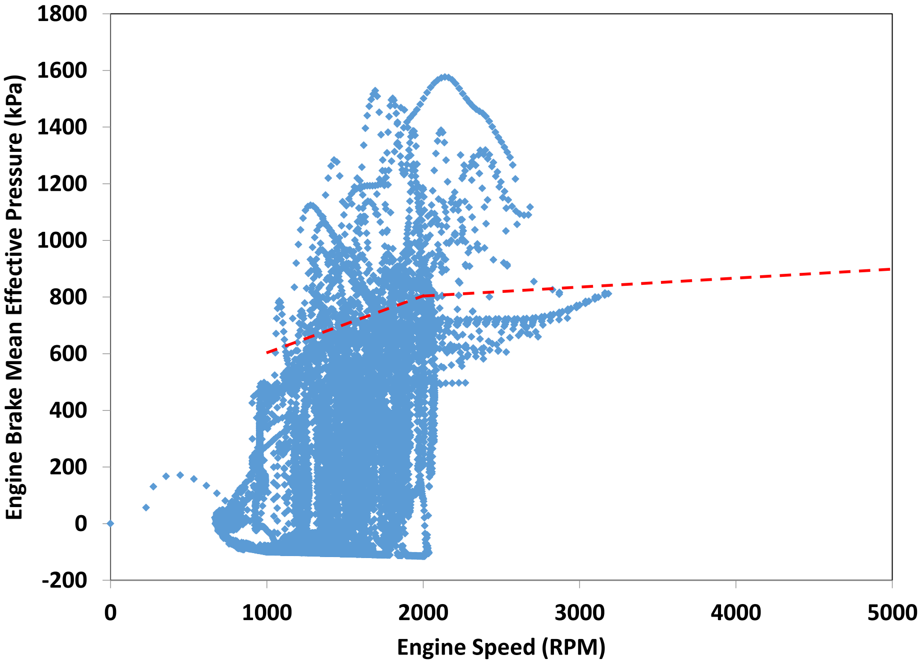


Figure 16. Speed and brake mean effective pressure conditions for the midsize sedan on the Urban Dynamometer Driving Schedule.
Red line indicates the edge of the maximum brake torque region.

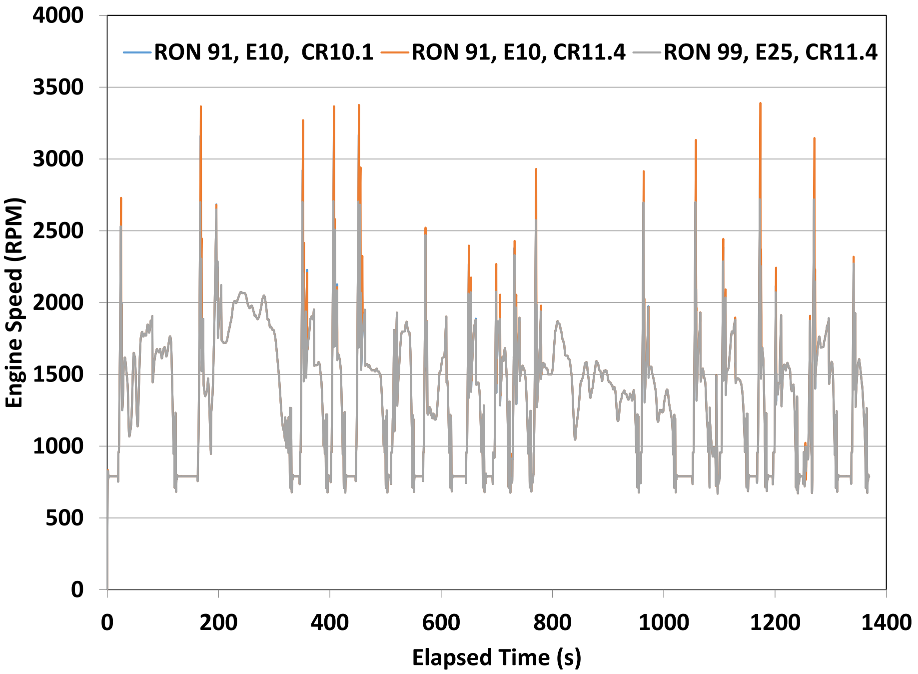


Figure 17. Engine speed traces for the Urban Dynamometer Driving Schedule.
(CR = compression ration; RON = research octane number.)

The US06 cycle includes higher vehicle speeds and accelerations than either UDDS or HWFET. As a result of these differences, the engine speed and BMEP conditions for this cycle also differ significantly. US06 results are often expressed for the city portion and highway portion of the cycle, as these portions are used to determine the fuel economy posted on the window sticker of new vehicles.[19,21] Figure 18 shows the engine speed and BMEP conditions for the city portion of the US06 cycle. The broken red line again denotes the approximate onset of knock for this cycle. The operating conditions for both the city and highway portions of this cycle cause just over 32% of the cycle to occur in the knock-limited region when the 91 RON fuel is used. Since knock-limited operation occurs for a substantial portion of this cycle, improving the antiknock properties of the fuel is expected to provide more benefit on both portions of the US06 cycle than on the MBT-dominated UDDS and HWFET.

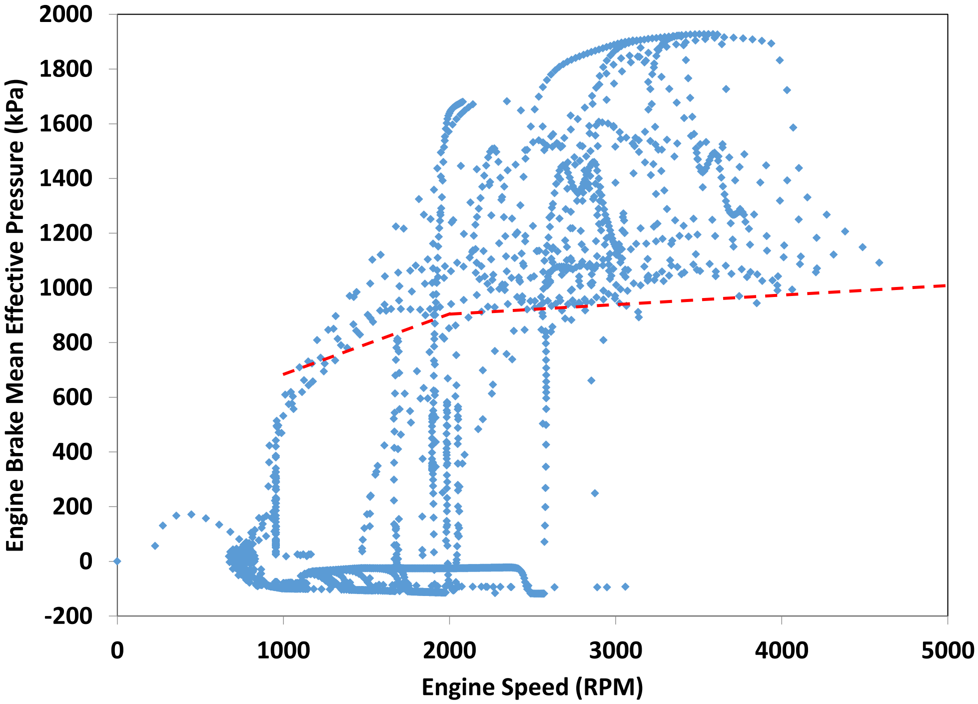


Figure 18. Engine speed and brake mean effective pressure conditions for the city portion of the US06 cycle. The red line indicates the approximate knock limit.

As discussed previously, midsize sedan operation on UDDS and HWFET is dominated by MBT conditions. These MBT conditions are not limited by the onset of knock, improving antiknock properties alone will not improve efficiency at these points. However, increasing the engine CR can improve fuel consumption in the MBT region. Increasing CR also results in increased knock propensity, so in the absence of improvements in fuel antiknock qualities, this approach could result in greater fuel efficiency losses to avoid knock in the knock-limited operating space. Increasing CR in combination with the use of a fuel with greater antiknock properties can improve vehicle fuel efficiency on UDDS, HWFET, and US06 simultaneously.

When the engine CR is increased to 11.4 through the use of pistons with reduced clearance volume, only marginal changes in the fractions of each cycle occurring in the knock-limited space are observed. However, within the knock-limited region, a greater degree of combustion phasing retard is needed to avoid knock. Use of the 99 RON fuel at this CR results in minor changes to the fraction of operating conditions within the MBT space. However, less combustion phasing retard is needed to avoid knock outside of the MBT space, resulting in increased fuel efficiency relative to the 91 RON fuel.

Figure 19 shows the energy consumption for the midsize sedan for all three cycles. Energy consumption is a useful metric as it shows the impact of the cycle severity and knock-resistance of the fuel without the confounding factor of energy density. For UDDS, the energy consumption increases by just less than 1% for an increase in CR from 10.1 to 11.4 if the 91 RON fuel is used for both cases. However, using the 99 RON fuel at CR 11.4 results in just less than a 1% decrease in energy consumption, resulting in a net efficiency difference of 1.7% between the two fuels on this cycle for the 11.4 CR. These small differences are rational based on the small amount of knock-limited operation on UDDS for this vehicle and powertrain. It is worthy of note that the relatively high RON rating of 99 for the E25 fuel could perhaps enable higher CRs than the 11.4 being used here, which could increase the benefits of this fuel on UDDS. HWFET shows similar impacts from the use of the 99 RON fuel and CR 11.4 to that of UDDS; that is, just less than 1% improvement in energy consumption. The difference between the CR 10.1 and 11.4 results for the 91 RON fuel is likely not significant.

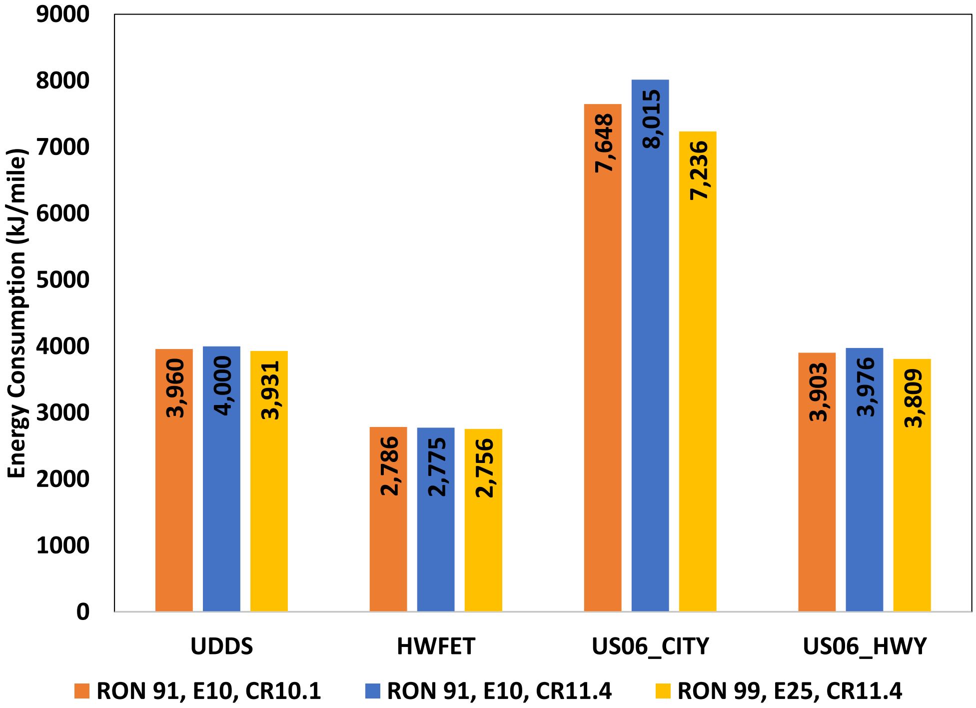


Figure 19. Energy consumption results for the midsize sedan. (CR = compression ratio, HWFET = Highway Fuel Economy Test cycle, HWY = highway, RON = research octane number, and UDDS = Urban Dynamometer Driving Schedule.)

The city and highway portions of the US06 cycle show larger differences than UDDS and HWFET, again, due to the greater fraction of operation in the knock-limited regime. For the city portion of the US06, increasing CR causes fuel consumption for the 91 RON fuel to increase by 5% as a result of increased knock propensity. Use of the 99 RON fuel at a CR of 11.4 demonstrates a 5% decrease in energy use compared to the 91 RON fuel at the CR 10.1 condition. For the highway portion of the US06, the energy use for the 91 RON fuel at a CR of 11.4 increases 2%, while the 99 RON fuel at a CR of 11.4 decreases 2%. Cumulatively, these results point to the importance of matching the antiknock properties of the fuel to the knock propensity of the engine. There is a trade-off between improving fuel efficiency on the cycles that are used to demonstrate CAFE compliance and cycles such as the US06 that capture more aggressive elements that are present in consumer driving behavior. Increasing the antiknock performance of the fuel provides the automakers with more flexibility in managing this trade-off so that overall fuel economy can be further increased.

Volumetric fuel economy is another important metric in judging the effects of increasing CR. As discussed above, the impact of a fuel on the energy consumption of a vehicle is strongly dependent on the knock propensity of the engine and the antiknock performance of the fuel. Volumetric fuel economy is dependent on these characteristics but is also strongly influenced by the volumetric energy density of the fuel. Figure 20 shows the volumetric fuel economy results for the midsize sedan.

The energy efficiency gain for the 99 RON CR 11.4 condition on UDDS and HWFET is not sufficient to overcome the 4.7% reduction in volumetric energy content of the 99 RON fuel, and thus the volumetric fuel economy on these cycles is lower than the baseline 91 RON CR 10.1 case. The energy efficiency gains made possible on the city portion of the US06 cycle enable the volumetric fuel economy for the 99 RON E25 fuel to slightly exceed the baseline fuel economy. The 99 RON E25 fuel also has lower fuel economy on the city portion of the US06 cycle but is able to overcome about half of the energy content detriment of this fuel relative to the 91 RON E10 fuel.

It is important to note that the fuel economy value calculated and used for CAFE compliance is not the same as the volumetric fuel economy discussed in the preceding paragraph. Fuel economy values for CAFE compliance are calculated as if the test had been conducted using an ethanol-free certification gasoline that was in use in 1975 when CAFE regulations were first introduced. This calculation takes the difference in volumetric energy content between the actual test fuel and the 1975 fuel into account.[22] As a result of this calculation, it is possible for fuels with decreased volumetric energy content (such as an E25 blend) to have slightly lower volumetric fuel economy results and still provide increased fuel economy values for CAFE compliance. EPA did not update the R factor as a part of the Tier 3 final rule, but the calculation that has been used in the past is currently being updated as a part of the implementation of EPA’s Tier 3 emissions requirements.[23]

Finally, reducing tailpipe CO_2 emissions is a strong motivation for making use of biofuels in gasoline. Figure 21 shows the tailpipe CO_2 emissions for the midsize sedan. These results do not include any CO_2 differences associated with production of the fuels. As expected, the 99 RON E25 fuel has lower emissions of CO_2 on all drive cycles compared to the baseline 91 RON E10 fuel.

5.3 VEHICLE MODEL RESULTS FOR SMALL SUV

The three metrics discussed previously for the midsize sedan (energy consumption, volumetric fuel economy, and tailpipe CO_2 emissions) were also investigated for the same engine in a small SUV platform. The results are presented in Figures 22–24. The small SUV exhibits greater energy consumption than the midsize sedan on all cycles. Because of this increase in energy consumption, the volumetric fuel economy results are lower and the tailpipe CO_2 results higher than for those of the midsize sedan. However, the trends observed among the fuels and CRs for each cycle are the same as noted previously for the midsize sedan.

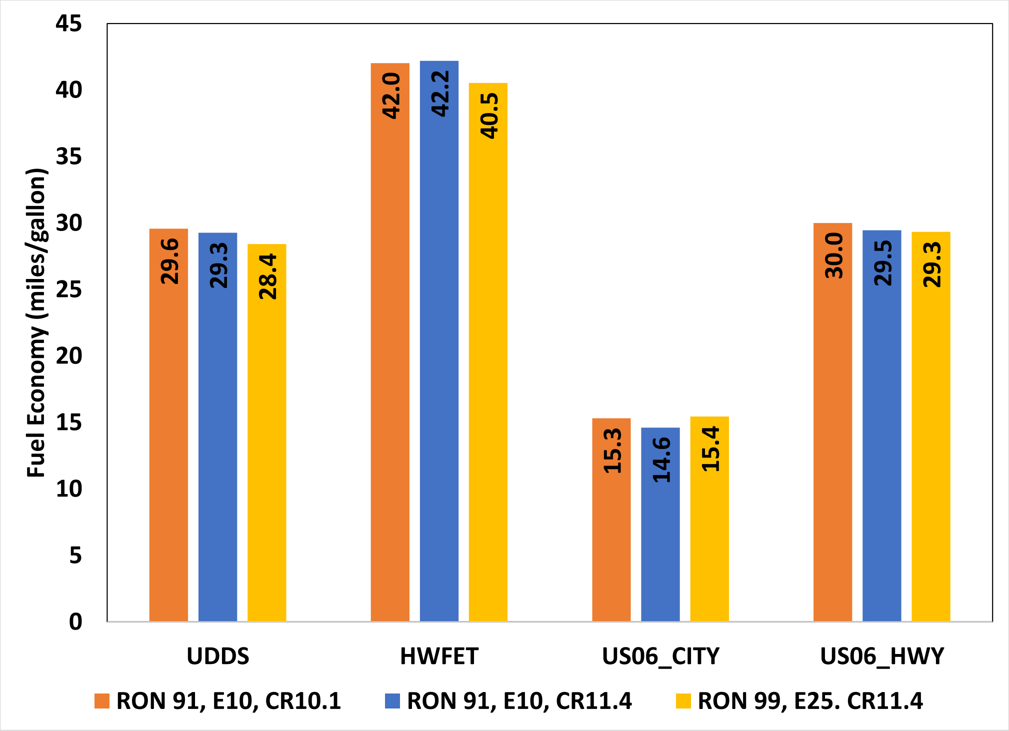


Figure 20. Volumetric fuel economy results for the midsize sedan. (CR = compression ratio, HWFET = Highway Fuel Economy Test cycle, HWY = highway, RON = research octane number, and UDDS = Urban Dynamometer Driving Schedule.)

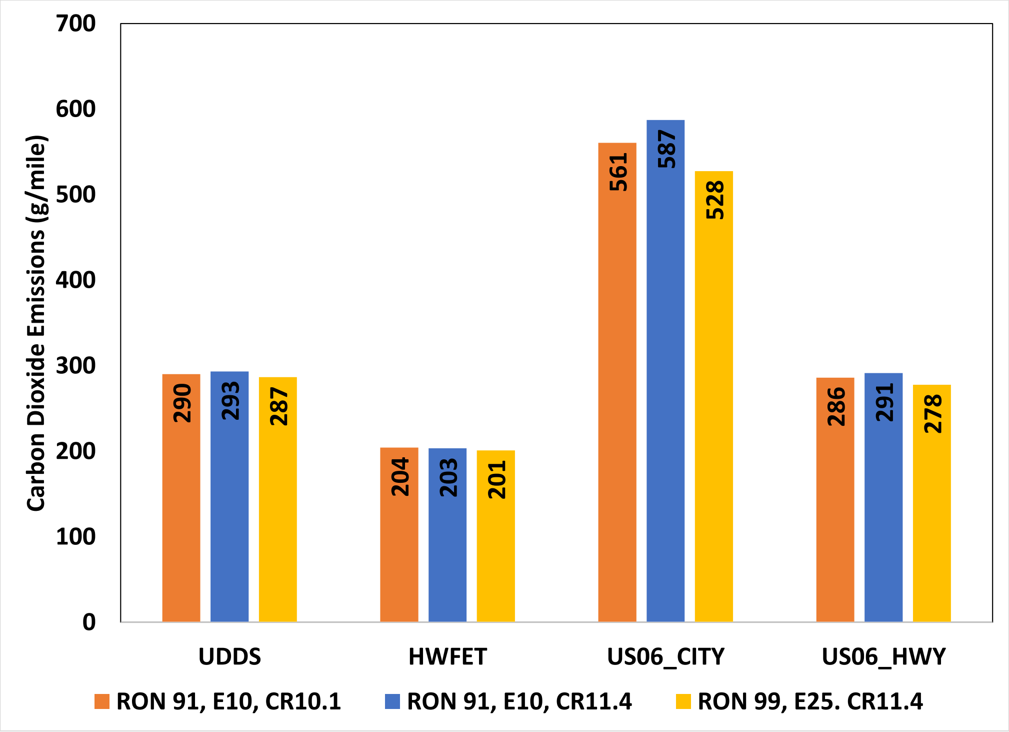


Figure 21. Tailpipe CO_2 emissions for the midsize sedan. (CR = compression ratio, HWFET = Highway Fuel Economy Test cycle, HWY = highway, RON = research octane number, and UDDS = Urban Dynamometer Driving Schedule.)

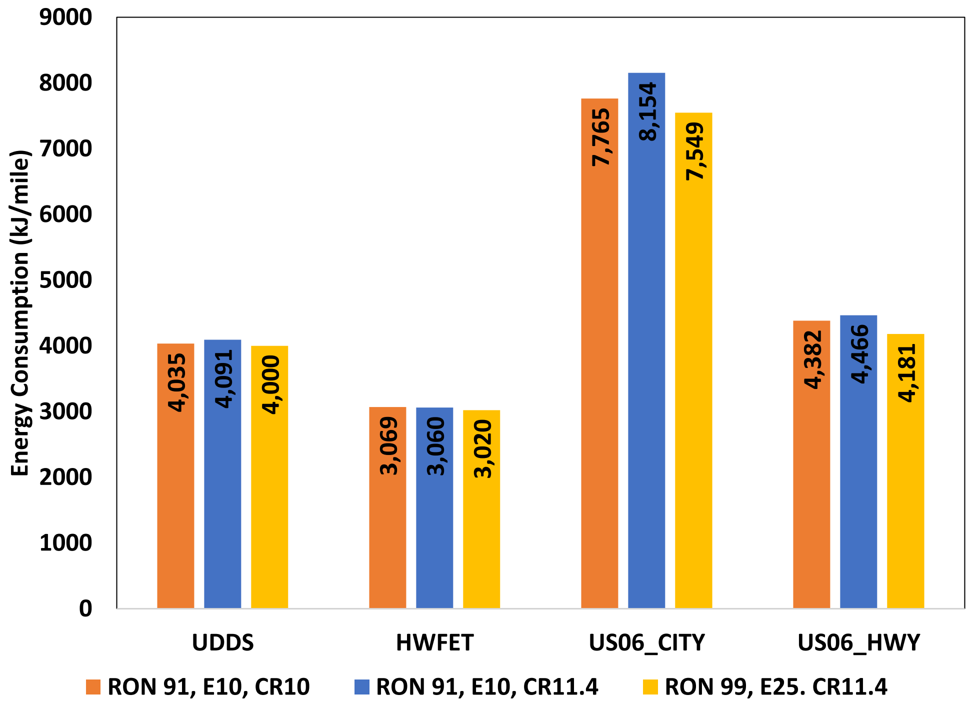


Figure 22. Energy consumption results for the small SUV. (CR = compression ratio, HWFET = Highway Fuel Economy Test cycle, HWY = highway, RON = research octane number, and UDDS = Urban Dynamometer Driving Schedule.)

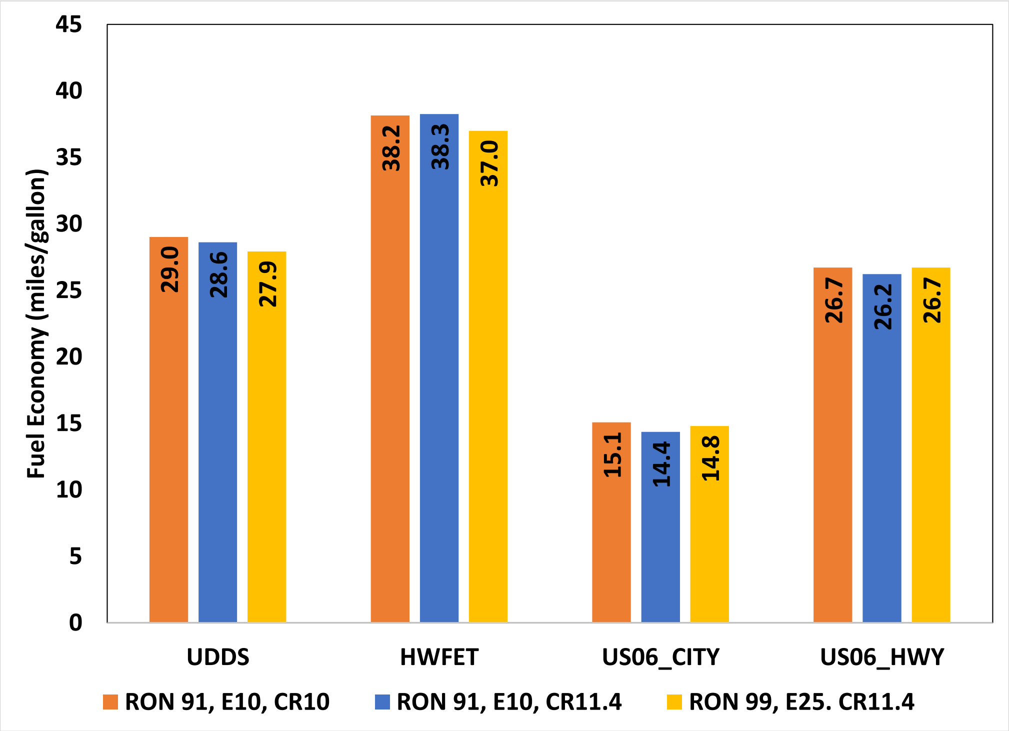


Figure 23. Volumetric fuel economy results for the small SUV. (CR = compression ratio, HWFET = Highway Fuel Economy Test cycle, HWY = highway, RON = research octane number, and UDDS = Urban Dynamometer Driving Schedule.)

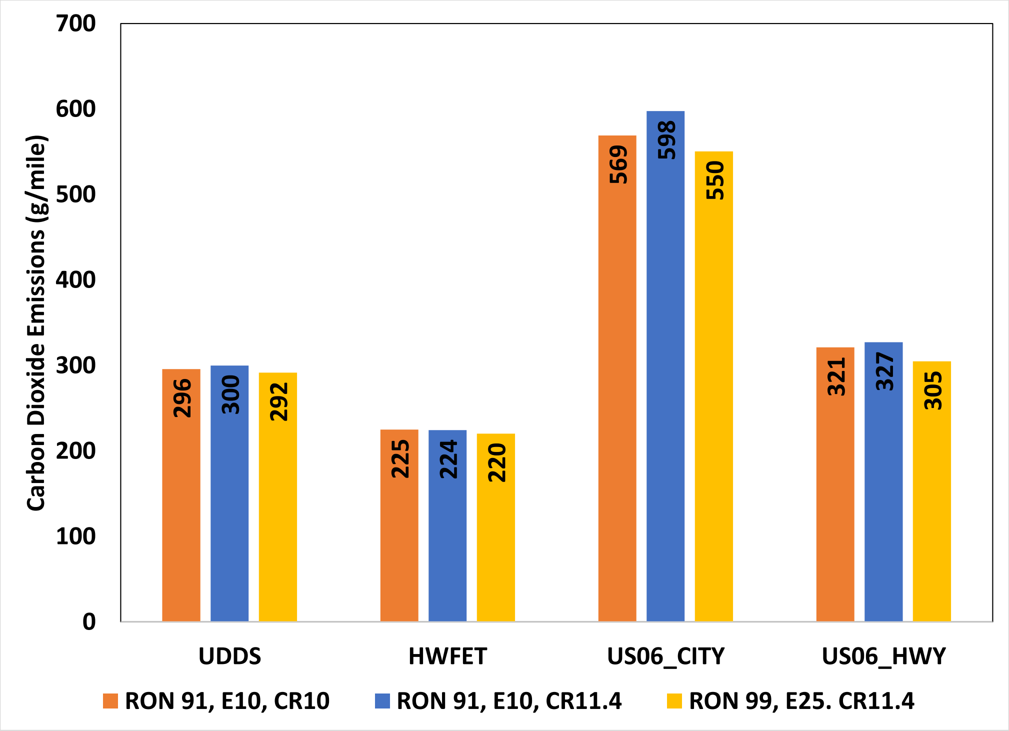


Figure 24. Tailpipe CO_2 emissions for the small SUV. (CR = compression ratio, HWFET = Highway Fuel Economy Test cycle, HWY = highway, RON = research octane number, and UDDS = Urban Dynamometer Driving Schedule.)

6. CONCLUSIONS

This study investigated the potential benefits associated with using a high-octane rating E25 fuel in a 1.6 L EcoBoost engine with a 1.3 increase in CR. The three primary metrics that were investigated were energy consumption, volumetric fuel economy, and tailpipe CO_2 emissions.

6.1 ENERGY CONSUMPTION

Increasing the engine CR from the 10.1 baseline to 11.4 increased engine efficiency in the MBT region. At the same time, this CR increase resulted in greater knock propensity for operation outside the MBT region. The results demonstrate that increasing the antiknock performance of the fuel reduces the energy penalty associated with knock avoidance outside the MBT region. Vehicle model results show that for an industry-average midsize sedan and small SUV, operation on the UDDS and HWFET is most significantly impacted by conditions in the MBT region of the engine operating map. Thus, the majority of the improvement in energy consumption that is possible on these cycles comes as a result of increasing CR. Nevertheless, both cycles contain enough operation under knock-limited conditions that this benefit is only attainable if the fuel antiknock properties (octane rating and sensitivity) are also improved. Otherwise, the increased knock propensity at higher CRs can cause energy consumption to increase rather than decrease, as is desired. This outcome was the case when the 91 RON E10 fuel was used with the CR 11.4 pistons. As noted previously, the E25 fuel had a RON value of 99 which could support a higher compression ratio than the 11.4 available for this study. In such a case, the energy consumption benefits of this fuel could be higher on the UDDS and HWEFET cycles.

Modeling operation of these vehicles on the US06 cycle results in a greater fraction of operating conditions being knock-limited. Thus, the opportunity for energy consumption improvements through the use of a fuel with improved antiknock performance is greater. Improvements in the energy consumption on both the city and highway portions of the US06 cycle were on the order of 2%–5%. The midsize sedan experienced the greatest improvement on the city portion of the US06 cycle, while the small SUV saw the greatest improvement on the highway portion of the cycle. As with UDDS and HWFET, use of the 91 RON E10 fuel in combination with increased CR caused energy consumption to increase.

6.2 VOLUMETRIC FUEL ECONOMY

Volumetric fuel economy results were dependent on both the energy efficiency of the engine and the volumetric energy content of the fuel. Because the E25 fuel has 4.7% less energy per gallon than the E10 fuel, only energy consumption improvements greater than 4.7% will achieve volumetric fuel economy parity. The results show that improvements in fuel economy associated with the use of a 99 RON E25 and a CR of 11.4 are achievable on the city portion of the US06 cycle for the midsize sedan and on the highway portion of the US06 cycle for the small SUV. In all other cases, the E25 fuel caused fuel economy to decline slightly even though energy consumption in these cases improved.

6.3 TAILPIPE CO_2 EMISSIONS

Use of the 99 RON E25 fuel in combination with increased CR reduced tailpipe CO_2 emissions on all drive cycles for both the midsize sedan and the small SUV. However, use of the 91 RON E10 fuel in combination with increased CR cause tailpipe CO_2 emissions to increase in several cases.

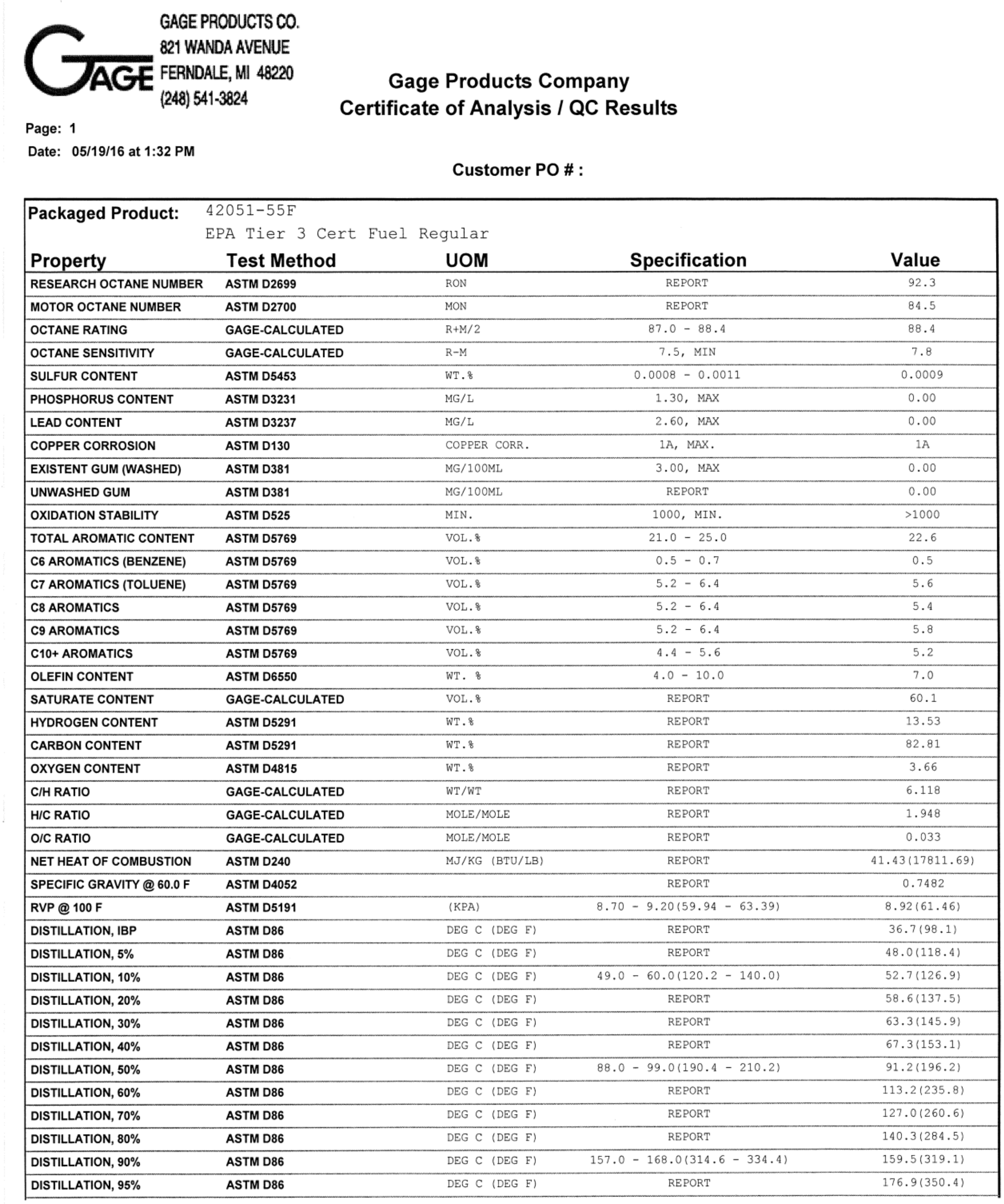
7. REFERENCES

1. Willems, S., “Automakers Want Higher Octane Gas and Are Starting to Do Something About It,” accessed April 22, 2017, at http://www.thetruthaboutcars.com/2017/04/automakers-want-higher-octane-stay-quiet-fear/.
2. 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.
3. 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.
4. 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.
5. Speth, R.L, Chow, E.W., Malina, R., Barrett, S.R.H., Heywood, J.B., and Green, W.H., “Economic and Environmental Benefits of Higher-Octane Gasoline,” *Environ. Sci. Technol.* 2014, 48, 6561–6568, doi:10.1021/es405557p.
6. Hirshfeld, D.S., Kolb, J.A., Anderson, J.E., Studzinski, W., and Frusti, J., “Refining Economics of U.S. Gasoline: Octane Ratings and Ethanol Content,” *Environ. Sci. Technol.*, 48, 11064-11071, doi:10.1021/es5012668.
7. Leone, T.G., Anderson, J.E., Davis, R.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.
8. Theiss, T., et al, *Summary of High-Octane Mid-Level Ethanol Blends Study*, Oak Ridge National Laboratory Report ORNL/TM-2016/42, 2016.
9. Sluder, C., Szybist, J., McCormick, R., Ratcliff, M. et al., “Exploring the Relationship Between Octane Sensitivity and Heat-of-Vaporization,” *SAE Int. J. Fuels Lubr.* 9(1):2016, doi:10.4271/2016-01-0836.
10. “Standard Test Method for Research Octane Number of Spark-Ignition Engine Fuel,” ASTM D2699 – 15.
11. “Standard Test Method for Motor Octane Number of Spark-Ignition Engine Fuel,” ASTM D2700 - 14.
12. Wu, W. and Ross, M., “Spark-Ignition Engine Fuel Consumption Modeling,” SAE Technical Paper 1999-01-0554, SAE International, 1999.
13. Shayler, P.J., Chick, J.P., and Eade, D., “A Method of Predicting Brake Specific Fuel Consumption Maps,” SAE Technical Paper 1999-01-0556, SAE International, 1999.
14. Ross, M. and An, F., “The Use of Fuel by Spark Ignition Engines,” SAE Technical Paper 930329, SAE International, 1993.
15. Leone, T.G., Anderson, J.E., Davis, R.S., Iqbal, A., Reese, R.A., Shelby, M.H., and Studzinksi, W.M., “The Effect of Compression Ratio, Fuel Octane Rating, and Ethanol Content on Spark-Ignition Engine Efficiency,” *Environ. Sci. Technol.*, 2014, 49(18): 10778–10789, doi: 10.1021/ace.est.5b01420.

16. Smith, P., Heywood, J., Cheng, W., "Effects of Compression Ratio on Spark-Ignited Engine Efficiency," SAE Technical Paper 2014-01-2599, 2014, DOI: 10.4271/2014-01-2599.
17. 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.
18. "Detailed Test Information," accessed May 22, 2017, at https://www.fueleconomy.gov/feg/fe_test_schedules.shtml.
19. "EPA Fuel Economy," accessed May 22, 2017, at http://www.greenercars.org/greenercars-ratings/epa-fuel-economy.
20. Kim, N., Rousseau, A., and Lohse-Busch, H., "Advanced Automatic Transmission Model Validation Using Dynamometer Test Data," SAE Technical Paper 2014-01-1778, 2014, doi:10.4271/2014-01-1778.
21. "Detailed Test Information," accessed May 22, 2017, at https://www.fueleconomy.gov/feg/fe_test_schedules.shtml.
22. 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, doi:10.4271/2014-01-1572.
23. "Control of Air Pollution from Motor Vehicles: Tier 3 Motor Vehicle Emission and Fuel Standards," 79 Federal Register 23547, April 28, 2014.

APPENDIX A. FUEL CERTIFICATES OF ANALYSIS

APPENDIX A. FUEL CERTIFICATES OF ANALYSIS



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

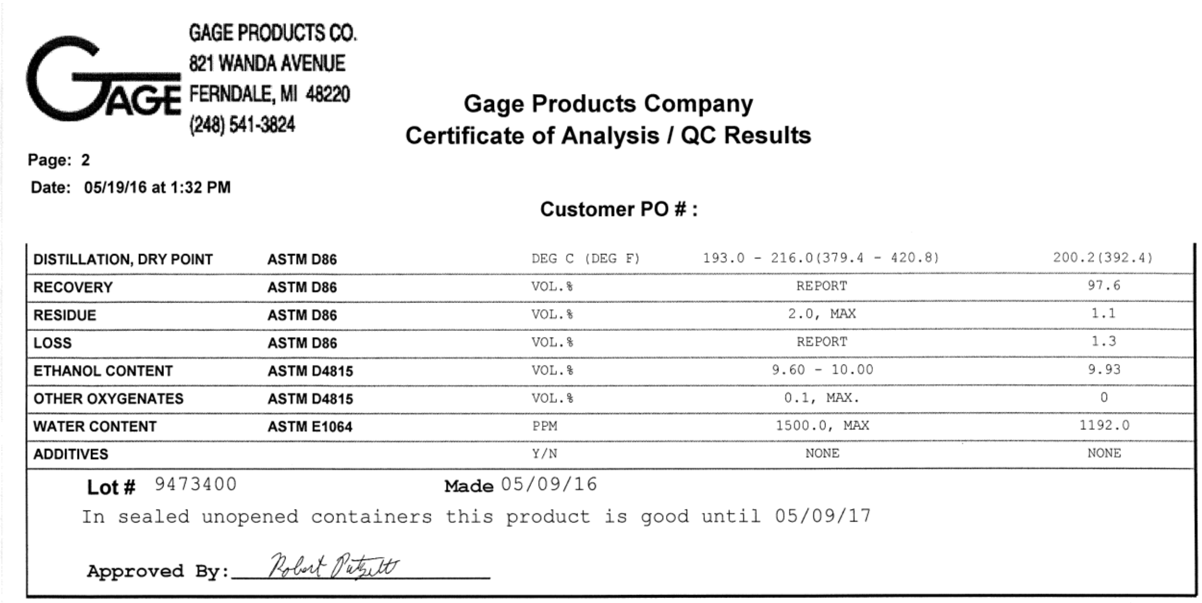
Gage Products Company
Certificate of Analysis / QC Results

Page: 1
Date: 05/19/16 at 1:32 PM

Customer PO # :

Packaged Product: 42051-55F
EPA Tier 3 Cert Fuel Regular

Property	Test Method	UOM	Specification	Value
RESEARCH OCTANE NUMBER	ASTM D2699	RON	REPORT	92.3
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	84.5
OCTANE RATING	GAGE-CALCULATED	R+M/2	87.0 - 88.4	88.4
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	7.5, MIN	7.8
SULFUR CONTENT	ASTM D5453	WT.%	0.0008 - 0.0011	0.0009
PHOSPHORUS CONTENT	ASTM D3231	MG/L	1.30, MAX	0.00
LEAD CONTENT	ASTM D3237	MG/L	2.60, MAX	0.00
COPPER CORROSION	ASTM D130	COPPER CORR.	1A, MAX.	1A
EXISTENT GUM (WASHED)	ASTM D381	MG/100ML	3.00, MAX	0.00
UNWASHED GUM	ASTM D381	MG/100ML	REPORT	0.00
OXIDATION STABILITY	ASTM D525	MIN.	1000, MIN.	>1000
TOTAL AROMATIC CONTENT	ASTM D5769	VOL.%	21.0 - 25.0	22.6
C6 AROMATICS (BENZENE)	ASTM D5769	VOL.%	0.5 - 0.7	0.5
C7 AROMATICS (TOLUENE)	ASTM D5769	VOL.%	5.2 - 6.4	5.6
C8 AROMATICS	ASTM D5769	VOL.%	5.2 - 6.4	5.4
C9 AROMATICS	ASTM D5769	VOL.%	5.2 - 6.4	5.8
C10+ AROMATICS	ASTM D5769	VOL.%	4.4 - 5.6	5.2
OLEFIN CONTENT	ASTM D6550	WT. %	4.0 - 10.0	7.0
SATURATE CONTENT	GAGE-CALCULATED	VOL.%	REPORT	60.1
HYDROGEN CONTENT	ASTM D5291	WT.%	REPORT	13.53
CARBON CONTENT	ASTM D5291	WT.%	REPORT	82.81
OXYGEN CONTENT	ASTM D4815	WT.%	REPORT	3.66
C/H RATIO	GAGE-CALCULATED	WT/WT	REPORT	6.118
H/C RATIO	GAGE-CALCULATED	MOLE/MOLE	REPORT	1.948
O/C RATIO	GAGE-CALCULATED	MOLE/MOLE	REPORT	0.033
NET HEAT OF COMBUSTION	ASTM D240	MJ/KG (BTU/LB)	REPORT	41.43(17811.69)
SPECIFIC GRAVITY @ 60.0 F	ASTM D4052		REPORT	0.7482
RVP @ 100 F	ASTM D5191	(KPA)	8.70 - 9.20(59.94 - 63.39)	8.92(61.46)
DISTILLATION, IBP	ASTM D86	DEG C (DEG F)	REPORT	36.7(98.1)
DISTILLATION, 5%	ASTM D86	DEG C (DEG F)	REPORT	48.0(118.4)
DISTILLATION, 10%	ASTM D86	DEG C (DEG F)	49.0 - 60.0(120.2 - 140.0)	52.7(126.9)
DISTILLATION, 20%	ASTM D86	DEG C (DEG F)	REPORT	58.6(137.5)
DISTILLATION, 30%	ASTM D86	DEG C (DEG F)	REPORT	63.3(145.9)
DISTILLATION, 40%	ASTM D86	DEG C (DEG F)	REPORT	67.3(153.1)
DISTILLATION, 50%	ASTM D86	DEG C (DEG F)	88.0 - 99.0(190.4 - 210.2)	91.2(196.2)
DISTILLATION, 60%	ASTM D86	DEG C (DEG F)	REPORT	113.2(235.8)
DISTILLATION, 70%	ASTM D86	DEG C (DEG F)	REPORT	127.0(260.6)
DISTILLATION, 80%	ASTM D86	DEG C (DEG F)	REPORT	140.3(284.5)
DISTILLATION, 90%	ASTM D86	DEG C (DEG F)	157.0 - 168.0(314.6 - 334.4)	159.5(319.1)
DISTILLATION, 95%	ASTM D86	DEG C (DEG F)	REPORT	176.9(350.4)



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

Gage Products Company
Certificate of Analysis / QC Results

Page: 2
Date: 05/19/16 at 1:32 PM

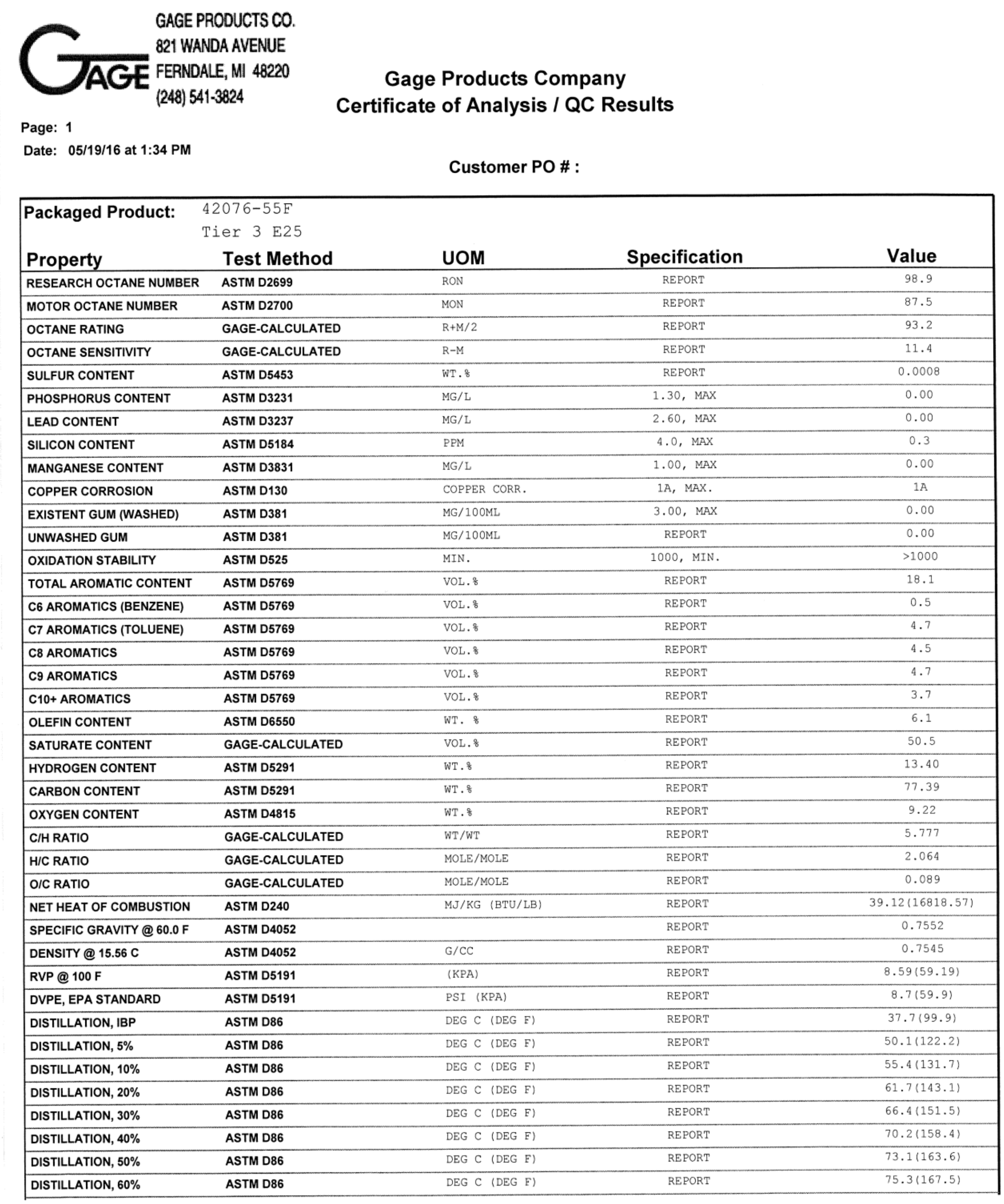
Customer PO # :

DISTILLATION, DRY POINT	**ASTM D86**	DEG C (DEG F)	193.0 - 216.0(379.4 - 420.8)	200.2(392.4)
RECOVERY	**ASTM D86**	VOL.%	REPORT	97.6
RESIDUE	**ASTM D86**	VOL.%	2.0, MAX	1.1
LOSS	**ASTM D86**	VOL.%	REPORT	1.3
ETHANOL CONTENT	**ASTM D4815**	VOL.%	9.60 - 10.00	9.93
OTHER OXYGENATES	**ASTM D4815**	VOL.%	0.1, MAX.	0
WATER CONTENT	**ASTM E1064**	PPM	1500.0, MAX	1192.0
ADDITIVES		Y/N	NONE	NONE

Lot # 9473400 **Made** 05/09/16

In sealed unopened containers this product is good until 05/09/17

Approved By: Robert Patzelt



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

Gage Products Company
Certificate of Analysis / QC Results

Page: 1
Date: 05/19/16 at 1:34 PM

Customer PO # :

Packaged Product: 42076-55F
Tier 3 E25

Property	Test Method	UOM	Specification	Value
RESEARCH OCTANE NUMBER	ASTM D2699	RON	REPORT	98.9
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	87.5
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	93.2
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	REPORT	11.4
SULFUR CONTENT	ASTM D5453	WT.%	REPORT	0.0008
PHOSPHORUS CONTENT	ASTM D3231	MG/L	1.30, MAX	0.00
LEAD CONTENT	ASTM D3237	MG/L	2.60, MAX	0.00
SILICON CONTENT	ASTM D5184	PPM	4.0, MAX	0.3
MANGANESE CONTENT	ASTM D3831	MG/L	1.00, MAX	0.00
COPPER CORROSION	ASTM D130	COPPER CORR.	1A, MAX.	1A
EXISTENT GUM (WASHED)	ASTM D381	MG/100ML	3.00, MAX	0.00
UNWASHED GUM	ASTM D381	MG/100ML	REPORT	0.00
OXIDATION STABILITY	ASTM D525	MIN.	1000, MIN.	>1000
TOTAL AROMATIC CONTENT	ASTM D5769	VOL.%	REPORT	18.1
C6 AROMATICS (BENZENE)	ASTM D5769	VOL.%	REPORT	0.5
C7 AROMATICS (TOLUENE)	ASTM D5769	VOL.%	REPORT	4.7
C8 AROMATICS	ASTM D5769	VOL.%	REPORT	4.5
C9 AROMATICS	ASTM D5769	VOL.%	REPORT	4.7
C10+ AROMATICS	ASTM D5769	VOL.%	REPORT	3.7
OLEFIN CONTENT	ASTM D6550	WT. %	REPORT	6.1
SATURATE CONTENT	GAGE-CALCULATED	VOL.%	REPORT	50.5
HYDROGEN CONTENT	ASTM D5291	WT.%	REPORT	13.40
CARBON CONTENT	ASTM D5291	WT.%	REPORT	77.39
OXYGEN CONTENT	ASTM D4815	WT.%	REPORT	9.22
C/H RATIO	GAGE-CALCULATED	WT/WT	REPORT	5.777
H/C RATIO	GAGE-CALCULATED	MOLE/MOLE	REPORT	2.064
O/C RATIO	GAGE-CALCULATED	MOLE/MOLE	REPORT	0.089
NET HEAT OF COMBUSTION	ASTM D240	MJ/KG (BTU/LB)	REPORT	39.12(16818.57)
SPECIFIC GRAVITY @ 60.0 F	ASTM D4052		REPORT	0.7552
DENSITY @ 15.56 C	ASTM D4052	G/CC	REPORT	0.7545
RVP @ 100 F	ASTM D5191	(KPA)	REPORT	8.59(59.19)
DVPE, EPA STANDARD	ASTM D5191	PSI (KPA)	REPORT	8.7(59.9)
DISTILLATION, IBP	ASTM D86	DEG C (DEG F)	REPORT	37.7(99.9)
DISTILLATION, 5%	ASTM D86	DEG C (DEG F)	REPORT	50.1(122.2)
DISTILLATION, 10%	ASTM D86	DEG C (DEG F)	REPORT	55.4(131.7)
DISTILLATION, 20%	ASTM D86	DEG C (DEG F)	REPORT	61.7(143.1)
DISTILLATION, 30%	ASTM D86	DEG C (DEG F)	REPORT	66.4(151.5)
DISTILLATION, 40%	ASTM D86	DEG C (DEG F)	REPORT	70.2(158.4)
DISTILLATION, 50%	ASTM D86	DEG C (DEG F)	REPORT	73.1(163.6)
DISTILLATION, 60%	ASTM D86	DEG C (DEG F)	REPORT	75.3(167.5)

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

Gage Products Company
Certificate of Analysis / QC Results

Page: 2
Date: 05/19/16 at 1:34 PM

Customer PO # :

DISTILLATION, 70%	**ASTM D86**	DEG C (DEG F)	REPORT	106.0(222.8)
DISTILLATION, 80%	**ASTM D86**	DEG C (DEG F)	REPORT	134.2(273.6)
DISTILLATION, 90%	**ASTM D86**	DEG C (DEG F)	REPORT	154.2(309.6)
DISTILLATION, 95%	**ASTM D86**	DEG C (DEG F)	REPORT	172.1(341.8)
DISTILLATION, DRY POINT	**ASTM D86**	DEG C (DEG F)	215.0(419.0), MAX	197.2(387.0)
RECOVERY	**ASTM D86**	VOL.%	REPORT	97.9
RESIDUE	**ASTM D86**	VOL.%	2.0, MAX	1.0
LOSS	**ASTM D86**	VOL.%	REPORT	1.1
ETHANOL CONTENT	**ASTM D4815**	VOL.%	24.50 - 25.50	25.27
OTHER OXYGENATES	**ASTM D4815**	VOL.%	0.1, MAX.	0
MTBE CONTENT	**ASTM D4815**	VOL%	REPORT	0.00
ETBE CONTENT	**ASTM D4815**	VOL%	REPORT	0.00
METHANOL CONTENT	**ASTM D4815**	VOL%	REPORT	0.00
WATER CONTENT	**ASTM E1064**	PPM	REPORT	2676.2
ADDITIVES		Y/N	NONE	NONE

Lot # 9508200 **Made** 05/14/16

In sealed unopened containers this product is good until 05/14/17

Approved By: Robert Patzelt